MONASH UNIVERSITY
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REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
ON.............. 4 October 2002 ....

.......................[redacted]......................

Sec. Research Graduate School Committee

Erratum

Note: line number does not include numbered headings

p. I line 21 should read – 'reach' scale.
p. II line 2 should read – recovery of this river
p. II line 3 should read – vegetated riparian
p. VII heading 5.4.3 should read – p102
p. XVII Table 5.6 should start with Slope
p. XVII Table 5.7 should read – Manning's n
p. XVIII Plate 4.12 should read – the river has since cut a new course
p. XXI ρ and ρ_s are the wrong way round
p. 2 line 5 should read – alternative definitions
p. 5 line 7 should read – disturbances
p. 8 line 21 should read – testable hypotheses
p. 9 line 8 should read – a diverse range of techniques is presented
p. 9 line 12 should read – using an Index
p. 14 line 8 and 9 should read – endpoints
p. 15 line 6 should read – Thorne et al.,
p.18 line 13 should read – level of geomorphic
p. 20 line 9 should read – changes in stream discharge are
p. 20 line 15 should read – surveying streams
p. 21 line 18 should read – the benefit of such techniques
p. 22 line 16 should read – there is a great
p. 31 line 1 should read – Nicholas et al., (1995) suggest
p. 34 line 4 should read – sediment that actually
p. 37 line 12 should read – and attempts to build
p. 39 line 26 should read – the impact on each slug
p. 41 line 16 should read – section of a stream
p. 51 line 10 should read – and increase braiding
p. 53 line 19 should read – many streams
p. 61 line 10 should read – upstream areas
p. 69 line 20 should read – occurred in a letter
p. 72 line 4 should read – Plate 4.9 was taken
p. 74 line 26 should read – Bass Strait
p. 76 line 15 should read – for streams in
p. 76 line 17 should read – supply sources
p. 76 line 17 should read – volumes delivered
p. 76 line 20 should read – mass-conservation
p. 77 line 20 should read – catchment is closely linked
p. 77 line 21 should read – the palaeogeological record
p. 78 line 2 should read – mainly in winter
p. 78 line 3 should read – daily minimum temperatures
p. 78 line 8 should read – the catchment includes
p. 83 line 19 should read – Herrick has been
p. 84 line 30 should read – most active port
p. 85 line 7 should read – over 5 year period
p. 85 line 12 should read – the Briseis Mine were 12 metres
p. 90 line 14 should read – streams were assessed
p. 94 line 14 should read – survey are also
p. 95 line 17 should read – parameters measured
p. 96 line 5 should read – the three different phases
p. 101 line 1 should read – Table 5.3: represents the type...
p. 101 line 8 should read – sediment depth and LWD are dependent variables
p. 102 line 8 should read – is still important
p. 102 line 30 should read – 'authors knowledge'
p. 103 heading 8.1.1 should read heading 5.4.4
p. 104 line 27 should read – due to the data
p. 105 line 17 should read – cross-section was used
p. 106 heading 8.1.1 should read as heading 5.5.4
p. 109 heading 8.1.1.1 should read as heading 5.5.5.2
p. 109 lines 18 should read – Reaches 1-7 was determined
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p. 112 line 22 should read – to which the dependent
p. 121 line 5 should read – representing more stable
p. 123 heading 8.1.1. should read heading 5.7.1
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p. 188 line 1 should read – provides a numerical estimate
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p. 189 line 8 should read – each of these techniques is described in more detail in
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p. 200 line 14 should read – number of adaptations
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p. 223 line 6 should read – significantly increased
p. 225 line 15 should read – the slugged and non-slugged areas
p. 238 line 8 should read – It is also

p. 241 line 12 should read – introduced mobile sand
p. 245 line 7 should read – suggesting that there are
p. 245 heading 8.1 should be 9.6
p. 246 line 8 should read – have relatively high values
p. 252 line 5 should read – stream systems change
p. 252 line 13 should read – streams according to the
p. 252 line 21 should read – models is also presented
p. 253 line 8 should read – response of the
p. 254 lines 8, 15, 26 should read – principal
p. 257 line 19 should read – the relatively small numbers
p. 258 line 10 should read – Reaches 4 and 12 is removed
p. 261 line 8 should read – Geomorphic Variability was
p. 262 line 20 should read – Geomorphic Variability was
p. 264 line 19 should read – Geomorphic Variability was
p. 265 line 4 should read – Variability were discussed
p. 266 line 2 should read – proving to be an important
p. 267 line 9 should read – impacted reaches been determined
p. 268 line 3 should read – The power function curves
p. 268 line 10 should read – greater than 1 metre
p. 269 line 1 should read – a drop in the level
p. 269 line 3 should read – is less than
p. 273 line 24 should read – the recovery process
p. 274 line 19 should read – to use all the data
p. 274 line 29 should read – recovery is made
p. 282 line 21 should read – streams disturbed by sediment slugs
p. 282 line 28 should read – that had relatively
p. 286 line 12 should read – that would be expected
p. 287 line 4 should read – according to the Geomorphic
p. 288 line 11 should read – this thesis was presented
p. 292 line 10 should read – techniques was then used
p. 294 line 4 should read – relationships need to be
p. 298 line 3 should read – undertaking macroinvertebrate
p. 324 line 5 should read – event that was
Appendix E velocity data should read – m/s not m^3/s

Persistent errors

- Where 'data is', data has', 'data shows' etc appears in the text, it should read as 'data are', 'data have', 'data show', respectively (e.g. p 18, 69, 101, 110, 130, 146, 154, 156, 185, 188, 190, 191, 208, 212, 214, 218, 226, 227, 231, 232, 235, 237, 238, 239, 242, 244, 249, 255)
- The word effect and affect have been misused in many places and should be swapped (e.g. p 122, 135, 136, 141, 150, 170, 194, 223, 229, 272, 273, 282)
- The word 'co-efficient' should be replaced with 'coefficient' on pages 259, 166, 195, 293.
- 'Each are/were/have' should read 'each is/was/has' in a number of cases (e.g. p 1, 1298, 189, 209, 250, 268, 293).

Addendum

Page 96, after paragraph 2, new paragraph:

A sediment depth of 1/5th the mean bank height was chosen based on preliminary field investigations. During initial reconnaissance field work, at least 20 streams that had been impacted by sediment slugs were examined. It was often difficult to differentiate between the naturally sandy bed loads of streams in granite or sand-stone catchments, and streams that actually contained a 'sediment slug'. During this preliminary investigation it was observed that roughly 1/5th of the mean bank height appeared to be the point that differentiated between sites that had been disturbed by an anthropogenically induced sediment slug, and sections of the stream that had not. In reaches where the sediment slug was beginning to evacuate (ie. recovering), it was also observed that the sediment depths were usually less than ~1/5th of the mean bank height, and declining. The other important visual association for choosing 1/5th of the mean bank height was that this value appeared to be the point at which pool features were drowned out, as well as the point at which features such as logs and snags became completely smothered.

Page 133, after paragraph 1, new paragraph:

The entrainment discharges for Creightons Creek do look very low for sand sized particles, however, continual bed material movement was observed along the impacted sections of the stream even under extremely low flow conditions. Hence, these values are considered appropriate, particularly in light of the ecological implications of the 'constantly shifting sand' as discussed in O'Conner and Lake (1994) and in Chapter 3.

Page 139, after paragraph 1, new paragraph:

The entrainment discharges for the Wannon River do look very low particularly in the impacted reaches, however, continual bed material movement was observed in the sandy reaches even during the driest year on record (2000). There were rather large differences between the sediment entrainment discharges required to move sediments in Reach 10 compared to Reach 11. This was because Reach 11 had a D_{50} of 0.062 mm and Reach 10 had a D_{50} of 0.44 mm. This subtle difference had major implications for the sediment stability results, and thus the observed differences.

Page 160, Equations 7.5, 7.6 and 7.7 should appear as:

$D_{P\text{-}Creightons} = 0.183(0.45C^{0.5})$ Equatio

$D_{P\text{-}Wannon} = 0.183(0.26C^{0.5})$ Equatio

$D_{P\text{-}Ringarooma} = 0.183(1.26C^{0.5})$ Equatio

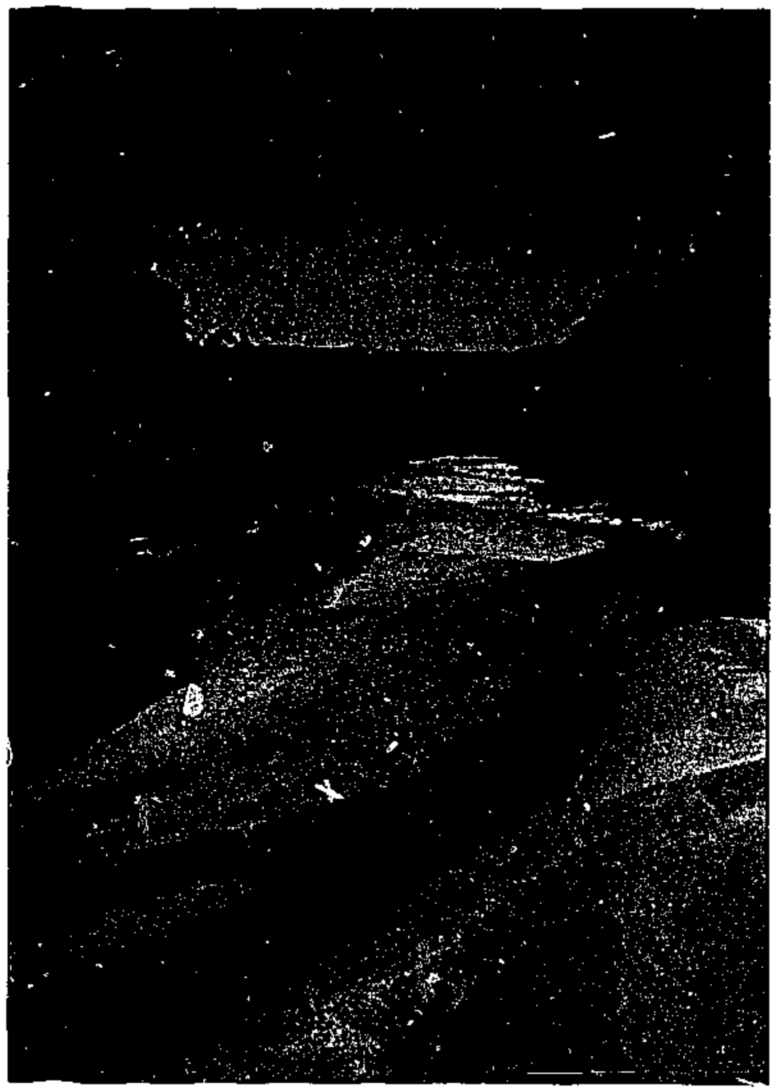
Page 194, paragraph 1, after sentence 4, insert sentence:

The parameter Z_{bf} is the maximum depth at bankfull.

Page 255, paragraph 4, after sentence 2, insert sentence:

Each of the data sets of the 4 variables that make up the Index were standardised (using the method described in Chapter 9 ie. Zar, 1996, p73: $Z = \frac{X_i - \mu}{\sigma}$). Standardising the data transforms the mean (μ) of each data set to equal zero (0), and variance (σ) equal to one (1). This produces the value Z, which is the normal deviate or standard score. This process allows all of the values to have the same order of magnitude, and it prevents bias in the data.

Quantifying the Geomorphic Recovery of Disturbed Streams: Using Migrating Sediment Slugs as a Model



Ringarooma River, Tasmania

By

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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Publications and Conference presentations:

Book chapters and conference proceedings:

- Bartley, R. and Rutherfurd, I. (2001) Ringarooma River (a case study of sediment delivery and recovery). In Marutani, T., Brierley, G., Trustrum, N., Page, M. "Source-to-Sink Sedimentary Cascades in Pacific Rim Geo-systems". Published by Nippon Alps Sabo Center, Ministry of Land, Infrastructure and Transport, Tokyo, p 132-139.
- Bartley, R., Rutherfurd, I., Davis, J. and Finlayson, B. (2001) Creightons Creek (a case study of sediment delivery and recovery). In Marutani, T., Brierley, G., Trustrum, N., Page, M. "Source-to-Sink Sedimentary Cascades in Pacific Rim Geo-systems". Published by Nippon Alps Sabo Center, Ministry of Land, Infrastructure and Transport, Tokyo, p 140-147.
- Rutherfurd, I. and Bartley, R. (Editors) (1999) Proceedings of the Second Australian Stream Management Conference. CRC for Catchment Hydrology, Adelaide. 774p

Conference Papers and Abstracts:

- Bartley, R. and Rutherfurd, I., (2001). Statistics, snags and sand: measuring the geomorphic recovery of streams disturbed by sediment slugs. In: I. Rutherfurd, F. Sheldon, G. Brierley and C. Kenyon (Editors), Proceedings of the Third Australian Stream Management Conference. Cooperative Research Centre for Catchment Hydrology, Brisbane, p15-21, Volume 1.
- Bartley, R. (2001). Predicting pre-disturbance pool depth: a tool for stream rehabilitation, 29th International Association of Hydraulic Research (IAHR) Congress, Beijing, Sept 2001, p166 - 177, J.F. Kennedy Student Paper Competition, Guifen LI (Ed).
- Bartley, R. and Rutherfurd, I. (2001). Quantifying the geomorphic recovery of streams disturbed by anthropogenically produced sediment slugs. Proceedings of the 5th International Conference on Geomorphology, Tokyo, August 2001.
- Bartley, R. (2001). Quantifying the recovery potential of disturbed river systems: a tool for stream rehabilitation, Australian Water Association 19th Federal Convention. AWA, Ozwater, Canberra, pp. 242-249. (Winner of CRC Young Water Scientist of the Year Award)
- Rutherfurd, I. and Bartley, R. (2000) Physio-therapy for your stream: the dangers and potential of geomorphic models of stream disturbance and recovery in stream rehabilitation. Murrumbidgee 2000 Conference, Charles Sturt University, Wagga Wagga, July 2000.
- Bartley, R. and Rutherfurd, I. (1999). The recovery of geomorphic complexity in disturbed streams: using migrating sand slugs as a model. In, Rutherfurd, I. and Bartley, R. (Eds) Proceedings of the Second Australian Stream Management Conference, Adelaide. CRC for Catchment Hydrology, Melbourne. p 39-44.
- Bartley, R. and Rutherfurd, I (1999) What is the impact of sediment slugs on the geomorphic variability of streams? Australian and New Zealand Society for Limnology Biannual Conference, Lake Taupo, New Zealand.

Other publications

- Bartley, R., Rutherfurd, I., Hairsine, P., Prosser, I., Wallbrink, P., and Perry, D. (2001) 'Australia is on the move...down the creek'. Australian Landcare Farm Journal, December, 2001.
- Bartley, R. and Cowell, P. (1998) Barrier translation for different rates of sea-level rise. The Australian and New Zealand Geomorphology Conference, Goolwa, SA.

Abstract

Stream rehabilitation involves accelerating the natural recovery processes in disturbed river systems. However, the definitions and techniques for measuring recovery, and the spatial and temporal scales over which recovery occurs within disturbed streams, are not well understood. The research described in this thesis has developed a framework for measuring and quantifying the recovery of streams that have been disturbed by anthropogenically produced pulses of sediment, known as sediment slugs.

Sediment slugs are increasingly recognised as an environmental disturbance, particularly in Australian stream systems. Many slugs have a well defined 'back-end' which make them suitable for measuring recovery. To conceptualise the recovery process, a Geomorphic Recovery model was developed; this model was an adaptation of existing recovery models, which were considered inappropriate for measuring recovery at a scale that is relevant to the habitat and biota in the stream. It is increasingly important to look at geomorphic processes at the habitat scale, as species diversity and abundance is the primary measure of stream health, and it has been shown that species diversity is directly linked to habitat diversity. Therefore, the model in this thesis used 'Geomorphic Variability' as a measure of recovery, instead of traditional indicators such as mean bed level.

The term Geomorphic Variability is made up of four main factors: thalweg variability, cross-sectional variability, sediment size variation and sediment stability. Each of the components was selected following a review of the methodology currently used to measure stream health and habitat. The selected factors are considered the most important for habitat at the 'reach' scale'.

To measure Geomorphic Variability in the field, a statistically based sampling framework was devised. Data were collected from three rivers in south eastern Australia each containing a sediment slug: Creightons Creek, the Wannon River and the Ringarooma River. These data were analysed using a range of quantitative techniques such as fractal analysis, vector dispersion and local linear smoothing. Following data analysis, each of the individual variables were incorporated into an Index of Geomorphic Variability. This Index was then used to evaluate the Geomorphic Recovery model.

The results of the analysis suggest that not all of the streams responded according the Geomorphic Recovery model proposed in this thesis. Only one stream, the Ringarooma

River, appears to be making a full recovery. The main factors that have contributed to the natural recovery of the this river are the bedrock and gravel bed which help stabilise the bed (preventing further incision beyond the original bed level), the well vegetation riparian zone, and the fact that the dominant source of sediment was from an exogenous rather than endogenous source. Because the sediment was from an exogenous (external mining) source means that the sediment supply is essentially finite.

Creightons Creek and the Wannon River have alluvial clay beds which are undergoing various degrees of channel incision following the evacuation of the sediment slug. This characteristic, along with other factors such as high levels of vegetation removal (both in the catchment and within the stream channel) is impairing the recovery process on these streams. Overall, the results from the research on these three streams have provided an idea of how other streams that have been impacted by sediment slugs can be expected to respond.

Results from this research also showed that sediment depths need to be reduced to less than 20% of the reach volume before geomorphic heterogeneity can develop. It was found that Geomorphic Variability (and thus habitat) decrease with increasing sediment depths according to a power function relationship .

In light of the research findings, a range of management outcomes are indicated. These include incorporating the natural recovery process into the management plans for disturbed stream systems, which has the potential to save considerable amounts of money now spent on stream restoration.

Statement

This thesis contains no material which has been accepted for the award of any other degree in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person, except when due reference is made in the text of the thesis.

Signed [redacted]

Rebecca Bartley

Acknowledgments

I have finally finished my thesis. As I reflect on the events of the last three and half years, and the process of completing such a major piece of work, there are a few simple thoughts that stand out:

- That was bloody hard work;
- I have learnt so much, yet I still have so much to learn;
- Had I not had such a great network of people around me, I doubt I would have been able to complete this thesis, at least not without losing my sanity!

I have many people to thank…

To my supervisors Dr Ian Rutherfurd and Professor Russell Mein. Ian, your constant infectious enthusiasm for 'all things rivers' inspired me into areas that I never thought I would go. Thankyou for your dedication and humour during the trials of my 'slug-bum' thesis. Russell, for putting your trust in me as I deviated from traditional hydro-geomorphology, and for your guidance, support and wisdom - thankyou. Thanks also to Ian Prosser and Peter Hairsine for showing enthusiasm in my work and its application to other areas within the Cooperative Research Centre for Catchment Hydrology (CRCCH).

To all the people from the CRCCH who helped conceptualise my thesis in its early days: Bruce Abernethy, Chris Gippel, John Gooderham, Kath Jerie, Phil Jordan, Mike Stewardson and Andrew Western. Thankyou for allowing me to pester you and absorb some of your knowledge.

For all those that helped with the field work. Thankyou to David Outhet, Tony Broderick and Tim Smith (NSW Department of Land and Water Conservation) for help with my early field site selection and sediment slug reports in NSW.

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To Mum and Dad for their love support through the entire eight years of University and to the McJannet family for giving me a home on return visits to Monash.

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List of Abbreviations

ARI	Average recurrence interval
AUSRIVAS	Australian River Assessment System
CoV	Co-efficient of variation
CRC	Cooperative Research Centre
CRCCH	Cooperative Research Centre for Catchment Hydrology
CRCFE	Cooperative Research Centre for Freshwater Ecology
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DPIWE	Department of Primary Industries, Water and the Environment (Tasmania)
HCA	Hierarchical Cluster Analysis
I. D & A	Ian Drummond and Associates (river management consultants)
Loess	Local Linear Smoothing technique
LWD	Large woody debris
MFFMI	Mean Flash Flood Magnitude Index
MSE	Mean Squared Error
MSW	Mean stream width
PDD	Pre-disturbance depth
RBS	Relative Bed Stability
SD	Standard Deviation
SE	Standard Error
SKM	Sinclair Knight Merz (river management engineering consultants)
SSAA	Soil Standards Association of Australia
TFR	Transient-form Ratio
VD	Vector Dispersion
WW2	World War II

Notation

A	cross-sectional area (m^2)
a,b,c,k,f,m	constants
C	catchment Area (km^2)
C_t	cycle or periodicity
CoV	coefficient of Variation
D_{50}	median size of bed material
D	fractal dimension
d_a	d_{50} armour layer
D_P	mean pool depth (m)
d_{sub}	d_{50} subsurface (below armour) layer
F	width/depth ratio
g	acceleration due to gravity (9.81)
G	Gini coefficient
k_1	Coefficient of abrasion
k_2	Coefficient of sorting
L	meander wavelength
L_A	apparent distance
L_P	pool length (m)
L_0	distance downstream
L_S	linear distance
n	Manning's n
m_t	trend or slope
P	sinuosity
Q	discharge
Q_2	1 in 2 year discharge (m^3/s)
Q_s	sediment load
R	hydraulic radius
Re_*	particle shear velocity Reynolds number
S,s	slope or channel gradient
t	time
v	velocity
w	channel width
W	weight of the particle
$\overline{w}$	non-dimensional degree of wiggliness
WP	wetted perimeter
$\bar{y}$	depth (mean channel depth)
X	scaling parameter
α	critical t value
ε_t	random component
$\Delta\Phi$	change in angle
$\varnothing$	Phi Mean
μ	mean
λ	abrasion co-efficient
ν	kinematic viscosity
ρ	density of particle
ρ_s	density of fluid
θ_t	angle from horizontal
τ_o	average bed shear stress
τ_c	average particle shear stress
θ_c	dimensionless critical shear stress constant
σ	standard deviation
ω	unit stream power
Σ	sum
Ψ	cross-section shape parameter

Chapter 1

Introduction

1.1 General Overview and Purpose of thesis
1.2 Background concepts, previous research and a new approach for evaluating recovery
1.3 Objectives and context of the study
1.4 Structure of thesis

1. Chapter 1 - Introduction

1.1 General Overview and Purpose of thesis

This thesis investigates the concepts of geomorphic disturbance and recovery in stream systems impacted by anthropogenically produced pulses of sediment, known as sediment slugs.

The notion of 'recovery', a term borrowed from the health sciences, is used to describe the process by which a *'disturbance reach returns to a state which closely resembles unstressed surrounding areas'* (Gore, 1985). Alternative definition's of recovery are presented in Chapter 2; however, Gore's definition will be used to describe recovery for the remainder of this thesis.

It is important to acknowledge that recovery is a natural process in river systems that occurs in response to disturbances such as floods and tectonic events; in this thesis, however, the focus is on increasing the understanding of recovery following anthropogenic disturbance. The rate and type of recovery is dependent on the nature and extent of the disturbance (such as a pulse or press disturbance eg. Underwood, 1996), the sensitivity of the river type to change (eg. Brunsden and Thornes, 1979), as well as the time scales involved with the recovery of different components of the system (eg. biological vs morphological characteristics).

Many river conservation and rehabilitation programs view river rehabilitation as a process of 'prompted' or 'accelerated' recovery, whereby management strategies are used to help the river adjust naturally (eg. Brierley and Fryirs, 2001; Brookes, 1995; Downs *et al.*, 1999; Erskine and Webb, 1999; Rutherfurd *et al.*, 2000; Sear, 1994). However, the definitions and techniques for measuring recovery, the spatial and temporal scales over which recovery occurs, and the recovery pathways (or trajectories) are not well understood (eg. Fryirs and Brierley, 2000; Prosser et al., 2001; Sear, 1994).

<u>Context of study</u>

In Australia, it is estimated that at least $100 million dollars is spent annually on stream rehabilitation (White et al., 1999). Other countries such as the United States and countries in Europe, are spending at least five times that amount (eg. Schlte-Wulwer-Leidig, 1995). For example, at least US$7.8 billion will be spent over 30 years on restoring the Everglades Catchment in Florida (see http://forests.org/archive/america/hoback78.htm).

Although large amounts of money are allocated to stream rehabilitation, there is little current knowledge as to how streams recover naturally (without human intervention). There is the possibility that much funding is wasted on streams that may either recover on their own, or are unlikely to recover following disturbance, despite human intervention. Hence, there may be considerable economic and environmental benefits if the natural recovery potential of streams can be incorporated into stream management plans. To achieve this, a better understanding of the processes and factors relating to recovery is needed; this is the main aim of this thesis.

The research in this thesis investigates the concepts of disturbance and recovery in degraded stream systems, with a specific focus on 'geomorphic' recovery. In this context, all disturbed streams can be categorised into one of three groups:

(1) streams that will recover independently of human intervention (ie. heal themselves);

(2) streams that will require some human intervention to accelerate the recovery; and

(3) streams that are not likely to recover (within human life spans).

By identifying the different factors associated with streams in these different groups, more appropriate stream management decisions can be made. For example, less funding should be allocated to category (1) streams that have the potential to heal themselves; similarly, less funding should be given to category (3) streams that are unlikely to recover. The most effective target for stream restoration funds is category (2) river reaches, which involve preventing further damage and accelerating recovery. These conservation areas could then act as data warehouses for future scientific work. These reaches may also form corridors connecting more degraded sites, which would then help accelerate the recovery by maintaining and increasing biological and geomorphological diversity.

1.2 Background concepts, previous research and a new approach for evaluating recovery

<u>*Spatial and temporal scales of disturbance and recovery*</u>

River systems are dynamic landscape features that respond to change at a variety of spatial and temporal scales. Most river systems strive for equilibrium, where equilibrium is best described as a constant relation between input and output or form, within some range of those parameters (Howard, 1982). Within this context, it is important to note that an equilibrium landform is not static or absolutely stable, but there is a tendency for the form to maintain relatively stable characteristics, and return to those characteristics following minor perturbations (Renwick, 1992). It is also important to note that both stability and variability can occur simultaneously (Renwick, 1992). The spatial and temporal scales over which systems adjust, depend on the scale of the disturbance; some responses may take thousands of years (eg. sea-level response), and others may take days (minor flood event). River systems are also nested hierarchical systems (Frissell et al., 1986), and different parts of the system may respond quite differently to perturbations.

This study focuses on the disturbance and recovery of streams at the 'reach' scale, within the time scale of engineering or human life-spans (discussed further in Chapter 5). The relative rates of recovery for different streams are also evaluated against the average time it took for a stream to be disturbed; this is assessed over the scale of 50-100 years (Chapter 10).

The role of disturbance in simplifying streams

Because disturbance can be a natural process, defining 'disturbance' for stream systems is difficult (as discussed further in Section 2.2). Increasingly, the term is used to describe impacts that are a direct result of human modification to the landscape. Many of these human induced disturbances have resulted in a massive shift in the 'natural regime' of the river, as well as resulting in a simplification of the channel at a variety of scales.

Examples of disturbances resulting in a simplification of streams include de-snagging of rivers (which removes habitat complexity), construction of dams (which reduces flow variability and sediment movement), channelisation and meander cut-offs (which simplifies morphological structure), and increased sediment delivery (often simplifying sediment size variation, flow depths and habitat).

In some parts of the world (eg. Australia, North America and Europe), many of these disturbances are being removed, or better managed. For example, dams are being pulled down, and meander bends put back into previously channelised systems (eg. Graf, 1996; Hasfurther, 1985). As a result, there is a keen interest in understanding how a stream will recover following the removal or reduction of such disturbances.

Previous research into the recovery of streams following disturbance

There have been a number of geomorphic studies carried out to describe the response and recovery of streams to specific types of anthropogenic change. These studies can be divided into three broad categories: (1) streams with dams or large water storage structures (eg. Bray and Kellerhals, 1979; Everitt, 1993; Jiongxin, 1990; Jiongxin, 1996); (2) streams impacted by channelisation and incision (eg. Hupp, 1992; Schumm et al., 1984; Simon and Hupp, 1987); and (3) streams that have been impacted by increased sediment load (eg. Gilbert, 1917). A more detailed review of these approaches is discussed in Chapter 2.

Research into the impact of each of these disturbances has been very thorough; however, knowledge of how streams will *recover* following removal or reduction of these disturbance is less comprehensive. Research into the recovery of streams that have, or will have, a major water storage removed is in its early stages, with most projects still assessing the feasibility of removing dams; most of these cases are in North America. Incised streams, however, have received considerable attention over the last 20 years, and a general model of geomorphic recovery has been developed for them (eg. Schumm et al., 1984, discussed further in Section 2.4.1).

However, unlike incised streams, research into the recovery of rivers impacted by massive increases in bed-load (termed sediment slugs) is not as advanced; the conceptual models of recovery that exist in the literature are not necessarily applicable to current stream rehabilitation theory. Hence, a revision of existing models is required (and presented in Chapters 2 and 3). Sediment slugs also provide an appropriate disturbance in which to assess the recovery process as these slugs are not static in space; they move through stream networks over time. This therefore allows the application of ergodic theory, or space for time substitution, to assess the impact and recovery process (discussed further in Section 3.6.1).

<u>*Justification for using sediment slugs to assess channel recovery*</u>

Sediment slugs occur where there is an increase in sediment delivery to streams which is beyond the natural bedload capacity of the channel (Schumm, 1977). It is estimated that approximately 28×10^9 t year^{-1} of sediment is eroded from catchments in Australia each year; a little less than half of this is estimated to be transported into streams and rivers (Wasson et al., 1996). The coarser eroded sediment that gathers in the stream network forms sediment slugs that have a number of detrimental impacts. These include:

- decreasing habitat quality and quantity;
- destabilising human infrastructure such as bridges;
- filling in and reducing the capacity of dams;
- increased flooding hazards due to reduced channel capacity;

- threatening downstream receiving waters such as coral reefs, wetlands and seagrass environments.

Tools for measuring geomorphic recovery

Current theories and models of the physical recovery of disturbed streams commonly use the return of mean conditions as an indicator of recovery (eg. Gilbert, 1917). For example, mean bed level is used as an indicator of recovery in the case of streams disturbed by sediment slugs or channel incision (see Sections 2.4.1 and 3.6.2). Such indicators are useful for making general large scale assumptions about the recovery of a system; however, it is increasingly important to incorporate the ecology of a stream in evaluations of recovery and stream health.

Given that species diversity and abundance is the main criteria for assessing stream health, geomorphic indicators also need to become more 'eco-compatible'. Eco-compatibility implies that the scale used to describe the recovery process will be relevant to both physical (eg. geomorphological and hydrological) as well as ecological conditions. This requires looking at changes in habitat diversity, rather than simply using the average morphological conditions as a measure of recovery.

There is a principle in ecology that diversity of habitat, if it can be described, paves the way for predicting the potential diversity of biota (Newson and Newson, 2000); physical diversity is increasingly acknowledged as one appropriate indicator or surrogate of stream health (Norris and Thoms, 1999). In addition, biologists increasingly acknowledge that geomorphological surfaces form the template for the development of both flora and fauna communities (Poff and Ward, 1990). Thus, using geomorphological features would appear to be an appropriate way of measuring changes in habitat diversity, stream health, and thus recovery.

Based on a review of the ecological, geomorphological and hydraulic literature (in Chapter 2), the description 'Geomorphic Variability' is presented in this thesis as a better way to measure and describe the impact and recovery of disturbed streams. The significance of variability in the context of stream restoration is best described by Chapman and Underwood (2000):

> " *If variability is as important as many of us believe, altering and managing habitats to restore unpredictability and variability in assemblages may be as important in its sustainability as us restoring average abundances and*

diversity - which are commonly the aims of restoration. This is an issue that has received little to no attention in research on restoration" (p34).

Geomorphic Variability is a more eco-compatible measure of physical channel change, and has the capacity to be linked directly to biological habitat studies. Geomorphic Variability can be used to test and revise existing models of recovery for streams impacted by sediment slugs (as detailed in Chapter 3).

1.3 Objectives and context of the study

This study aims to improve the understanding of geomorphic recovery by investigating the following general research objectives:

1. To review the role of morphology in stream health and habitat studies and thus identify appropriate factors for quantifying the Geomorphic Variability of a stream reach;
2. To evaluate and adapt models of Geomorphic Recovery to provide a more 'eco-compatible' approach by using Geomorphic Variability as an indicator of recovery;
3. To identify a range of suitable techniques for quantifying the variability of geomorphic field data, and thus habitat.

To evaluate the general objectives above, a number of more specific areas of research were investigated. These included:

- The design of a rigorous statistically based sampling framework for measuring Geomorphic Variability;
- Determining appropriate methods for assessing stream recovery using spatial data only;
- Investigating the possibilities for integrating the individual factors that make up Geomorphic Variability into a single model, index or term that can be used to evaluate the Geomorphic Recovery Model.

Following a review of the literature relating to the measurement of habitat (Chapter 2) and the potential for streams to recover following disturbance by sediment slugs (Chapter 3), a number of more specific testable hypothesis were formulated. These are presented in Section 3.7.1.

These general and specific objectives were investigated using streams that have been severely disturbed by sediment slugs. It is acknowledged that Australia's stream systems are under increasing pressure from a wide range of disturbances (eg. irrigation and water extraction, riparian vegetation clearing and salinisation), however, sediment slugs were chosen as an appropriate disturbance type because of the increasing impact that they are having on river systems both in Australia, and overseas. Sediment slugs have also been subject to considerable geomorphic research in the past, and a review of the models of recovery for these streams was required. Finally, the movement of sediment slugs through river systems as discrete waves provides an appropriate sampling environment for testing the different stages of disturbance and recovery.

1.4 Structure of thesis

This thesis is presented in eleven chapters. This introductory chapter has presented a brief overview and purpose of the study as well as the background concepts, before defining the research objectives.

Chapter 2 expands on the concepts of disturbance and recovery in stream systems. It also discusses some of the existing tools that are used to quantify geomorphic recovery and reviews techniques for measuring instream habitat. The term 'Geomorphic Variability' is presented as a new approach for evaluating recovery in disturbed stream systems.

A definition of what constitutes a sediment slug, as well as a summary of sediment slug research, is presented in Chapter 3. This chapter also discusses the potential impacts of sediment slugs from both a geomorphic and ecological perspective. A review of the different sediment slug movement models is presented, and a new model for the geomorphic recovery of streams impacted by sediment slugs proposed. Ergodic theory is also presented as a suitable approach for evaluating the recovery process. Based on the theory presented in this chapter, a number of testable hypothesis are presented.

Chapter 4 introduces the three study sites selected to evaluate the recovery model - Creightons Creek, Wannon and Ringarooma Rivers. The physiographic setting, previous research conducted, geology, vegetation, hydrology and climatic conditions for each catchment are discussed. A short description of the history of landuse which resulted in the formation of the sediment slug in each stream is presented.

The experimental design, and field work techniques used to collect data from the three field sites, is presented in Chapter 5. The reach concept, statistical framework for the study, and theoretical and practical considerations for measuring each of the variables that make up Geomorphic Variability (thalweg, cross-sections, sediment variability and sediment stability) are discussed.

Chapter 6 presents the field data from each of the study sites. Chapter 7 then focuses on identifying whether changes in Geomorphic Variability in different parts of the catchment are due to the presence of the sediment slug, or are simply a function of natural variability inherent in any stream.

Chapter 8 outlines a range of techniques used to quantify the variability of each of the data sets. A diverse range of techniques are presented and tested for correlation between the techniques using synthetic data sets and factor analysis.

Chapter 9 presents the results of the application of each of the data analysis techniques, which are then evaluated with respect to the Geomorphic Recovery Model. Chapter 10 evaluates the overall response of each stream to sediment slug disturbance using a an Index of Geomorphic Variability. Space for time substitution is reviewed as a tool for assessing stream recovery, and a summary of the different recovery processes is presented for the different stream types.

The final chapter, Chapter 11, presents an overview of the investigation and a summary of the important study findings. The implications of this research for the management of disturbed stream systems is discussed, and suggestions made for further research.

Appendices A-G describe methodologies or data relating to developing flood frequency curves, application of Manning's equation for estimating bankfull, sediment size analysis, analysis of flow duration curves and the cross-sectional data for each of the study sites, respectively. Publications and awards that have resulted from this study are presented in Appendix H.

Chapter 2

Disturbance and Recovery in Stream Systems: Theoretical Concepts and Previous Research

2. Chapter 2 - Disturbance and recovery in stream systems: theoretical concepts and previous research

2.1 Introduction

The main purpose of this chapter is to summarise the range of existing approaches that are used to measure recovery in disturbed streams The most appropriate tools for understanding, testing and measuring geomorphic recovery are discussed, and a new eco-geomorphic method for measuring recovery is presented: Geomorphic Variability.

Section 2.2 discusses the concept of disturbance as the recovery of a stream is often directly related to the type and magnitude of the disturbance. Section 2.3 then discusses concepts of recovery, with an emphasis on geomorphic recovery. Current approaches to assessing geomorphic recovery are presented in Section 2.4 with a discussion on the need for integrating the disciplines of geomorphology and ecology in habitat studies. Section 2.5 then describes the existing approaches for measuring habitat and Section 2.6 presents a new approach for measuring geomorphic recovery in disturbed streams.

2.2 Disturbance in stream systems

Background

To understand the processes of recovery in stream systems, it is important to first understand the role of different types of disturbance. Disturbance in stream systems can be divided into two categories:

1. Natural disturbance eg. floods;
2. Anthropogenic or human induced disturbance eg. dams, channelisation or mining.

Defining disturbance in stream systems would initially appear to be a relatively simple process; however, as Rykiel (1985) pointed out, disturbance, perturbation and stress have often been used in various contexts, often synonymously, inconsistently and ambiguously. Some of the reasons that it is difficult to differentiate between natural and human induced disturbance are outlined below: .

- Events such as floods are natural processes, however, human modification of a catchment may result in flood magnitudes and frequencies that are much higher, or lower, than the 'natural' or 'un-modified' flood cycles;

- In geomorphology, it is often difficult to distinguish between natural processes of erosion, and erosion that has been accelerated due to human activities;
- A process that is a disturbance for one feature of the stream (eg. vegetation), may actually be a requirement for species development. In fact, the intermediate disturbance hypothesis (after Townsend and Scarsbrook, 1997;Ward and Stanford, 1983; Death and Winterbourn, 1994) describes how often the greatest species diversity is often found in areas with intermediate levels of disturbance (Sparks et al., 1990);
- Humans are also part of the environment, yet to what extent is the level of disturbance we create acceptable?

Both Milner (1996) and Underwood (1996) discuss the importance of distinguishing between a 'press' and 'pulse' disturbance, as the rate of change in a stream is dependent on the magnitude of the disturbance. A 'pulse' disturbance is of limited and easily definable duration (eg. floods), whereas 'press' disturbances are longer and frequently involve changes in the catchment or river channel (eg. mining or logging). This thesis specifically deals with sediment slugs (Chapter 3) that act as a long term impact, or press disturbance. Small, event-driven sediment slugs are not considered in this thesis. Only sediment slugs that are the result of human modification to the landscape will be assessed.

Definitions of disturbance

Environmental conservation on a global scale generally deals with the preservation of plant and animal species, and most definitions of disturbance use the loss of biological organisms as the key variable (eg. Poff, 1992; Rykiel, 1985; Sousa, 1984; Sparks *et al.*, 1990; Townsend and Scarsbrook, 1997; Ward and Stanford, 1983; White and Pickett, 1985). It is, however, increasingly acknowledged that physical landscape features are important for species diversity and should be preserved in their own right. Hence, geo-diversity has emerged as a new term in the management of our natural environment (Eberhard, 1997).

Geo-diversity is specifically defined as 'the natural variety of geological, geomorphological, pedological, and hydrological features if a given area, encompassing the purely static features at one extreme, to the assemblage of products and their formative processes at the other' (Semeniuk, 1997).

Just as biological disturbance is considered as 'any discrete event in time that disrupts ecosystem, community or population structure' (White and Pickett, 1985), geomorphic disturbance can be considered as any process that acts to disrupt or destroy either the natural geomorphic processes, or the geo-diversity of a stream. An example of a decrease in fluvial geo-diversity in Australian streams are 'chain of ponds' sequences which have been severely altered since European settlement (eg. Eyles, 1977). It is important, however, to remember that the different types of disturbances (biological and geomorphological) do not operate in isolation, nor do they operate over the same spatial and temporal scales.

Disturbance results in simplification

It is important to re-emphasise that in many cases anthropogenic disturbance results in a simplification of stream morphology and the ecosystems associated with it (as discussed in Section 1.2) (eg. Alexander and Hansen, 1986; O'Connor and Lake, 1994; Palmer et al., 1997). There are, however, a number of cases, usually related to natural disturbance, whereby the impact does not necessarily simplify the system, it just changes or rearranges it (eg. during flood events). Such events are important for biological evolution (Townsend and Scarsbrook, 1997), yet, the majority of large scale anthropogenic disturbances generally result in a simplification of river systems, at least in the short term. Sediment slugs are an example of a disturbance that acts to simplify the stream environment. The processes relating to this simplification are discussed further in Chapter 3. The next section outlines the theoretical concepts relating the recovery of streams following simplification.

2.3 Concepts of recovery

Understanding the process of recovery for disturbed streams is a relatively new area in geomorphology. Up to now, scientists have been more concerned with understanding the processes of disturbance; recovery has received less attention. This is often due to the difficulty in defining recovery, the lack of pre-disturbance data to assess the recovery process (Niemi et al., 1990), and the time-scales over which geomorphic systems evolve.

Just as there is no straight-forward way of defining what a disturbance is in stream systems, defining recovery is also fraught with difficulty. This is because the term "recovery" has been used in many fields of science (eg. medicine) and therefore has various meanings depending on the feature being disturbed and the magnitude of the disturbance (Cairns, 1990).

There are many definitions and applications of the term 'recovery' in the limnology literature. In general, these can be divided into two categories: biological research (eg. Fuchs and Statzner, 1990; Gore *et al.*, 1990; Kelly and Harwell, 1990; Milner, 1996) and geomorphological research (eg. Erskine, 1996; Hogan, 1987; Knighton, 1989; Lisle, 1982; Madej and Ozaki, 1996; Pitlick, 1993; Smith and Turrini-Smith, 1997).

Milner (1996) provided a well rounded definition of recovery, describing it as:

> *'a natural process distinct from restoration, enhancement or rehabilitation...and the end-points of recovery are potentially different according to the nature of the disturbance...the common endpoint's used in assessing the recovery of river systems are divided into either biotic or abiotic...abiotic end points to recovery are considered to be such parameters as physical habitat quality or water quality'* (p. 206-207).

Yet Gore's (1985) definition (in Milner, 1996) is probably the most applicable:

> *'recovery refers to the disturbance reach returning to a state which closely resembles unstressed surrounding areas'* (p. 206).

There are a number of differences between the definitions of recovery for ecology and geomorphology. Ecological recovery usually involves assessing changes to the flora and fauna of a system to determine if the diversity and abundance of species have returned following disturbance. Biological definitions of recovery generally involve measuring quantifiable features (eg. fish or macroinvertebrates) and use statistical techniques to determine if there is a significant difference between expected and observed values. Thus, in theory, ecological recovery can be objectively quantified.

Geomorphic recovery, however, is far from an exact science. This is because the quantifiable, measurable features are more difficult to identify (what is the geomorphic equivalent of a fish?) and the time scales over which these features respond are at least an order of magnitude longer than ecological indicators. [A review of the existing approaches for measuring geomorphic recovery are discussed in Section 2.4.1].

Most of the definitions used in the literature to describe geomorphic recovery are qualitative, and lack the support of rigorous methodological tools. For example, authors such as Fryirs (1999), have discussed the importance of identifying and describing reaches in terms of their recovery potential. This is based on first characterising river reaches or sections into 'styles'. Recovery potential is then defined as the capacity of each river style to attain a 'suitable river structure and function for the position it occupies in the catchment' (Fryirs, 1999). This process may be appropriate for very experienced, trained geomorphologists, however, it lacks quantitative rigour, and identifying a 'suitable river structure' is open to subjectivity and error.

Thorne (1996) suggests that the role of geomorphologists in fluvial studies will remain limited due to the lack of rigorous and repeatable methods used in geomorphic research. Hence, there are three main problems:

1. Despite the increased importance of geomorphic processes and features in the management of disturbed stream systems (eg. James, 1999; Sear, 1994; Sear *et al.*, 1994) there is no suitable definition of geomorphic recovery;
2. Given a suitable definition, there are no tools available to quantitatively measure geomorphic recovery using repeatable, objective measures;
3. Despite the fact that biologists and geomorphologists increasingly acknowledge that geomorphological surfaces form the template for the development of both flora and fauna communities (Poff and Ward, 1990), the measurement of recovery is still carried out using very different techniques; the interdisciplinary nature of ecology and geomorphology is still only at the theoretical level. Hence, there needs to be a more practical and definitive link between the science of recovery with regards to the ecology, geomorphology and the hydrology of stream systems.

The challenge for geomorphologists is to assess recovery at a scale that is more relevant to instream biota. This can be done by integrating quantitative research design with the process-based methodologies characteristic of geomorphology. This approach will also require:

- An eco-compatible definition of geomorphic recovery;
- Tools for measuring and quantifying geomorphic recovery;
- Application of these tools to test the suitability and applicability of these techniques for quantifying geomorphic recovery in disturbed streams.

2.4 *Tools for Quantifying Geomorphic Recovery*

2.4.1. Existing Approaches for measuring recovery in geomorphology

Some of the early work on system recovery following disturbance was presented by authors investigating system response to perturbations (eg. Brunsden and Thornes, 1979; Chorely, 1962; Graf, 1977; Graf, 1979; Schumm, 1973). In much of this work, emphasis was on system 'response' rather than recovery. It is important to note that although these processes can overlap, recovery is usually a secondary process based on the initial response of the system to disturbance.

Much of this work represented the building blocks for understanding how a system recovers, however, the term 'recovery' was rarely used. Instead, phrases such as 'returning to a steady state', 'relaxation' time, and 'equilibrium reinstatement' were applied (Graf, 1977; Howard, 1982). There are a number of principles from this early work that can be incorporated in to the study of geomorphic recovery. These include:

- That for many geomorphological systems 'initial rapid change is succeeded by an exponential change towards very slowly changing values' (Brunsden and Thornes, 1979); and
- In geomorphological systems change is not uniform; it involves complex, threshold based changes and in some cases catastrophic behaviour. It will also depend on the sensitivity of each system to change.

These studies have advanced the understanding of the processes and mechanisms relating to system response, however, they did not provide a great deal of insight into appropriate techniques for measuring or quantifying geomorphic response or recovery.

<u>Current methods for measuring geomorphic recovery</u>

Current theories and models of the physical recovery of disturbed streams commonly use the return of mean conditions as an indicator of recovery. For example, the return of mean bed level in the case of streams disturbed by sediment slugs (eg. Gilbert, 1917) or the aggradation of bed levels and re-establishment of woody bank vegetation in the case of incised and channelised streams (eg. Hupp, 1992; Schumm *et al.*, 1984; Simon and Hupp, 1987). Figure 2.1 shows the diagrammatic representations of the recovery process for incised streams described by Schumm (1984). Other authors, such as Lisle (1981) and Wolman (1960), have used changes in channel width to describe recovery, and Fryirs and Brierley (2000) use an evolutionary framework to assess the recovery potential of disturbed streams. Pitlick (1993) also describes recovery as 'the re-establishment of a quasi-equilibrium channel in response to changes in discharge and sediment load', which leads to the question: 'what is quasi-equilibrium'?

Wolman and Gerson (1978) suggested that geomorphic recovery involves the attainment of a pre-existing landform. This definition follows the true meaning of the word recovery, however, such a definition is not necessarily practical as the pre-disturbance condition is not always known. Also this definition does not always apply to stream systems where the end-point following disturbance is a new stable condition, rather than the pre-disturbance morphology (eg. in incised streams; Figure 2.1).

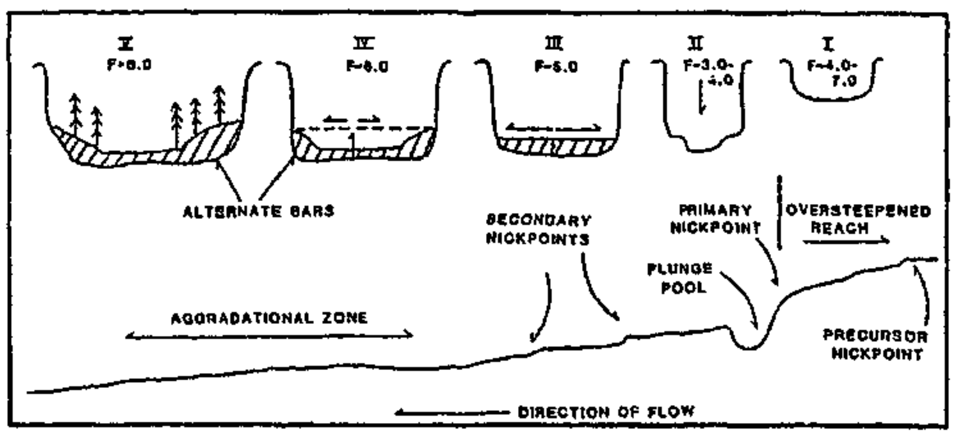


Figure 2.1: Schematic diagram of the longitudinal changes that cross-sections undergo in response to incision (Schumm et al., 1984) (the F values represent width to depth ratio).

Although all of the above factors are important, recovery also involves re-instating the appropriate geomorphic variability, such as pools and riffles, bars, appropriate sediment size and a variable cross-sectional form. Essentially, if disturbance results in a simplification of the stream system, then the recovery involves reinstating some of the natural variability or complexity. It cannot be assumed that the return of the channel to a 'mean condition' is synonymous with the recovery of a heterogenous geomorphic form. A more 'eco-compatible', habitat based approach is needed. As described in Section 1.2, eco-compatibility will involve incorporating smaller, habitat scale processes and features into understanding how stream systems recover from disturbance.

2.4.2. Linking ecology and geomorphology: the 'eco-compatible' approach

As described by Newson and Newson (2000) (and indicated in Section 1.2), diversity of habitat, if it can be described, paves the way for predicting the potential diversity of biota. As a result of this principle, the physical diversity of a stream is increasingly used as an indicator or surrogate of stream health. This is because surface roughness and heterogenous habitats have an important effect on measurements of species diversity, population abundance and dispersal (eg. McCoy and Bell, 1991; O'Connor, 1991). Physical diversity in streams is also known to correlate well with biological diversity (eg. Chisholm *et al.*, 1976; Downes *et al.*, 1998; Gorman and Karr, 1978). High levels of heterogeneity interfere with competition and thus allow for higher species diversity (Harris, 1986 in Kolasa and Rollo, 1991), reduce the impact of predation and increase population stability (Huffaker *et al.*, 1963 in Kolasa and Rollo, 1991), and help maintain genetic polymorphism (Kolasa and Rollo, 1991).

If the physical diversity or geomorphic variability of a reach can be measured and quantified, this can be used as a surrogate for habitat diversity, and a measure of geomorphic health. Then, given the appropriate experimental design, it can be used to assess the level of simplification of habitat following disturbance, as well as the geomorphic recovery of the stream.

To measure the level geomorphic variability within a channel, a method is required in which data is relatively easy to collect, is independent of discharge and has relevance to both geomorphologists and ecologists (and is thus eco-compatible). The next section describes a range of existing techniques that are used to quantify physical diversity in a stream.

2.5 *Measuring habitat in streams systems*

When a stream is disturbed, the physical diversity of the instream environment is often simplified. Quantifying physical diversity in a stream is traditionally related to measuring aquatic habitat. In general, habitat structure can be defined as 'the physical arrangement of objects in the environment' (McCoy and Bell, 1991). Thus, habitat in stream systems is essentially the interaction of sediment, water, rock surfaces and vegetation. The interaction of these key fluvial elements has resulted in a range of identifiable habitat units that can be measured in the field (eg. pools, riffles, runs). The next sub-sections outline a number of approaches for defining and measuring habitat in streams; both the positive and negative implications of each approach are presented.

2.5.1. Existing Approaches for quantifying habitat

Existing approaches for quantifying physical habitat in streams can be broken up into six general categories:

(i) Hydraulic habitat surveys

Hydraulic habitat surveys generally involve measuring water depth, water velocity and sediment size along a number of stream transects, with the premise that the greater the variability in the data sets, the greater the habitat. Often the data are converted to habitat-area discharge functions. The main purpose of this type of survey is to measure the available habitat for specific species of fish, and relies on an understanding of their lifecycle and habitat requirements. The data are then analysed using a variety of well established techniques such as the Shannon-Weiner equation (Gorman and Karr, 1978; Petersen, 1992), parametric statistical tests (eg. Schlosser, 1982), Instream Flow Incremental Methodology (IFIM) (eg. Bovee, 1982; Irvine *et al.*, 1987; Orth and Maughan, 1982), Physical Habitat Simulation System (PHABSIM) (eg. Gan and McMahon, 1990; Orth and Leonard, 1990; Williams, 1996) and RYHABSIM (Jowett, 1989).

The above techniques are very useful for identifying habitat availability of specific fish species for streams that have extensive and accurate gauging and flow data; however, a number of limitations of these techniques have been identified. In many situations, quantitative information about the micro-habitat preferences of fishes is scarce (Orth and Maughan, 1982), which is particularly the case for Australian streams. Gan and McMahon (1990) highlighted an IFIM assessment of the Colorado River (USA) in which three different authorities reported quite different results, and environmental flow recommendations for the sustainable habitat ranged from 2.5-8 cusecs, 30-90 cusecs and 15-100 cusecs (Jensen, 1989 in Gan and McMahon, 1990). IFIM and PHABSIM have also been criticised for being very complicated in concept, exacerbated by software problems (King, 1995a), and fail to view rivers as non-static features in the landscape (Bleed, 1987). Essentially hydraulic habitat survey techniques are very useful when a project has ample funding, numerous staff and equipment, lots of time and relatively small areas of stream to assess. Unfortunately stream restoration projects in Australia rarely present such situations.

(ii) Hydraulic biotope or meso-habitat surveys

Hydraulic biotope or meso-habitat surveys are based on the arrangement of different 'patches' within a reach (Jowett, 1993; Kershner *et al.*, 1992; Palmer *et al.*, 1991; Roper and Scarnecchia, 1995; Rowntree, 1995; Rowntree and Wadeson, 1996; Tickner *et al.*, 2000; Wadeson, 1995; Wadeson and Rowntree, 1998). Biotopes can be defined as a spatially distinct in-stream flow environments characterised by specific hydraulic attributes

(Wadeson, 1995). The background to this approach is that there is an important link between morphological units and biotopes.

The biotope concept is sound in theory and provides an inventory of the various habitat features in any one reach; these can be observed over time to assess stream change following disturbance. Unfortunately there is a flaw with this approach, which is that habitat characteristics change with changing discharge. Although the basis for measuring individual habitat units is based on flow variables such as Reynolds and Froude numbers (Wadeson, 1995), there is little consideration for how these habitat units will change with changing discharge, and changes in stream discharge is a major factor for Australian streams due to the highly variable climate and stream flow. For example, an area that is a run in low flow may become a pool in high flow. The changes in habitat with varying discharge could be accommodated if accurate water level and discharge data are recorded for multiple discharge events or at the same water level each time; however, this type of approach is recognised as being very time consuming. There are also safety issues related to surveying stream during very high discharges (King, 1995b).

(iii) Hierarchical studies of habitat classification

Hierarchical habitat studies generally fall into two groups: those that deal with conceptual frameworks for classifying stream habitats (eg. Frissell *et al.*, 1986; Hawkins *et al.*, 1993) and those that provide a more practical and rigorous example of the application of hierarchical concepts. Examples of the application of these concepts were presented by Davies *et al.* (2000) who assessed the applicability of using larger-scale characteristics to predict local-habitat features, and Li *et al.* (2001) measured the variability of macroinvertebrate assemblages at seven different spatial scales, which included scales from eco-regions down to transects within different habitat types. The River Habitat Survey (RHS) (Jeffers, 1998a; Jeffers, 1998b; Newson and Newson, 2000; Tickner et al., 2000) also attempted to correlate large scale catchment features with meso-scale biotope characteristics. These types of methods are slightly more sophisticated than biotope type techniques in that they are able to identify the habitat features that should exist in the absence of disturbance. However, the main limitation of this technique is again the subjectivity that is involved in classifying habitat features over varying discharges.

(iv) Hydraulic geometry

Singh (1989) suggested that because there are predictable relationships between width, depth and velocity for a given catchment area and discharge, it is possible to be able to predict average depth and velocity values for any site using probability distribution models developed from field measurements of pool and riffle sequences. The generated data is then considered appropriate for application into models such as the IFIM. This type of approach has considerable potential, as it only requires intensive data collection from a small number of representative sites; then the data can be extrapolated to other areas in the catchment. Thus, this approach is less time intensive than previous methods. However, it is acknowledged that hydraulic geometry will, at best, provide only rough estimates of the true state of the system (Knighton, 1977; Park, 1977), and the natural variability that is important for small scale habitat features is essentially ignored.

(v) Technology-driven techniques

A number of novel approaches have emerged that use technological application for quantification of in-stream habitat. These range from small scale habitat assessment of substrate conditions using stereo photography (eg. Evans and Norris, 1997) to predicting meso-scale habitat features using aerial multi-spectral videography and hydroacoustic techniques (Gubala et al., 1996; Hardy, 1998). The benefits of such techniques is that they provide a more objective assessment of habitat features (ie. relatively free of human subjectivity) which simply quantify spatial complexity. However, it is often the cost and size of the equipment, and expertise required to run the apparatus, that prevent these techniques from being more widely used.

(vi) Geomorphological based studies

Although geomorphological studies are traditionally related to dealing with inanimate material such as sediment (rather than ecologically based features such as habitat), many of the procedures that are commonly used by geomorphologists are directly applicable to quantifying habitat. For example, many geomorphologists have attempted to quantify the physical structure of a pool-riffle sequence using time series techniques such as auto-correlation, spectral analysis and semi-variograms (eg. Carling and Orr, 2000; Knighton, 1983; Madej, 1999; Richards, 1976; Robert, 1988; Robert and Richards, 1988). The main focus of their research, however, has been to quantify stream morphology for the purpose of predicting how streams adjust under natural conditions, and not necessarily for quantifying habitat. Other geomorphologists (eg Lisle, 1995; Jungwirth *et al.*, 1993) have measured geomorphological features (eg. variance of thalweg depth) and used this to quantify habitat heterogeneity. From another perspective, Downs *et al.* (1999) evaluated the success of 'prompted recovery' techniques by the post-implementation flows that have exceeded critical threshold for sediment transport.

Problems with the current approaches

Measuring geomorphic recovery would be made a lot easier if existing techniques could be used; however, there are a number of conceptual and practical problems with many of the techniques described above. Such problems include:

- That most of the definitions of hydraulic bio-topes are reliant on measuring some flow parameter which is dependent on discharge. Thus, if a habitat is going to be reliably categorised, it must be measured over a range of discharges, which is often time consuming, expensive and dangerous;
- That depths and velocities in adjacent pools and riffles converge as discharge increases, which makes flow-dependent indices difficult to measure and impractical for predictive purposes (Richards, 1976);
- That with many of these studies there a great deal of error in identifying and classifying habitat types. Roper *et al.* (1995) found that differences among observer's classifications increased with the number of habitat types and decreased with level of observer training. For this reason, habitat should be described using non-subjective quantitative techniques; otherwise, results both within and between habitat studies will vary considerably;
- That the geometry of channels has almost been totally ignored at the habitat scale (Newson and Newson, 2000);
- That habitats operate in a hierarchical manner and at a variety of spatial scales and different species have different habitat requirements (Downes et al., 1995; McCoy and Bell, 1991);
- That habitats that are visually distinct is not necessarily the same as habitats that are ecologically distinct (Harper et al., 1995).

Useful features from existing techniques

Although there are a number of faults with many of these techniques, many of the procedures mentioned would be helpful for quantifying geomorphic diversity in streams. The main techniques that are of interest are those that can be applied to relatively large lengths of stream (ie. tens of kilometres). These include:

- Features that can be adapted to measure physical diversity independently of discharge (eg. thalweg variability using bed level rather than water depth);

- Techniques that do not rely on human interpretation to identify a feature ie. quantitative techniques such as time-series analysis. 'The techniques of spatial analysis that are now common place in terrestrial landscape ecology should be applied to these more complete survey data sets in an attempt to refine our predictive abilities for habitat diversity' (Newson and Newson, 2000);
- Procedures that can estimate the pre-disturbance stream condition; and
- Techniques that involve measuring variability at a variety of spatial scales (and thus potential habitat types).

As none of the existing approaches fully meets the requirements for quantifying physical diversity, a new approach is proposed.

2.6 A new approach to measuring physical diversity: Geomorphic Variability

In developing a new approach to measuring physical diversity in streams, it is important to note that there is no single "correct" scale at which to describe populations or ecosystems and no single mechanism explains pattern at all scales (Levin, 1992). Thus, attempts will be made to cover a range of scales, rather than one specific scale.

2.6.1. Specific variables used for quantifying Geomorphic Variability

The adjustment of river channels to changes in the water and sediment regime can be described by nine degrees of freedom (velocity, flow depth, energy grade slope, width, bed-form, wavelength and amplitude, meander sinuosity, and arc length) (Phillips, 1991). Combined, these changes can be described more succinctly by four inter-dependent variables: cross-sectional form, bed configuration, channel pattern and channel bed slope (Knighton, 1984). In addition to these morphological variables, the dominant controlling factor, often dictating the magnitude of the above variables, is the bed sediments through which the channel flows, as well as the sediment the channel transports.

Based on the description of the inter-dependent variables above, and the existing approaches to quantifying habitat or physical diversity in streams, there appear to be four main variables useful for describing and quantifying geomorphic variability. They are:

- The *thalweg* or longitudinal profile, as this provides important information about the reach scale characteristics and incorporates pool and riffle sequences;

- *Cross-section* shape, as this provides considerable information about stability of the stream, and many habitat features can be identified from a single cross-section;
- *Sediment size* and the variation in sediment sizes appears to be a very important indicator of healthy habitat;
- *Sediment stability* is considered important in many aquatic habitat studies, as the stability of the substratum directly determines the rates of disturbance (Sousa, 1984), and thus habitat health.

For the remainder of this thesis, the term *Geomorphic Variability* will refer collectively to the four variables described above.

Although flow and velocity characteristics are considered important environmental factors affecting instream biota (Allan, 1995), this thesis puts forward the argument that the morphology of the stream represents the range of flows that move through the channel more accurately than can be measured. The morphology of a stream can be used as a surrogate (or summary) of the flow conditions in any one reach. Removing flow related variables from the process of quantifying physical diversity also considerably reduces the time and financial costs of collecting data.

Measuring thalwegs, cross-sections, sediment size and sediment stability is not new in geomorphic research; however, this thesis proposes to use the *'variability'* of each of these variables, rather than their mean conditions, to assess Geomorphic Variability and thus, recovery. This will essentially provide an estimate of the level of simplification that has occurred in response to disturbance, as well as an estimate of the variability that has returned to the stream during the recovery process. Table 2.1 shows the scale over which these data are collected.

Table 2.1: Variables used to define Geomorphic Variability and the scales over which they operate (after Frissell *et al.*, 1986).

Variable	Scale	Spatial or temporal
Thalweg variability	Reach scale (10^1 - 10^3 m)	Spatial
Cross-sectional variability	Meso-scale (10^0 - 10^1 m)	Spatial
Sediment size variability	Micro-habitat or unit scale (10^{-1} m)	Spatial
Sediment stability	-	Temporal

This type of approach has a number of benefits:

- The use of variance as an independent variable may lead to new understandings of how pattern and process are linked (Palmer et al., 1997);
- Embracing new analytical techniques (eg. fractal analysis; see Chapter 8) will increase our understanding of how and why heterogeneity is important (Levin, 1992);
- The study of spatial heterogeneity in streams has been hampered by a lack of tools for quantitatively measuring spatial heterogeneity (Cooper *et al.*, 1997). This thesis presents a new range of tools for quantifying geomorphic diversity (Chapter 8);
- Using measures of variability may allow comparison within and between streams rather than persisting with the 'case study' approach that dominates geomorphic studies;
- This study will help to understand how streams alter naturally at a number of scales, as streams are essentially nested hierarchical systems (Frissell et al., 1986).
- This study will look at the overall effect of heterogeneity, which may be greater than the sum of the individual units (Palmer and Poff, 1997). Chapter 10 of this thesis presents a method for combining each of the individual variables into an overall Index of Geomorphic Variability;

The theoretical and practical requirements for measuring the thalweg, cross-sections, sediment size and sediment stability are described further in Chapter 5.

2.6.2. A new definition of Geomorphic Recovery

As described in Section 2.3, there is currently no suitable definition to describe the Geomorphic Recovery of stream systems. This thesis proposes a new definition:

> *Geomorphic Recovery is attained when a disturbed reach has the same level of Geomorphic Variability as that of the less stressed surrounding areas.*

To evaluate this new definition of Geomorphic Recovery, a rigorous sampling framework needs to be developed (Chapter 5). Chapter 7 describes the process of estimating the pre-disturbance condition, and Chapter 8 describes a range of mathematical and statistical techniques for quantifying the data. These steps will make it possible to determine if streams that have been disturbed by sediment slugs have actually attained *Geomorphic Recovery.*

2.6.3. Assumptions relating to the application of this research

As with any of the techniques used to quantify the physical diversity of a stream, there are a number of assumptions. These include:

- An assumption that physical diversity is correlated with high species diversity at all scales and for all organisms. This has only been rigorously tested in a limited number of situations (eg. Downes *et al.*, 1998);
- Water quality is assumed to be of a sufficiently high standard (ie. capable of supporting diverse and abundant assemblages of biota) at all sites. Water quality parameters are not measured in this study;
- An assumption that any deviation in the 'mean' condition of the stream, as a result of disturbance, implies that there is a corresponding change in the variability of the channel (however, the reverse of this statement is not assumed).

The following list describes some of the factors that were not included in this study:

- No biological variables were measured;
- The habitat requirements of specific organisms were not considered. This includes the potential of some organisms to utilise different habitat types during different parts of their lifecycle.
- The spatial variability measured will be a function of the scale of analysis or, as described by Levin (1992), will depend 'on the size of window that is used to view the world'. This thesis chose the smallest, yet most practical interval for collecting data (discussed further in Chapter 5).

2.7 Summary

This Chapter has provided an overview of the concepts of disturbance and recovery in stream systems, and has highlighted that there is a need for a more integrative approach between the disciplines of geomorphology and ecology for assessing recovery following disturbance.

The main points from Chapter 2 can be summarised as follows:

- Disturbance in stream systems can be natural or anthropogenic; a range of definitions of disturbance exist, most of which use the loss of bio-diversity as indicator. This chapter highlighted the need for including 'geo-diversity' as an indicator of disturbance;

- Recovery in streams can be divided into ecological or geomorphic definitions, which often operate at different space and time scales. Nonetheless, the fact that ecology and geomorphology are intrinsically linked in stream systems, meant that a new definition of recovery was needed;
- Existing definitions of geomorphic recovery use qualitative indicators or mean conditions; it was argued here that such definitions need to be made more 'eco-compatible';
- A range of existing approaches for quantifying habitat in streams exist; both their strengths and weaknesses were discussed;
- Some of the existing tools for quantifying habitat were incorporated into a new approach for measuring physical diversity in streams. This resulted in the new term: Geomorphic Variability;
- The specific variables that make up Geomorphic Variability are the thalweg, cross-sections, sediment size variation and sediment stability. The important component of each of these indicators is actually the variability rather than the mean condition. Hydraulic flow indicators were not included in this definition;
- Using Geomorphic Variability, a new definition of geomorphic recovery was presented: "*Geomorphic Recovery is attained when a disturbed reach has the same level of Geomorphic Variability as that of the less stressed surrounding areas*".

Chapter 3 will now discusses sediment slugs as an example of geomorphic disturbance. The effects sediment slugs have on stream systems will be described, and a new model of Geomorphic Recovery is presented.

Chapter 3

Sediment slugs - an example of disturbance and recovery in Australian streams

3. Chapter 3 - Sediment slugs: an example of disturbance and recovery in Australian streams

3.1 Introduction

Chapter 2 presented a new approach for quantifying the geomorphic recovery of disturbed stream systems: Geomorphic Variability. This chapter now presents an example of a disturbance which can be used to test the suitability of Geomorphic Variability as a measure of stream recovery. Streams disturbed by sediment slugs have been chosen for this purpose.

This chapter has two main functions: (1) to review the impacts that sediment slugs have on stream systems; and (2) to provide a review of the current models used to describe sediment slug movement and recovery. In light of the second point, a new more appropriate model of recovery for streams disturbed by sediment slugs will be presented.

This chapter is divided into eight sections. Section 3.2 begins with a definition and description of sediment slugs. Section 3.3 outlines the existing research that has been conducted on sediment slugs internationally, and presents a more comprehensive summary of sediment slug research in Australia, including a critical evaluation of contemporary sediment slug studies. The impact of sediment slugs on the geomorphology, ecology and human infrastructure of a stream is outlined in Section 3.4. Section 3.5 summarises the large scale sediment movement models. Section 3.6 discusses some of the geomorphic approaches used for measuring recovery including space for time substitution, and Section 3.7 presents a new model for the recovery of streams that have been disturbed by sediment slugs. Specific thesis hypotheses are also presented with the new model. Finally, Section 3.8 summarises the chapter.

3.2 What is a sediment slug?

Sediment slugs, or bedload waves, have been described as areas where sediment production has increased beyond the natural bedload transport capacity of the channel (Schumm, 1977). Sediment slugs were first presented in the literature by Gilbert (1917), when he described the movement of mining debris in the Sierra Nevada as a 'sediment wave'. Nicholas *et al.* (1995) also described sediment slugs as 'bodies of clastic material associated with disequilibrium conditions in fluvial systems over time periods above the event scale'. Other definitions include those by Erskine (1994b) "alternating bed aggradation and degradation represent a sand slug or bed load wave" and Rutherfurd (1996) described them as 'large pulses of sand (sand slugs) or gravel'. An example of a sediment slug in the Bega River in south-east NSW is shown in Plate 3.1.

Plate 3.1: Sediment slug in the Bega River, NSW.

There have been reports of bed-load pulses and bed waves in rivers at almost all spatial and temporal scales (Hoey, 1992). To properly describe and define sediment slugs, it is necessary to be able to distinguish between the different slug types. This is important because the recovery of streams that have been disturbed by sediment slugs will be dependent on the magnitude and type of disturbance.

To differentiate between the different scales of sediment slug impact, Nicholas *et al.* (1995) classified sediment slugs into macro, mega or super slugs depending on the dominant control and impact to the fluvial system (Table 3.1). The magnitude and type of changes that occur are generally positively related to the scale of the slug. Whether there is a correlation between the physical changes that take place on a stream relative to both the size of the sediment slug, and the channel, has not been rigorously tested.

Table 3.1: Classification of sediment slugs (after Nicholas *et al.*, 1995)

Slug scale	Dominant control	Impact on fluvial system	Bed-form class associated with scale
Macroslug	Fluvial process form interactions	Minor channel change	Mesoforms (particle clusters)
Megaslug	Local sediment supply and valley-floor configuration	Major channel change	Macroforms (gravel sheets, unit bars and complex bars)
Superslug	Basin-scale sediment supply	Major valley-floor adjustment	Mega-forms (bar assemblages)

Nicholas *et al.* (1995) suggests that the larger scale bedforms, which persist within the channel as 'recognisable features over longer time periods', provide a basis for identifying sediment slugs. This definition relies on having either appropriate historical evidence, or considerable amounts of pre-disturbance data to show that a sediment slug exists within a stream.

Many sediment slugs in stream systems have been there over one hundred years. In such cases, there is rarely any evidence available to describe the pre-disturbance condition. Thus, the method described by Nicholas *et al.* (1995) for identifying a sediment slug is not appropriate, and a more rigorous quantitative approach for identifying sediment slugs is required.

In this thesis, a large quantity of bed load in a stream can be termed 'sediment slug' when the following properties exist:

- the depth of sediment is greater than 1/5 of the mean bank height for that section of the river;
- the bed level is about the same at the outside of meander bends as at the point bars;
- greater that 50% of the volume of sediment is dominated by 1-3 size classes (eg. 0.5mm, 1mm, 2mm), and the bed sediments are obviously different from the bed material from nearby non-impacted sections;
- the aggraded sediment covers a distance of at least 10 times the channel width. This allows for 'sluglettes', which are small discontinuous slugs of 200-500 m in length, to be included in the definition (after Rutherfurd, 1996);
- when there is a distinct difference between bed and bank material. Knox (1972) used this as an indicator of excess sediment within the system. For example, a channel with clay banks would not normally have coarse sand grains as its natural dominant bed load (although many clay streams will carry some coarse fractions; the true indicator of a slug would be a amount of coarse sediment compared to less disturbed reaches).

As many streams in Australia have naturally sandy bed-loads, this definition provides enough detail to distinguish between streams that contain sediment slugs from those with naturally sandy beds.

3.2.1. Sources of sediment

Another way of defining sediment slugs in streams is to categorise them according to the source of the sediment. Hoey (1992) used the terms exogenous and endogenous to describe the source of the sediment fuelling the slug. Exogenous materials are introduced by non-alluvial controls (eg. tectonic uplift or mining) and endogenous materials are produced from processes occurring within the channel which are formed from alluvial material. Nicholas *et al.* (1995) adapted this definition further to link the type of slug with the source of the sediment, producing the terms 'endoslugs' and 'exoslugs'.

Endoslugs

Endoslugs are sediment slugs that have resulted from instream processes, such as erosion. Considerable changes in landuse and inappropriate land management have resulted in severe erosion in many catchments in Australia (see Abrahams, 1972; Chatres *et al.*, 1992; Erskine and Melville, 1984; Eyles, 1977; Fryirs and Brierley, 2001; Melville and Erskine, 1986; Morse and Outhet, 1986; Prosser, 1991; Prosser and Winchester, 1996; Walling, 1984; Wasson, 1994; Wasson *et al.*, 1998). It is also estimated that up to two thirds of Australia's streams have been cleared of native vegetation (Prosser et al., 2001), which has lead to increased bank erosion and sedimentation. The typical cause of endoslugs is bank and gully erosion. Gullies, which are essentially extensions of the drainage network, supply sediment directly to the tributaries and/or the main trunk of the stream.

Exoslugs

Exoslugs are sediment slugs which result from processes outside of the stream network. The main cause of exoslugs in Australian streams is mining. In some areas mine waste is put directly into streams from the mine, and in other cases, the sediment may be sourced from in the channel using methods such as sluicing and/or dredging. In either case, the processes are completely controlled by humans and the resulting sediment is essentially exogenous.

Multiple versus single point sources

Regardless of whether a sediment slug is created from endogenous or exogenous sources, it is expected that slugs that have evolved from multiple sources will initially be more complex than single source slugs. This is due to the interaction of the tributaries and the complex temporal sequence of sediment delivery. However, given enough time, even slugs that evolve from a number of sources generally form one slug in the main trunk of the channel (Rutherfurd, 1996).

3.3 *Existing research into sediment slugs*

3.3.1. Non-Australian sediment slug studies

A considerable amount of research has been done to look at how sediment slugs enter and move through stream networks; much of this research has been conducted outside Australia. It is possible to put these studies into different categories according to the source of the sediment that fuels the slug.

One of the most studied causes of sediment slugs is mining (eg. Bull and Scott, 1974; Gilbert, 1917; Graf, 1979, 1990; Higgins *et al.*, 1987; James, 1989, 1991,1999; Lewin *et al.*, 1977; Macklin and Lewin, 1989; Marron, 1992; Pickup *et al.*, 1983), but there are studies describing slugs formed by glaciation, snowmelt and geological processes (eg. Meade, 1985; Meyer and Martinson, 1989), slugs formed by flood events and fire (eg. Beschta, 1983a, 1983b; Harvey *et al.*, 1987; Knox, 1972), catchment erosion resulting from processes such as land clearing and logging (eg. Madej, 1987; Madej and Ozaki, 1996; Meade, 1982; Orbock Miller *et al.*, 1993; Roberts and Church, 1986; Trimble, 1983), and slugs formed as a result of naturally large loads in braided rivers (eg. Griffiths, 1993). A number of more general studies have also provided a summary and description of the main characteristics of sediment slugs (eg. Hoey, 1992; Nicholas *et al.*, 1995). Finally, a number of studies that look at the smaller scale processes relating to sediment slugs have been carried out in flumes (eg. Jackson and Beschta, 1984; Lisle *et al.*, 1997).

A detailed review of many of the sediment slug studies described above was presented in Nicholas *et al.* (1995) and will not be repeated here. A more detailed description of the impact and movement processes of sediment slugs is given in Sections 3.4 and 3.5.

3.3.2. Australian sediment slug studies

Australia is traditionally considered to have low (and variable) sediment yields, which means that many rivers are sediment starved (eg. Wasson, 1994; Olive and Reiger, 1986). However, much of this research is based on erosion rates from sheet and rill erosion; when gully and instream erosion is taken into account, the sediment volumes entering Australia's waterways increase considerably.

Wasson *et al.* (1996) estimated that continental soil erosion in Australia approximates to 28 $\times 10^9$ t year^{-1}. Although Wasson *et al.* (1996) do not put an exact figure on the amount of sediment delivered to stream systems each year, he suggests that about 50% comes from sheet and rill erosion and the remaining 50% from gully and instream erosion. Thus, the amount of sediment delivered to streams based could be anything up to 14×10^9 t year^{-1} [However, it must be noted that there is a large difference between the amount of sediment eroded from the landscape and the amount of sediment that is actually reaches the stream network (and other receiving waters, eg. coastal zones)].

More recent research by Prosser *et al.* (2001) has revised these predictions suggesting that the total amount of sediment reaching stream systems from hill-slope, gully and riverbank erosion is only 127 Mt/year. This is considerably less than the figures in Wasson *et al.* (1996), because it is estimated that only 7.5% (of the 666Mt/y of sediment from hill-slope erosion) actually reaches the stream. This is a function of the low relief and variable climate in Australia. The study by Prosser *et al.* (2001) also looked at the wetter inhabited coastal catchments (Figure 3.1), whereas Wasson based his estimates on the whole of Australia. Nonetheless, the sediment delivery rates estimated by Prosser *et al.* (2001) represent the major contributing catchments in terms of sediment delivery (although the rivers in NW Western Australia and the Northern Territory were not included). The total amount of bed sediments stored in Australian rivers has been estimated at 36 Mt/y (Prosser et al., 2001).

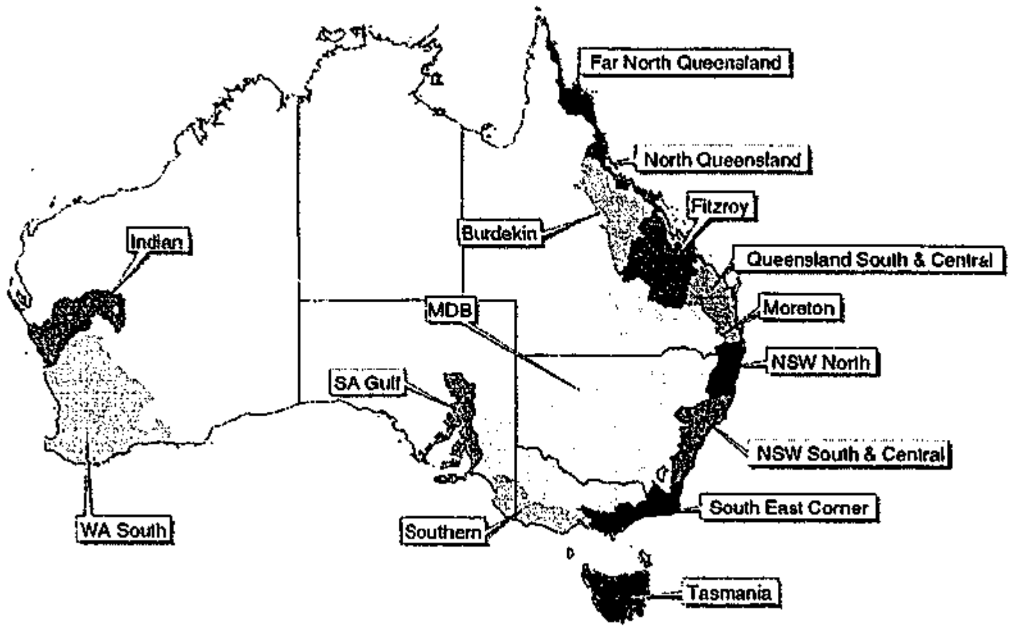


Figure 3.1: The catchments used by Prosser *et al.* (2001) to estimate sediment delivery to Australian streams

Despite the lower estimates of sediment delivery to streams made by Prosser *et al.* (2001), it is still suggested that over 30,000 km of stream length has been impacted by sediment accumulation greater than 0.3 m since European settlement (Prosser et al., 2001). Thus, in recent years, research into the impacts of sediment on Australia's waterways has increased considerably.

There are at least 50 documented studies that describe sediment slugs or large scale sediment problems within Australia; a summary of these is given in Table 3.2. Note that this list identifies only those streams with sediment slugs that have been published in papers or government reports. It was not possible to include all the Australian studies that have looked at sediment erosion. The sediment slugs in these papers vary in size from a few kilometres to entire stream systems (eg. > 100 km). It is also noted that there are a considerable number of other stream systems that have been impacted by sediment slugs that are yet to be documented.

Table 3.2: Australian streams that have been identified in the literature to be containing sediment slugs

No.	River	State	Author/Source
1	Bega	NSW	Brooks and Brierley, 1997, 2000; Fryirs, 1999, Fryirs and Brierley, 2001; Fryirs and Brierley, 2001a
2	Bell	NSW	Anon, 1979
3	Clarence	NSW	Erskine, 1990; Gardiner, 1995
4	Colo	NSW	Dyson, 1966
5	Crawford's Ck (Picton)	NSW	Pickup, 1975
6	Dumeresq	NSW	Gregory, 1977
7	Goulburn	NSW	Erskine, 1994b
8	Gwydir	NSW	Morse and Outhet, 1986
9	Hawkesbury	NSW	Sherrard and Erskine, 1991; Erskine, 1990
10	Hunter	NSW	Lockie and Martin, 1993; Erskine et al., 1985; Erskine, 1982; Erskine, 1992a; Erskine, 1996
11	Jugiong Ck	NSW	Zierholz et al., 2001
12	La Trobe	NSW	Rutherfurd, 1983; Bird, 1989
13	MacDonald	NSW	Erskine, 1986; Monteith,
14	McCleay	NSW	Boulton, 1999
15	Nepean	NSW	Wem, 1988; Warner, 1983
16	Orara	NSW	Ferguson and Brierley, 1998
17	Rocky River (near Uralla)	NSW	Warner and Bird, 1988; Hancock et al., 2001
18	Tarcutta	NSW	Outhet and Faulks, 1993; Smith et al., 1996
19	Wollombi Brook	NSW	Melville and Erskine, 1986; Erskine, 1996
20	Molonglo	NSW/ ACT	JCTC, 1974; Norris, 1986
21	Murrumbidgee	NSW/ ACT	Anon, 1981; AWT and Fluvial Systems, 1999; Wasson et al., Draft; Wasson et al., 1998
22	Alligator River	NT	East et al., 1988
23	Magela Creek	NT	Wasson, 1992
24	Ord	NT	Wasson et al., 1994
25	Burdekin	Qld	Brodie, 2000; Prosser et al., 2001
26	Condamine	Qld	Rutherfurd, 2000
27	Herbert	Qld	Ladson and Tilleard, 1999
28	Tully	Qld	Pringle, 1986
29	Don	Qld	Rieger and Olive, 1988; Kapitzke et al., 1996
30	Hindmarsh	SA	Bourman, 1975
31	Inman	SA	Burston and Good, 1996
32	Nangkita	SA	Bourman, 1975
33	Onkaparing	SA	Bourman, 1975

34	George's River	Tas	Bird, 2000; Knighton, 1991
35	King	Tas	Locher, 1996; Locher, 1997
36	Ringarooma	Tas	Knighton, 1987;1989;1991;1999; Bartley and Rutherfurd, 2001a
37	South Esk	Tas	Norris et al., 1982
38	Avoca	Vic	Rutherfurd and Smith, 1992
39	Avon	Vic	Brizga and Finlayson, 2000; Davis et al., 2000; Department of Water Resources Victoria, 1989
40	Bendigo	Vic	Rural Water Corporation, 1994
41	Cann	Vic	Brooks, 1999
42	Creightons/Branjee	Vic	Davis and Finlayson, 2000; O'Connor, 1991a; O'Connor, 1991b; O'Connor and Lake, 1994; (Bartley et al., 2001)
43	Genoa	Vic	Erskine, 1992b
44	Glenelg	Vic	Rutherfurd and Budahazy, 1996; Strom, 1947; Erskine, 1994a; I.D.&A. et al., 1992b; Sinclair Knight Merz, 1997; Rutherfurd, 2001
45	Various streams in the **Goulburn-Broken** catchment and surrounds Eg. Bendigo Ck, Ovens River, Mitta Mitta, Omeo etc	Vic	Shakespear et al., 1887;Erskine et al., 1993
46	Lang Lang	Vic	Bird, 1980; East, 1935
47	Pranjip	Vic	Erskine et al., 1993; O'Connor and Lake, 1994
48	Pyalong	Vic	Rutherfurd, 1993
49	Pykes	Vic	Forbes, 1948
50	Snowy	Vic	Abrahams, 1972; SMEC, 1967; Finlayson and Bird, 1989
51	Tambo	Vic	Erskine et al., 1990
52	Thompson	Vic	Erskine et al., 1990; Brizga and Finlayson, 1990
53	Wannon	Vic	Erskine, 1994a; I.D.&A. et al., 1992a; Marker, 1976; Rutherfurd and Budahazy, 1996a; Sinclair Knight Merz, 1997
54	Blackwood	WA	Olsen and Skitmore, 1991
55	Frankland	WA	Olsen and Skitmore, 1991

Of the 55 or so Australian streams containing sediment slugs, approximately 20% have resulted from mining activities; these represent exogenous sediment sources. The other 80% of cases are from erosion linked to either catchment clearing, logging, flooding or meander cut-offs; most of these disturbances result in a change to instream sediment production, and are thus endogenous. The main difference between sediment slug studies in Australia and overseas is that Australia has no sediment slugs that result from glacial processes.

3.3.3. Critical evaluation of sediment slug studies (in Australia)

Most of the sediment slug studies, particularly in Australia, have been single case studies which have focused predominantly on the sources and distribution of sediment (eg. Brooks and Brierley, 1997; Davis and Finlayson, 2000; Erskine and Saynor, 1996; Fryirs and Brierley, 2001; Knighton, 1987). Very few have looked at the recovery of streams that have been disturbed by sediment slugs. Those which have, are generally very qualitative, and lack quantitative rigour with which to assess the recovery potential of the stream (eg. Erskine, 1996; Fryirs, 1999; Fryirs and Brierley, 2000).

Considerable progress has been made in previous studies in terms of understanding the process by which sediment gets into streams, as well as the response of slugs to processes such as flood events. There are, however, a number of factors that the current (mainly Australian) studies have failed to address. These include:

- the development of appropriate quantitative tools to assess the impact and recovery of sediment slugs on instream physical diversity and habitat;
- the development of a conceptual framework or model that describes the recovery process following disturbance, and quantitative techniques that can be tested on a range of stream types (rather the case study framework that is currently more widely used);

The work discussed in this thesis addresses these points, and in an attempts to build and enhance the research that has been carried out on sediment slugs in Australian streams.

3.4 The impact of sand slugs on stream morphology, ecology and human infrastructure

The impact of sediment slugs in the Australian landscape resulting from anthropogenic disturbance has been acknowledged for a long time:

> '*...the filling up of large clear water holes in the creeks and rivers (used for stock and domestic purposes), the silting up of the river beds, causing the sludge to overflow on the adjacent lands to the destruction of vegetation and fruit trees; the liability of horses and cattle going to water in the creeks being bogged and perishing there...the deterioration of the wool of sheep in the vicinity of the silted-up streams, by reason of the sand being blown into the fleeces by the wind and the depreciation in the values of the lands affected'*...Shakespear *et al.*, 1887 in a report to His Excellency the Governor-In-Council to enquire into the sludge question resulting from gold mining in the Goulburn-Broken catchment, Victoria.

More recently, research into sediment slugs has focused on the large scale morphological and ecological impacts on the stream. The following sub-sections outline the impacts and previous research that has been conducted on sediment slugs; Section 3.4.1 looks at changes to the morphology of the stream, and Section 3.4.2 describes the changes that occur to instream habitat following disturbance by sediment slugs.

3.4.1. Impact of sediment slugs on stream morphology

The effect of increasing sediment on alluvial river systems has been well documented in the literature for changes over large scales (eg. 10^3 m) (eg. Leopold and Maddock, 1953; Leopold *et al.*, 1964; Schumm, 1969; Schumm, 1971). The changes that occur to the morphology of a river when there is an increase in sediment load were described by Schumm (1969) using Equation 3.1 and Equation 3.2 . These equations represent the changes to the system when there is an increase and decrease in sediment load (Q_s) respectively.

$$Qs^- \cong \frac{w^- L^- S^-}{\bar{y}^+ P^+} \qquad \text{Equation 3.1}$$

$$Qs+ \cong \frac{w^+ L^+ S^+}{\bar{y}^- P^-} \qquad \text{Equation 3.2}$$

where w is width, $\bar{y}$ is depth, L is meander wavelength, P is sinuosity, S is gradient, F is width/depth ratio, and the + and – represent an increase or decrease in the parameter specified. Based on Equation 3.2, an increase in sediment load (without an associated increase in discharge) will result in channel widening, an increase in meander wavelength and channel slope, and a decrease in depth and sinuosity. However, if there is an increase in the percentage of bed material load, Qt^+ and subsequent decrease in mean annual discharge, Qw^- (Equation 3.3), the stream may change such that the channel depth and sinuosity will decrease and the gradient and width-depth ratio will increase (Schumm, 1969).

$$Qw^- Qt^+ \cong \frac{d^- P^-}{S^+ F^+} w^{\pm} L^{\pm} \qquad \text{Equation 3.3}$$

A change in the mean annual discharge at the time of increased sediment load can have quite different implications for channel change. The main situation where Equation 3.3 will be relevant is when there is a sediment slug downstream of a dam or water storage (eg. on the Murrumbidgee River, ACT, Australia). The changes represented by these equations can be considered as the large scale impacts of sediment slugs on stream systems.

There are many other impacts sediment slugs have on the morphology of the stream that cannot be described as neatly as Equation 3.2. A common effect of sand slugs on typically erosive areas is to change the channel from being sediment sink to a sediment source as the slug moves downstream. Schumm *et al.* (1987) also described how, for larger slugs, aggradation may involve the transition from a single channel to a braided network.

Jackson and Beschta (1984), outlined how increased sand delivery alters the morphologic response and roughness of channels. Based on a number of flume studies, they found that channel widening, combined with decreased average channel depth (from sand build-up) meant that overall channel stability is reduced. In addition, if the increase in sand delivery is great enough, gravel features will be smothered even though sediment transport rates will have increased (Jackson and Beschta, 1984). Increased sand concentrations in transport will also enable lower stream discharges to transport the gravel materials in riffles. This suggests that armouring will be less effective and the amplitude of the riffles may diminish.

In addition to the morphologic changes, the hydraulic changes associated with aggradation indicate that there will be an increase in the effectiveness of moderate discharges (less than 1-2 year recurrence interval) to transport bedload and shape the bed. As a result, bars become smaller, pools preferentially fill, and riffles armoured with relatively small gravel tend to erode head-ward during falling stages and form a gentler gradient (Lisle, 1982).

<u>Summary of the large scale impacts</u>

For almost all of the documented cases of streams affected by sediment slugs, there is a collection of common response processes. In general, channels aggrade and widen, have a change in the bed material, pools infill, channel roughness decreases, and braiding may occur.

Understanding the impacts sediment slugs have on the morphology of streams is important for determining which sections are appropriate for rehabilitation. It is also important to note that although there are a number of characteristic changes that sediment slugs impose on stream systems, the impact of each slug will differ according to the local conditions and the temporal and spatial characteristics of the stream.

3.4.2. Impact of sediment slugs on stream habitat

There are many ways in which sediment slugs can impact the ecology of a stream. Slugs are often composed of a single sediment size, commonly sand, that acts to fill the channel, blanketing the stream. Visually, the slugs have a considerable impact of the macro-habitat features such as pools, riffles, runs, backwater zones, large woody debris (LWD), bedrock outcrops and macrophytes. There has, however, been little quantitative research looking at the changes of the different habitat groups in streams disturbed by sediment slugs.

Perhaps the most comprehensive study to date was a 15 year investigation by Alexander and Hansen (1986), which monitored the effects that increasing bed load had on trout numbers, habitat, and benthic organisms. The increased sand (4-5 times the natural bed load) caused the stream to become wide and shallow, pools and riffles filled in, and the bed profile became uniform, and void of cover such as woody debris, undercut banks etc. The implications of this morphology reduced the stream to one long run, making the water shallower, and leaving the fish vulnerable to predation. The water temperatures also increased (due to increased surface area) and the loss of diverse water velocities reduced the resting areas for young fish. The sand bed substrate, which results in a continuously moving bed, is also considered the poorest habitat for the production of benthic food organisms. Overall, both trout numbers and benthic populations dropped to half their pre-treatment levels (Alexander and Hansen, 1986). However, it must be noted that 'runs' are of importance to stream systems, as they contain some unique species; they are only undesirable when they replace other habitat forms, reducing the total habitat heterogeneity (Smith and Harper, 1990).

Another comprehensive review of the impact of sediment on aquatic habitats was carried out by ASCE (1992). This report outlined specifically what happens to instream habitat when a gravel or coarse bed stream is impacted by finer sediment. This report stresses that the relationship between benthic communities and sediment is complex; however, they did highlight that 'surficial bed material is often the primary influence on community composition and density'. This has been proven in a number of scientific studies (eg. Wene and Wickliff, 1940; Williams, 1978; Williams, 1980; Williams and Smith, 1996). Thus, rapid changes in bed material due to impacts such as sediment slugs can have severe implications for instream fauna.

Studies have shown that benthic diversity is greatest in streams with cobble and gravel sediments whilst sand bed and soft sediment streams are characterised by high densities, but low species diversity, and organisms are considerably smaller than those found in coarse substrates (ASCE, 1992). Strommer and Smock (1989) also found that the anaerobic conditions below 10 cm, and sediment scouring during storm events were important factors controlling the subsurface invertebrate communities in sand bed streams.

Recent work by Boulton (1999) on several Australian streams and rivers has revealed the extent that the sub-surface ecosystem plays on the fauna of a stream. The hydrological exchange of nutrients and water between gravels on the stream bed is vital for sustaining the hyporheic zone and the organisms it supports. In other studies, the impact of increased sediment was shown to be detrimental to the water circulation, sediment size and thus small scale habitat features in the hyporheic layer (eg. Des Chatelliers and Reygrobellet, 1990).

At the pool scale of habitat, sediment slugs can have a major influence, as slugs tend to fill in pools and reduce their depth. This is detrimental to streams, as pools are one of the more stable habitats and they also have high habitat heterogeneity. These factors have been shown to increase species richness and population density (Shields et al., 1998).

Other authors have suggested that one of the main reasons that sand bed channels and sediment slugs represent poor habitat is their instability and vulnerability during flood events (eg. Bhowmik and Adams, 1990; Culp *et al.*, 1986; Death and Winterbourn, 1995). An Australian study by O'Connor and Lake (1994) has shown that the input of sand from incised streams has rendered the upper and middle sections of a streams more susceptible to damage from floods; these have produced unstable substrata and a reduction of refugia. This study also showed that there was a decline in macroinvertebrate species richness and numbers of individuals, resulting in changes to the community structure in areas impacted by the sediment slug.

Despite considerable evidence that increased sediment is detrimental for instream habitat, some studies summarised in Harper *et al.* (1995) describe how certain macroinvertebrate species can actually increase in abundance following an increase in sand sized particles (eg. *Ptychopteridae*, *Centroptilum luteolum*). Also streams that have been impacted by increased sand, but contain considerable woody debris, can support rich invertebrate communities.

Most of these studies have highlighted the effect that fine sediment can have on coarser bed material, yet there has been little research to look at the impact of coarse sediments on fine clay materials. In Australia, many streams have natural clay beds and, in a number of cases, these streams are being impacted by sand slugs from erosion of the granite or sandstone reaches upstream (eg. Davis and Finlayson, 2000; Rutherfurd, 1996; Rutherfurd and Budahazy, 1996). Thus, it is difficult to determine if there would actually be an increase or decrease in habitat diversity by adding larger sized sediment into naturally fine grained clay streams.

Overall, this section has shown that sediment slugs can decrease the level of habitat and species diversity in most streams.

3.4.3. The impacts of sediment slugs on human infrastructure

Other than the direct impact that sediment slugs have on the instream environment, there are a number of other effects that sediment slugs can have on the river and its surrounds.

Gilbert (1917) reports of farms being inundated, and towns having to build levee banks to protect against the rising flood waters, from increased bed levels due to sediment slug formed by mine tailings in the Sierra Nevada. As well as increasing the flood frequency of streams, sediment slugs can distort stream gauging records and stream flow estimates (James, 1991). Sediment slugs also have the potential to fill in dams, reducing the expected life of the water supply (Ebisemiju, 1990; Klaghofer et al., 1992).

Many authors have discussed the potential impacts of sediment slugs on bays and estuaries (eg. Gilbert, 1917; Meade, 1982; Ricks, 1995; Steane, 1972). This not only affects the biotic ecosystems in these areas, it also poses a problem for navigation. For example, the mouth of the Ringarooma River (Tasmania) was once used as the main port in Tasmania carrying tin to Europe during World War II (Knighton, 1987; Steane, 1972). At the mouth of the Ringarooma River today, it is difficult to drag a canoe through the sediments, let alone have large shipping vessels sail in.

One of the main processes to occur in streams after sediment slugs have moved downstream is channel incision; this occurs as the stream re-establishes its former bed levels. Incision following sediment slug movement has been observed by a number of authors (eg. Gilbert, 1917; James, 1991; Knighton, 1999), and it has been shown to pose problems for human made infrastructure such as bridges and roads. Galay (1983) describes a number of cases of bridge failure and even the breach of small dams as a result of channel incision. Knighton (1989) also describes how many public road bridges on the Ringarooma River (Tasmania) 'had to be replaced long before their natural lifespan had elapsed because of either burial beneath a rising bed level or undermining during degradation'.

It is acknowledged that sediment slugs also pose a threat to streams in the form of chemical pollution. In many cases, the sediment slugs carry pollutants or nutrients which travel with the slug, either as solid particles attached to the sediment, or absorbed (eg Marron, 1992; Meade, 1985); however, the physio-chemical interactions that the sediment slugs have on stream systems is not further addressed in this thesis.

3.5 Sediment slug propagation and movement

It is not the purpose of this thesis to provide a review of the small scale sediment transport phenomena that move sediment slugs along rivers; details of sediment transport and the associated equations and mechanisms can be found elsewhere (eg. ASCE, 1971; Beschta, 1987; Gomez, 1991; Gomez *et al.*, 1989; Higgins *et al.*, 1987; McLaren and Bowles, 1985; Neill, 1987; Pickup *et al.*, 1983; Shen, 1978; Yang, 1996; Yang, 1973). However, the main qualitative models that have been put forward to describe the large scale movement of sediment slugs down river systems are pertinent to the thesis topic, and are presented in this section.

Lewin and Macklin (1986) characterised the response of a stream to introduced mining sediments into two groups: passive dispersal and active transformation. Passive dispersal is where the sediment is transported alongside the 'natural' load so as not to disrupt the natural system, and active transformation is where the whole fluvial system is transformed (Lewin and Macklin, 1986). For both types of response, a number of approaches have been put forward to explain the movement of sediment slugs through stream systems. The approaches can be broken up into two general groups: (1) research using the conceptual 'wave' model, and (2) empirical models.

<u>Wave models of sediment slug movement</u>

Gilbert (1917) was one the first to describe the movement of sediment slugs. He described the movement of mining debris in a river to be analogous to that of water in a flood. The sediment "travels in a wave, and the wave gets longer and flatter as it goes" (p. 31). Gilbert described the actual mechanism of sediment movement as 'sorting', by which the finer grained sediments move downstream first, followed by the coarser gravels. He also suggested that 'the depth of the deposit was affected by the quantity of water flowing through the channel…a quantity which tended to increase as access to lateral basins were restricted by levees' (Gilbert, 1917, p. 29). This suggests that as well as sorting, changes in discharge and stream power were also mechanisms for wave propagation. Gilbert then concluded that once the sediment has been transported through the system, the stream will return to pre-disturbance bed levels and sediment delivery rates.

This 'wave model' has been observed and supported in a number of sediment slug studies (eg. Griffiths, 1993; Madej and Ozaki, 1996; Meade, 1985; Pickup *et al.*, 1983); however, other studies such as Knighton (1989) and Bird (2000) did not observe the characteristic wave-like form until the later stages of slug development. This was probably due to the multiple rather than single source of sediment, and the storage of sediment along these streams.

James' (1989; 1991) work on the hydraulic mining sediments of the Bear River California resulted in a revised version of Gilbert's (1917) symmetrical wave model producing the 'asymmetrical wave model'. This model resulted from the observation that sediment storage and remobilisation is an important component of sediment transport on a variety of scales, and this aspect was not included in Gilbert's model. The newer asymmetrical model is possibly more realistic for Australian river systems, as long periods of drought often result in the sediment being colonised by vegetation (eg. Zierholz *et al.*, 2001), and intense flood frequencies can result in the remobilisation of sediments that have been stored for many decades (Erskine, 1996a).

Empirical models of sediment slug movement

In addition to the large scale conceptual models of sediment movement, there are a number of more quantitative numerical models that have been used with varying degrees of success for predicting the movement of slugs of bedload down stream systems (eg. Hoey, 1992; Kesley et al., 1986; Kesley et al., 1987; Knighton, 1991; Macklin and Lewin, 1989; Nicholas et al., 1995; Pickup et al., 1983); as well as in flume environments (eg. Lisle et al., 1997; Warburton and Davies, 1994).

Many of these models are extremely useful for predicting sediment movement at different scales; however, they can only be used as a tool for predicting the rates of sediment movement, and not the recovery condition itself. Adaptation of more conceptual models of sediment movement is required before numerical models can be applied to predict the rates of recovery.

Summary of sediment slug movement models

Essentially there are two conceptual models that describe the impact and subsequent recovery of streams disturbed by sediment slugs. These are the symmetrical wave model by Gilbert (1917) and the asymmetrical model proposed by James (1989). These conceptual models are similar in that they both assume that the recovery of the stream is dependent on the return to pre-disturbance bed levels and sediment loads. The difference between the models is that James (1989) incorporates sediment storage into his model of sediment slug movement.

In reality, the pattern of sediment delivery and movement depends on several factors: the timing and location of supply events, the location of potential sediment accumulation zones, and the timing and magnitude of flood events (Hoey, 1992). Understanding the large scale sediment movement processes is important for understanding the recovery potential for streams that have been disturbed by sediment slugs. However, the current wave models used to describe the response of streams to disturbance by sediment slugs are too coarse, and not appropriate for small scale eco-geomorphic studies. Thus, a new model for the recovery of slugged streams is proposed in Section 3.7.

3.6 Geomorphic approaches for measuring the recovery of disturbed streams

As described in previous sections, the impact of a sediment slug on a stream system can result in considerable changes to the morphology and habitat of a stream. Madej and Ozaki (1996), suggested that 'this may lead to the re-establishment of previous condition or to a new state'. Trying to predict the state of the system following disturbance is difficult. There are a number of possible methods for estimating the response and recovery of streams to disturbance. These include:

(1) Monitoring the changes in the stream over the duration of the disturbance including the recovery phase;

(2) Using predictive numerical modelling to forecast the state of the system following recovery; or

(3) Using ergodic theory or space for time substitution.

Few research projects have the time and funding to monitor the full lifecycle of disturbance and recovery for streams impacted by sediment slugs, as some sediment slugs may take hundreds of years to move through a stream. Predictive modelling is becoming increasingly sophisticated in the area of sediment transport, however, at this stage, there are no models that are able to predict the recovery of the geomorphic structure of the stream following disturbance. Hence, the most practical option for predicting the recovery of streams disturbed by sediment slugs is to use space for time substitution.

3.6.1. Ergodic Theory and Geomorphic Recovery

Ergodic theory, or space for time substitution, has been used extensively in geomorphic studies to document long term impacts to river systems (eg. Fryirs and Brierley, 2000; Hupp, 1997; Keller, 1972; Schumm *et al.*, 1984; Simon, 1989; Simon, 1995). Space for time substitution is commonly used in studies where the time frames of disturbance and recovery are too long for conventional scientific research. Essentially, space for time substitution involves selecting a series of landforms (eg. channel cross sections), that will represent conditions at other locations in the future (Schumm et al., 1984). In statistical terms, ergodicity is when means and variances are constant; the ergodic hypothesis states that, "an infinitely long record at one point has the same statistical properties as a record taken over an infinite number of spatial assemblages at a particular point in time" (Harvey, 1967).

Application of ergodic theory to streams disturbed by sediment slugs

Streams that have been disturbed by sediment slugs have yet to be evaluated using the ergodic approach, and it appears that this study would provide an appropriate test. In streams disturbed by sediment slugs, the disturbance progresses along the channel forming a gradient through space, with the areas furthest away from the slug being most recovered, and areas near to the slug being the most disturbed. This spatial pattern is similar to what would be expected to occur at any one point on the river over time. Therefore, if the full spectrum of channel evolution can be measured along the river, from the disturbance through to recovery, then this would be analogous to the phases of disturbance at one place through time. This approach was used successfully for incised streams (eg. Hupp, 1997; Schumm et al., 1984; Simon and Hupp, 1987), and examples of the results of such work are presented diagrammatically Figure 3.2 (as well as in Figure 2.1, Chapter 2).

As with most approaches in science, there are assumptions and limitations to be considered. Paine (1985) outlines those applicable to ergodic theory: (1) the assumption that processes operating in the stream are the same as they were in the past, (2) that we correctly understand the cause of variability in our models, and (3) that characteristic (and suitable) sample sites can be identified. With these assumptions in mind, ergodic theory appears to be an appropriate tool for assessing the recovery process on streams disturbed by sediment slugs.

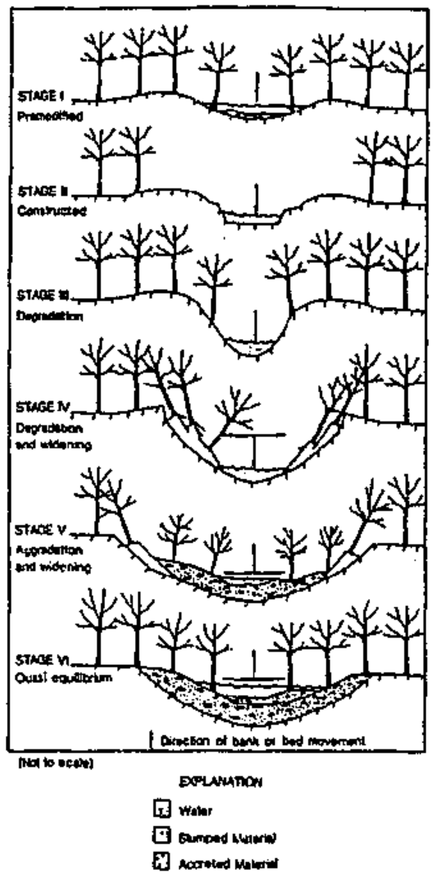


Figure 3.2: The application of space for time substitution to evaluate channel evolution and recovery following channelisation (Hupp and Simon, 1991).

3.6.2. Current indicators of recovery for streams disturbed by sediment slugs

In addition to the ergodic approach for evaluating recovery in disturbed streams, geomorphologists need to choose a specific variable or indicator for actually measuring recovery. There are four key indicators of recovery for streams that have been disturbed by sediment slugs:

(i) The return of the stream to pre-disturbance bed levels (eg. Gilbert, 1917; Knighton, 1989; Madej and Ozaki, 1996; Madej, 1987);

(ii) The return to pre-disturbance sediment loads (eg. James, 1989);

(iii) The presence of stable large scale morphological features, namely benches (eg. Erskine, 1996);

(iv) The return of a 'suitable river structure and function' or 'quasi-equilibrium' (eg. Fryirs, 1999; Hoey, 1992; Pitlick, 1993).

Of the four different categories, it is the return to the pre-disturbance bed-levels that is the most common measure of recovery in slugged streams. As described in Section 2.4.1, these definitions may be appropriate in theory, yet they are impractical bench-marks for recovery due to the lack of data describing the pre-disturbance condition (eg. bed level or sediment supply). As discussed by Madej and Ozaki (1996), bed-level is only one measure of channel recovery and the re-establishment of a previous channel morphology (in particular pools and riffles) is also important. Thus, there is need to re-define recovery for geomorphic disturbances.

3.7 Using Geomorphic Variability to assess disturbance and recovery: a new model

Using the information on sediment slug impact and recovery, it is possible to conceptualise a model of recovery. As described in Section 3.5, the two current models used to describe the response of streams disturbed by sediment slugs are the symmetrical and asymmetrical models. These models use bed level to represent the movement and recovery of streams impacted by sediment slugs.

Based on the habitat studies discussed in Section 3.4.2, it is appropriate to change the dominant indicator of recovery from bed level, to a more eco-compatible measure such as Geomorphic Variability (Chapter 2). Using this new indicator of recovery it is possible to formalise the conceptual models of sediment slug impact and recovery into a schematic diagram which is presented in Figure 3.3.

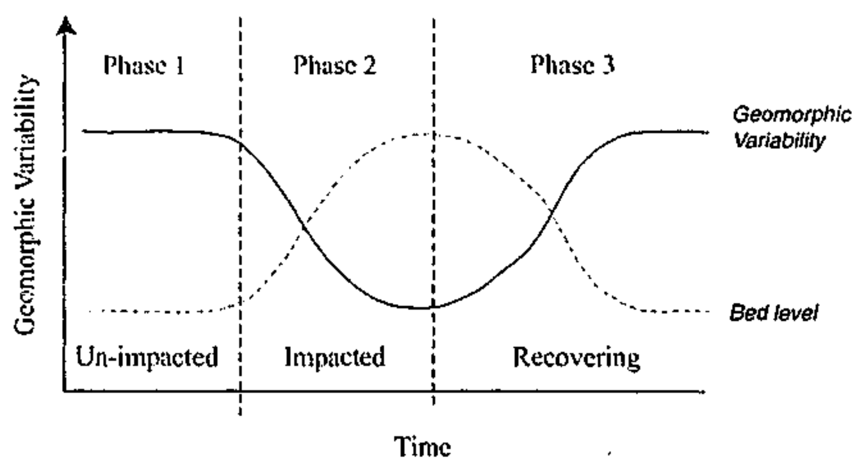


Figure 3.3: A model of disturbance and recovery for streams disturbed by sediment slugs

This model replaces existing measures of recovery such as bed-level with 'Geomorphic Variability'. Geomorphic Variability is now the dependent variable against which the recovery of streams is evaluated; sediment depth or bed level changes are simply an indicator of change. Figure 3.3 uses Gilbert's (1917) conceptual symmetrical wave model as the basis for predicting the recovery of streams disturbed by sediment slugs. The asymmetrical model (after James, 1991; 1999) was considered in the development of this model, however, given the time frames of sediment storage in these systems (ie. often hundreds of years), this model could not be practically applied.

The new recovery model (Figure 3.3) is broken into 3 phases:

Phase 1: has a stable bed-level and represents the natural level of Geomorphic Variability that you would expect to find in the river had there been no disturbance. A reach in Phase 1 could be considered as a reference or control reach. A control reach could be located either up or downstream of the impact zone, or on another river with similar geomorphic and hydrological features.

Phase 2: is a reach where the bed has aggraded due to a sediment slug filling in the channel. This essential represents the stream in a highly disturbed state. A reach in Phase 2 would be considered as an impacted reach, and the model suggests that the level of Geomorphic Variability will be lowest when the bed level is aggraded;

Phase 3: represents a point in the stream where the sediment appears to have passed through the channel and the bed level is returning to near pre-disturbance levels. According to the model, the recovery of the bed-levels should also result in the recovery of Geomorphic Variability. Recovery in this case does not specifically refer to its original condition as this is often not possible (Cairns, 1991; Milner, 1996). In this study, a reach will be considered to have recovered if the Geomorphic Variability in the recovering reach (Phase 3) has the same statistical properties as a reach in Phase 1 (un-impacted condition). Tools for identifying the different phases on each stream will be described in detail in Chapter 5.

<u>Application of ergodic theory to the Geomorphic Recovery Model</u>

As described in Section 3.6.1, ergodic theory has been successfully applied to other disturbance studies, and is also considered suitable for testing the recovery of streams disturbed by sediment slugs. Figure 3.4 shows how ergodic theory is used to replace temporal sampling when testing the recovery model. For example, data could be collected over time at one site, showing the different phases of disturbance (eg. in 1900, 1950 and then in 2000 in Figure 3.4). Alternatively, space for time substitution can be employed to measure the recovery gradient along different sections of the river. Using this approach, it is assumed that the area of maximum disturbance will be closest to the sediment slug; the level of disturbance will then gradually decline with distance away from the slug (Figure 3.4).

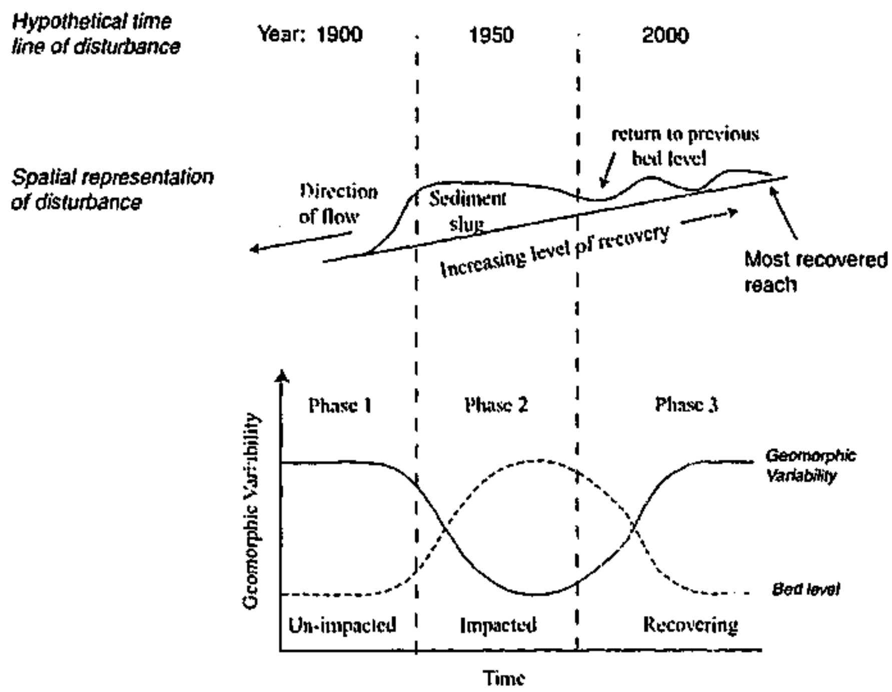


Figure 3.4: Application of ergodic theory to sediment slug movement and the recovery model presented in Figure 3.3.

3.7.1. Testing the Geomorphic Recovery Model: thesis hypotheses

In light of the Geomorphic Recovery Model presented in Section 3.7, a number of hypotheses are proposed.

Thesis hypotheses:

(i) Ergodic theory is a suitable approach for evaluating the recovery of streams disturbed by sediment slugs;

(ii) That the return of pre-disturbance bed levels following the impact by a sediment slug is a good measure of the return of Geomorphic Variability to a stream;

(iii) That the Geomorphic Recovery Model proposed in this thesis accurately predicts the response of streams disturbed by sediment slugs.

These hypotheses form the basis for the research presented in the remaining chapters.

3.8 Summary

This Chapter has provided an overview of the distribution, impact and movement of sediment slugs within stream systems. Following the review of the literature relating to models of recovery for streams disturbed by sediment slugs, a new revised model was presented.

The main points from Chapter 3 can be summarised as follows:

- Sediment slugs are composed of coarse material, such as sand and gravel. Sediment slugs are becoming increasingly recognised as an environmental problem in Australia;
- A more quantitative method was proposed for identifying sediment slugs in streams. This method involved using sediment depth (and other morphological characteristics) to identify the presence of a sediment slug in a stream;
- An increase in sediment delivery resulting from human disturbance can have a dramatic effect on both the morphology, ecology and human infrastructure of river systems;
- Sediment slugs aggrade and widen the channel, change the bed material, in-fill pools, decrease channel roughness and braiding;
- Sediment slugs affect organisms by increasing sediment movement and susceptibility of sediments to flood damage, changing variable habitats into uniform features, increasing water temperatures, decreasing flow depth and variability, smothering spawning riffles and the hyporheic zone, and covering up LWD;
- Previous research on the impact of sediment slugs have commonly been single case studies which focus on the impacts and delivery of sediment to the stream. There has been little research into the recovery mechanisms of such disturbances; in those studies that have looked at the recovery process, the criteria for measuring recovery have been qualitative and subjective;
- The movement and recovery of streams impacted by sediment slugs is currently described using both a symmetrical and asymmetrical wave model, with the main indicator of recovery in these models being the return to pre-disturbance bed-level;
- As the return to pre-disturbance bed-level does not necessarily provide appropriate information about the recovery of Geomorphic Variability (and thus river health), a new model was presented;
- The new model of recovery for streams impacted by sediment slugs replaces indicators such as bed-level with 'Geomorphic Variability';
- The Geomorphic Recovery Model presented will be evaluated using an ergodic approach. This was considered the most suitable approach given the time frames of this study.

The remainder of this thesis deals with setting up a rigorous quantitative field study to test the Geomorphic Recovery Model proposed in this Chapter. Chapter 4 will now outline the field sites chosen to test the new recovery model.

Chapter 4

Description and historical background of study sites

4. Chapter 4 - Description and historical background of study sites

4.1 Introduction

Chapter 3 described the impact of sediment slugs on the morphology and ecology of stream systems and a new model for evaluating the recovery of streams impacted by sediment slugs was proposed. This chapter now describes the field sites that were chosen to test the recovery model. Chapter 4 is divided into five main sections. Section 4.2 describes the selection process undertaken to identify appropriate field sites. The remainder of the chapter then details the specific characteristics of the field sites used in this study.

The three streams chosen were Creightons Creek, the Wannon River and the Ringarooma River, which are presented in Sections 4.3, 4.4, and 4.5, respectively. For each stream, the suitability of the site and the previous research conducted are described. In addition, the physiographic setting, geology, vegetation, climate and hydrology are discussed for each site. The history and landuse of each stream, and the subsequent formation of the sediment slug is also described in detail.

4.2 Choosing the field sites

4.2.1. Initial Field Investigation

There were no real limitations to the number or location of field sites for this project; a lot of sand slugged streams could have been chosen. For theoretical reasons, more than one field site was considered important to be able to evaluate the recovery model effectively. Practical reasons, however, relating to the time frame and funding considerations for this research, limited the number of field sites to three. The initial process of identifying appropriate field sites from which to collect data involved a reconnaissance field trip to many stream's in South-East Australia known to contain sediment slugs. The rivers that were assessed as potential field sites are shown in Figure 4.1.

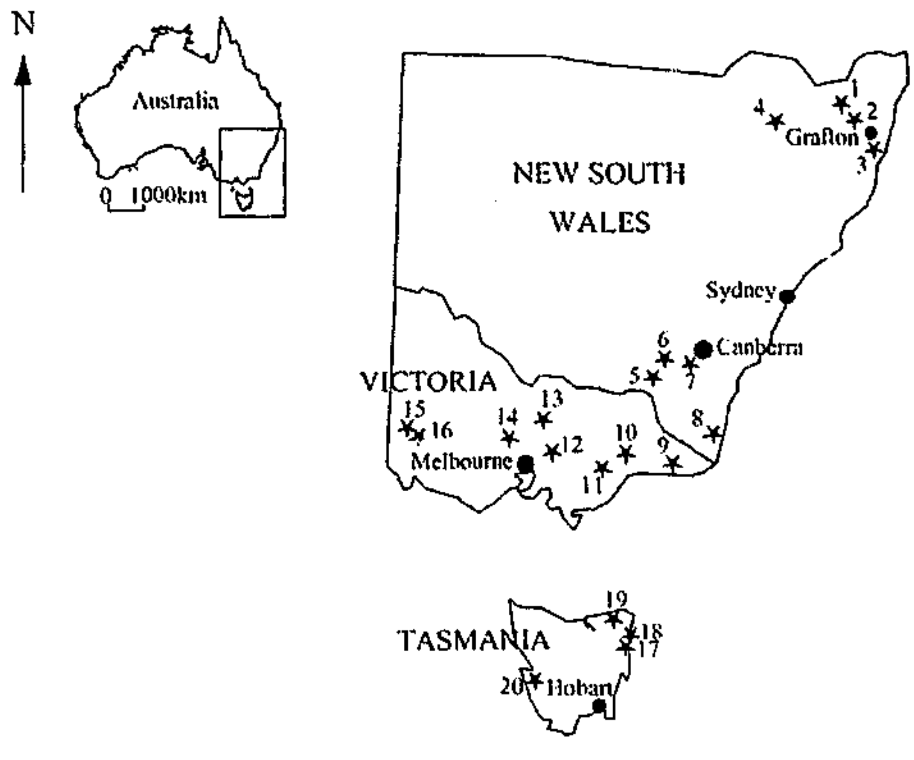


Figure 4.1: Streams initially assessed as a field site

In choosing sites from which to collect data, and test the model of sediment slug impact and recovery, a number of conditions had to be met:

(i) The site had to have historical evidence showing that the stream did have a sediment slug, and was not simply a naturally sandy stream;

(ii) It was important to be able to identify the back end of the slug using historical and/or geomorphic evidence, so the recovery process could be measured and described;

(iii) There needed to be a section of the stream that had not been disturbed by the sediment slug. This enabled a series of 'control' sites, representing the pre-disturbed condition, to be established;

(iv) The streams chosen had to represent a diverse range of stream environments and sediment slug forms, so that the hypotheses (presented in Section 3.7.1) could be broadly tested;

(v) Priority was also given to sites that had already had significant research carried out on the site, as this gave a greater knowledge base for interpreting the results;

(vi) Finally, sites that were within the Cooperative Research Centre for Catchment Hydrology (CRCCH) 'Target Catchments' were also given priority as the results would potentially be transferable and useful in other research projects.

Although at least 20 streams were initially considered as field sites, three sites best met the criteria outlined above. These sites are briefly outlined in Section 4.2.2.

4.2.2. Field sites chosen for this study

The three field sites chosen for this study (in order of field work) were Creightons Creek (Central Victoria), the Wannon River (Western Victoria) and the Ringarooma River (North East Tasmania). The location of the three field sites is shown in Figure 4.2. One of the main criteria that lead to the selection of each of these three sites was the amount of research already undertaken on these streams. This previous research had identified that these streams actually contained a sediment slug of sizeable interest.

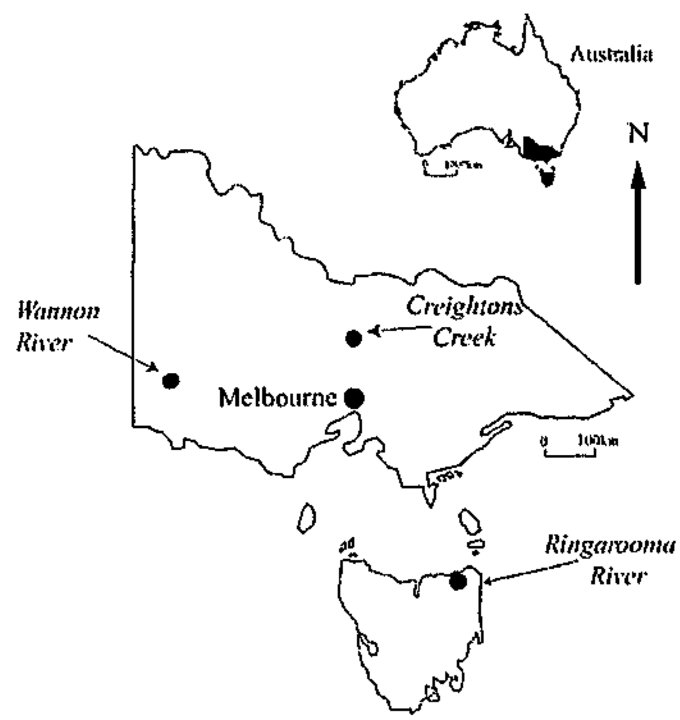


Figure 4.2: Location of field sites used in this study

The three sites are not 'replicate streams'; they are very different in character, with different sedimentation histories. This allows the recovery model to be tested on three streams with different types of slugged environment. A summary of the physiographic conditions for each stream is given in Table 4.1.

Both Creightons Creek and the Wannon River are alluvial streams, dominated by natural clay sediments in the study sections. The Ringarooma River is very different from the Victorian streams in both structure and sedimentation history. It is a gravel bed and bed-rock controlled, and the source of sediment was tin mining. Essentially, the three streams represent three different cases of sediment slug delivery which provided further experimental rigour for the model:

- Creightons Creek can be considered as an endoslug, as the main source of sediment was from erosion within the main trunk of the stream as well as a number of headwater tributaries;

- The sediment slug in the Wannon river has come from an exogenous source, although the sediment was generated through a typically endogenous process. The main source of sediment was actually the result of incision (of both streams and gullies) in a large tributary to the Wannon River: Bryans Creek. The sediment from Bryans Creek feeds directly into the Wannon and represents the main source of sediment for the slug. This provides a control area (upstream of the Bryans Creek and Wannon River junction) and a downstream impact site (downstream of the junction). Thus, the Wannon River represents a classic single injection study;
- The Ringarooma River is an example of an exoslug as all the sediment fuelling the slug was the result of tin mining.

Table 4.1: Physiographic conditions and volume of slug for each of the three study sites

	Creightons Creek	Wannon River	Ringarooma River
Basin size	141 km^2	4491 km^2	912 km^2
Total length of stream	52 km	230 km	120 km
Length of stream impacted by sediment slug	40 km	30 km	75 km
Average annual rainfall	600-800 mm	600-700 mm	980 mm
Approx. sediment volume forming the slug	~240,000 m^3 (Davis and Finlayson, 2000)	~280,000 m^3 (Rutherfurd and Budahazy, 1996)	~40 million m^3 (Knighton, 1987c)

The physiological setting, geology, hydrology, landuse characteristics and sedimentation history of Creightons Creek, the Wannon River and the Ringarooma River are given in Sections 4.3, 4.4, and 4.5 respectively.

4.3 Creightons Creek

4.3.1. Physiographic setting

Creightons (Creightons-Branjee) Creek (Figure 4.3), is an anabranching stream in Central Victoria which flows west off the Strathbogie Ranges and forms part of the Goulburn-Broken River Basin. It crosses the Hume Highway just south of Euroa (145^0 55'E and 36^0 76'S), and is one of several streams that form the 'Granite Creeks' system. Creightons Creek has a catchment area of approximately 141 km^2, and is roughly 52 km in length. The stream can be broken into two physiographic sections: the upper catchment and the floodplain zone.

The upper catchment refers to the steeper, incised areas upstream of the Hume Highway (Figure 4.3). In the upstream sections of the catchment there are four tributaries; Threlfalls

Creek, Ramages Creek, Baronga Creek and Pearsons Creek. The downstream areas or 'river flats' (below the Hume Highway) are of low relief; most of this section of the stream contains a sediment slug (Figure 4.3). The difference in the gradient changes between the upper and lower sections of Creightons Creek is highlighted in Figure 4.4.

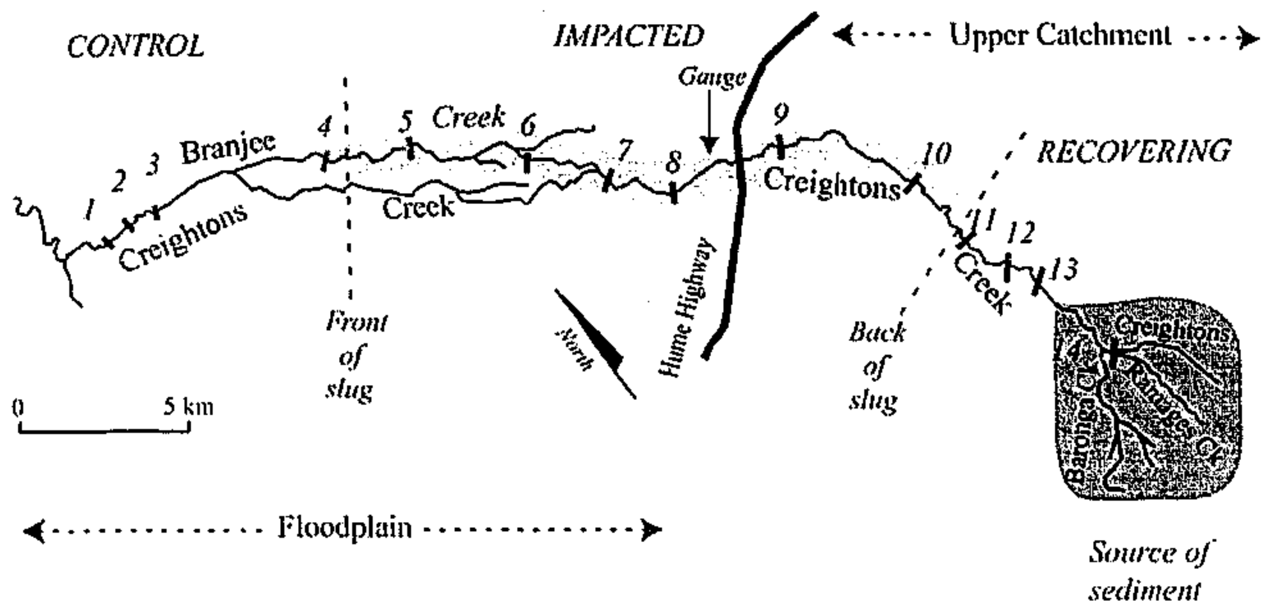


Figure 4.3: Creightons Creek study site showing study reaches and sediment source

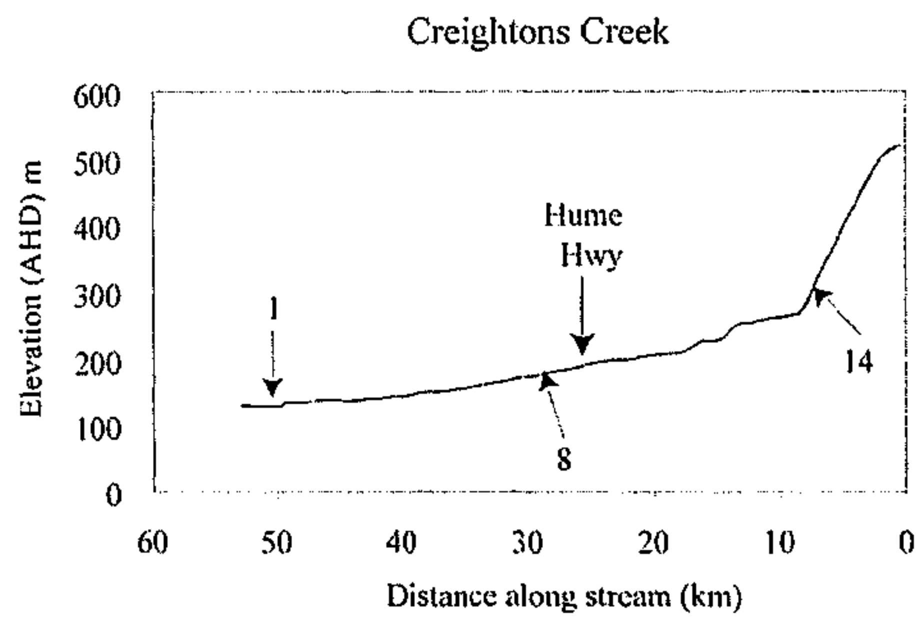


Figure 4.4: Elevation changes along the length of Creightons Creek. The position of Reaches 1, 8 and 14 and the Hume Highway correspond with Figure 4.3 (Source: 1:100, 000 Map sheets - Euroa 8024 and Nagambie 7924).

Downstream on the plains, Creightons Creek becomes an anabranching system with Branjee Creek. During the 1960's, the main channel of Creightons Creek became blocked with sediment, diverting remaining sediment and water down Branjee Creek (Davis and Finlayson, 2000). This natural avulsion was assisted by the construction of a drain by the local farmer in 1969. For the last 40 years, Branjee Creek has been operating as the main channel and Creightons Creek carries water and sediment only during extreme flood events which often coincide with out of bank flow. Hence, the name Creightons Creek refers to Branjee Creek downstream of the Hume Highway.

4.3.2. Suitability of site and previous research conducted

Ecological research

A number of research projects have been carried out on Creightons Creek since the early 1990's. The earliest work was carried out by O'Connor (1991a; 1991b) and O'Connor and Lake (1994) from the Cooperative Research Centre for Freshwater Ecology (CRCFE), Monash University, Melbourne. This research looked at the short and long term impacts of the sediment slug on the macroinvertebrate community, as well as the effect of wood as a substrate for macroinvertebrates. The main findings from this research were that the easily disturbed sites, those with a sand substrate, underwent greater seasonal changes in terms of community structure than the muddy sites downstream. At the downstream sites, not yet been disturbed by the sand slug, O'Connor and Lake (1994) found that the invertebrate colonisation was dependent on the accumulation of leaf and twig matter. In the slugged reaches, the twig matter is still available, as there are considerable stands of Eucalypts in most reaches; however, the sand appears to smother most of the litter. Overall, it was found that in the middle reaches, the increased sand storage rendered the stream more susceptible to disturbance. O'Connor and Lake (1994) also suggest that there is scope for the long-term recovery of the Creightons Creek system. Following the work by O'Conner, a number of other projects have been conducted to look at the impact of sediment on macroinvertebrate habitat and fish numbers (eg. Bruno, 1998; Graham, 1999; Swingler, 1999).

Geomorphological research

Thompson and Assoc. (1992) were one of the first to classify the Granite Creeks streams as being unstable or showing severe instability. Subsequently, Davis and Finlayson (2000) undertook a project documenting the historical changes and the source of sediments to the Creightons Creek. This report has provided extremely useful information regarding the historical development of the sediment slug. Davis and Finlayson (2000) estimated that approximately 320,000 m^3 of sediment had been liberated from the headwater reaches of the stream. Analysis of the bank samples from the source areas showed that at least 30% of the sediment was finer than 63 μm, and therefore would be transported in suspension. The remaining sand and gravel currently moves as a sediment slug. This volume was estimated to be approximately 240,000 m^3, which included some instream deposits not sourced from upstream. Other findings from their research will be discussed in following sections.

<u>*Gaps in the research*</u>

The work by Davis and Finlayson (2000) determined the sources of the sediment, but they did not look at the physical small scale changes that occurred as a result of the sediment slug impact on Creightons Creek; nor did they assess the recovery potential of the stream. This project will fill that gap, and relate the distribution of the sediment slug to the Geomorphic Variability, and recovery potential of Creightons Creek.

4.3.3. Geology and vegetation

The Granite Creeks catchment contains two distinct geologies. In the headwater reaches, the geology is dominated by granitic Strathbogie Massif (Davis and Finlayson, 2000). The streams then flow out of the headwaters onto the flats which are composed of alluvial sediments.

The vegetation also broadly corresponds to the geology of the catchment. In the upper sections, the vegetation is dominated by messmate-stringybark open forest, peppermint open forest, red stringybark-long-leafed and swamp gum open forest (LCC 1984). On the riverine plain, open forests/woodlands comprising grey box, yellow box, red gum and bull-oak are found, with red gum common along the drainage lines (LCC 1983). In the 1800's, large scale clearing of the vegetation in these catchment means that there are only small patches of vegetation remaining on both the hills and flats. Today, remnant native vegetation can still be found in the area but it is restricted to some of the rocky ridges in the headwaters, reserves and road edges (Davis and Finlayson, 2000).

4.3.4. Climate and hydrology

The Granite Creeks area in central Victoria tends to experience hot dry summers and cool wet winters (Land Conservation Council, 1984). The local temperatures range from 5.9°C (average minimum) to 18.5°C (average maximum) at Strathbogie (headwater range) and between 13.4°C and 20.9°C at Euroa (on the floodplain). The local rainfall regime has a moderate winter maximum, with the annual average rainfall of 985 mm in Strathbogie and around 650 mm in Euroa.

A flow regulation structure does exist on Creightons Creek (shown in Figure 4.3); however, it is no longer active. The period of record for the gauge was from 30/5/76 to 14/2/89 (TES Hydrographics), fortunately, long enough to construct some meaningful hydrologic relationships. Figure 4.5 shows the flood frequency curve for the period of record and the 1 in 2 year discharge (AEP = 50%) for the gauge is 10.3 m^3/s or 887 ML/day. The methods for devising a flood frequency curve are described in Appendix A.

Creightons Creek is spring fed, which allows it to flow all year round in all years accept drought years (O'Connor, 1991b).

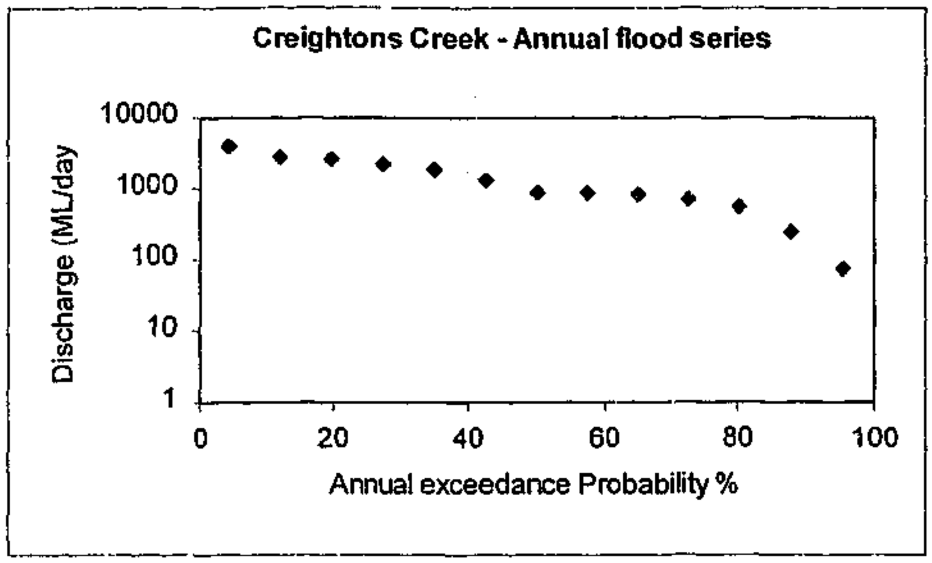


Figure 4.5: Flood frequency curve for Creightons Creek

4.3.5. Instream Ecology

The various studies that have been carried out to look at different aspects of the instream ecology in Creightons Creek were discussed in Section 4.3.2. In these studies, analysis of macroinvertebrate data showed that there is a significant difference between the sand and clay reaches. This difference occurs in both abundance and species richness (pers. com Professor Sam Lake, CRC Freshwater Ecology, Monash University).

Studies of fish fauna indicate that there is a difference in species composition between upstream (sand) and downstream (clay) sections. Five native species, and three introduced species, have been collected during two surveys (summer and winter). The native River Blackfish (*Gadopsis marmoratus*) has been found only upstream whereas the ubiquitous, introduced species Carp (*Cyprinus carpio*) occurs in the downstream sites (pers. com Professor Sam Lake, CRC Freshwater Ecology). This result is un-expected considering that the upstream areas are considered to have poorer habitat; however, the difference in the distribution of fish may have more to do with the preferential habitats of these species, ie. carp are a competitive species that prefer muddy banks.

4.3.6. History of landuse and evolution of the sediment slug

A comprehensive historical analysis, including landuse changes for the Creightons Creek catchment was carried out by Davis and Finlayson (2000). Hence, this thesis will not go into great detail as to the source and causes of erosion; readers are directed to Davis and Finlayson (2000) for more detail. A summary of the important findings from the historical research relating to the timing of the sediment slug within the stream, and evidence showing the evacuation of sediment from the upper reaches, is presented here.

Historical evidence from circa 1820's is not well established for the Granite Creeks area. Entries in Major Mitchell's diary (1839) suggest that the Granite Creeks streams were made up of a series of 'chains of ponds'; however, it is not certain if this description matches the morphological definition of 'chain of ponds' described by Eyles (1977). There is a stretch of approximately 10 km of stream in front of the slug that has not yet been impacted (Figure 4.3). This provides an indication of the natural condition of the stream prior to disturbance. There is very little evidence describing the pre-disturbance morphology of the upstream area's; however, it is expected that the incised areas upstream of the Hume Highway would have been similar either to the remaining 'chain of ponds' downstream of the slug, or they may have had a swampy meadow appearance (Prosser, 1991).

The earliest evidence of channel change was suggested to have occurred in the late 1870's, when early settlers ploughed drainage lines into the swampy zones around the creek (Davis and Finlayson, 2000). Such activities set a wave of head-cuts up through the channel, initiating erosion and the development of the sediment slug. A major flood event in 1916 is suggested to have eroded many of the stream sections in the upper reaches, mobilising sediment to areas downstream. Evidence suggests that these head-cuts continued to occur up until the 1950/60's, and often corresponded to large flow events (Davis and Finlayson, 2000).

Channel changes in the downstream reaches were noted as early as the 1930's and 1940's; however, the 1950's and 1960's were the peak period in terms of sediment production in Creightons Creek. It was during this period that sediment began to noticeably fill the pools in the upper reaches above the Hume Highway. Since then, the slug has been progressively moving downstream filling the channel. The slug in the floodplain reaches appears to have stabilised, and is neither increasing or decreasing. The front of the slug can be found near Reach 4 (Pranjip Road), and is continuing to move down Branjee Creek; the low gradients mean that the sand is moving very slowly. This has been shown by cross-sections taken at the Longwood-Shepparton road bridge (near Reach 7) in 1989 suggesting that there has been little change since 1990 (Davis and Finlayson, 2000).

However, bridge cross-sections taken near Reach 13 (Figure 4.3) have shown that the stream bed level has dropped approximately 0.5-1.0 m since 1957 and there is a bed control structure immediately below the bridge that is preventing another 0.5 m head-cut from moving upstream. Other evidence from hanging tributaries (Plate 4.1) near Reach 10 (see Figure 4.3) also suggest that the bed is lowering in the reaches upstream of Reach 10. The final piece of evidence suggesting that the bed level is lowering is the reduction in sediment depth (discussed further in Chapters 5 and 9). Together, this evidence suggests that the bed-levels are at or near pre-disturbance bed levels.

Plate 4.1: This hanging tributary is one piece of evidence showing decreasing bed levels in the reaches upstream of Reach 10.

<u>Time scales associated with the sediment slug in Creightons Creek</u>

It is of interest to be able to quantify the time since the sediment slug left the recovering reaches. This allows the recovery process to be given a temporal as well as spatial dimension. The recovery time scales refer specifically to the time since the bed level had returned to pre-slugged levels. The most practical way of determining when the sediment slug left the channel would be to use aerial photos. Unfortunately, Creightons Creek is too narrow (the actual channel is very difficult to see), and other methods were required.

The best source of information regarding the evacuation of sediment from Creightons Creek is based on anecdotal evidence from the landholders as well as bridge cross-sections. Discussion with landholders during the surveying of the stream revealed that areas upstream of Reach 11 have been incising for at least 25 years (Pers. Comm. Dino Furlanetto, landholder, September 1999). This is consistent with the bridge surveys from further upstream (Davis and Finlayson, 2000). It is difficult to precisely date the evacuation of sediment, nor can it be certain exactly how far downstream the incision has occurred, as multiple erosion heads have been observed moving up the creek bed. For the purposes of this investigation, however, the recovery phase will be considered to have been occurring for at least 25 years.

Visual description of Creightons Creek

Creightons Creek was broken up into three zones, based on the location of the sediment slug, and corresponding with each of the three phases described in the Geomorphic Recovery Model (Section 3.7). The section downstream of the sediment slug was considered to be a control site (Phase 1). The main body of the slug is situated between Pranjip Rd (Reach 4) and the Longwood Mansfield Rd (Reach 10). Areas upstream of Reach 10 are considered to have evacuated their sediment, and are in the recovering phase. The reaches located in each section are shown in Figure 4.3, and are discussed further in Chapter 5.

To provide a visual representation of each section of Creightons Creek, a number of photos are included in this thesis. Plate 4.2 was taken at Reach 1 and is typical of the highly sinuous 'chain of ponds' morphology of the un-impacted reaches. Plate 4.3 was taken at Reach 6 and represents a 'slugged' site; note that the gross scale morphology is similar between Reaches 1 and 6. Plate 4.4 was taken from the top of the banks on Reach 14; evidence of the massive incision and erosion can be seen in the 10 m high banks.

4.3.7. Summary

The geomorphic structure of Creightons Creek can be described as a 'classic' erosional and depositional sequence (after Davis, 1899). The headwaters of the system are steep and erosive. The slope then drops dramatically over a short distance to a gentle depositional floodplain area. The position and characteristics of the sand slug greatly reflect this slope change; however, Creightons Creek does not represent a 'classic' sediment slug in terms of the recovery model, as the sediment was not sourced from a single injection point. Nonetheless, it provides a good test of the model for streams where the sediment source is from erosion of the main channel ie. endogenous source. This type of erosion is typical of many incised streams in Australia.

Plate 4.2: Reach 1 is a control reach showing the typical 'chain of ponds' type morphology

Plate 4.3: Reach 6 is an impacted reach and has a similar structure to Reach 1 but has been filled up to bankfull with sand

Plate 4.4: Reach 14 is located in the incised headwater reaches. The banks on the right hand side of the picture are approximately 10 m high.

4.4 Wannon River

4.4.1. Physiographic setting

The second site, the Wannon River (Figure 4.6), is highly sinuous and much larger than Creightons Creek, with a catchment area of approx 4490km^2. It is located in the drier parts of Western Victoria, and is the largest tributary of the Glenelg River. The Wannon River starts in the southern parts of the Grampians National Park, and the area studied occupies the lower 50 km of stream that is, in total, approximately 260 km long. The study area lies between Coleraine and Casterton (141^0 41' E and 37^0 59'S). The main source of sediment fuelling the sediment slug has come from Bryans Creek; two smaller tributaries Henty and Dwyer Creeks also contribute sediment (see Figure 4.6) (Erskine, 1994; Rutherfurd and Budahazy, 1996) . The relative elevation of the study site is shown in Figure 4.7, which also shows the position of Reach 1 and 12, and the location of Bryans Creek. The area studied is extremely flat with an easily distinguishable floodplain and the elevation remains the same for the entire length, at ~60 m above sea-level.

On the Wannon River, it was difficult to identify the front or 'nose' of the slug. This also made it hard to determine the sites that had been impacted by the sediment slug. The different sections of stream are differentiated based on sediment depths measured (discussed further in Chapter 5). There was some evidence of sediment passing through the lower reaches (eg. over-bank deposition, see Plate 4.10; Erskine, 1994); however, the sediment depths in the bed of the river were much lower in Reaches 10-12. For these reasons, the downstream impacted sites on the Wannon River were broken into two groups. Group 1 represents the main 'Impacted' site (Reaches 7-9), and Group 2 represents a secondary 'Impact' site (Reaches 10-12). Both sections have been impacted by the sediment slug to some degree, with Group 1 being more severely impacted than Group 2. The number of groups in each section is discussed further in Chapter 5.

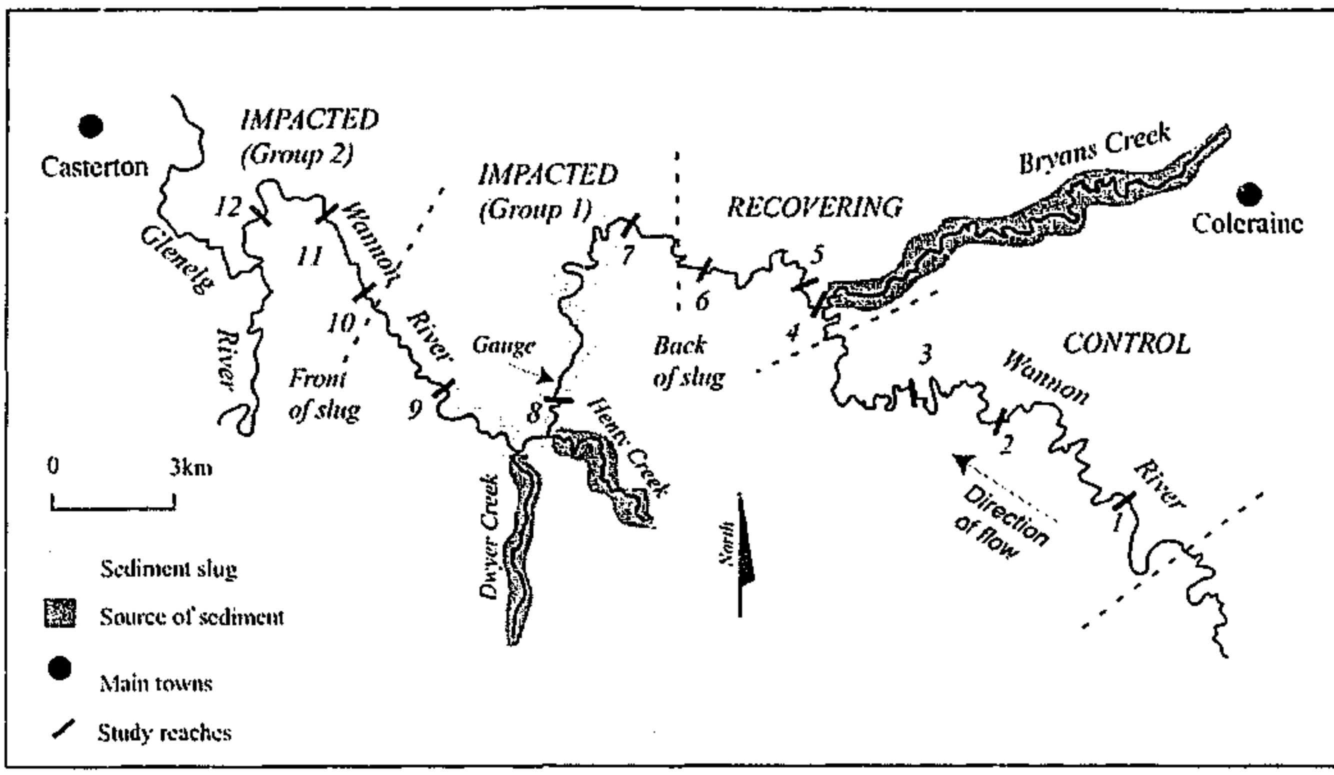


Figure 4.6: Wannon River site showing the study reaches and source of sediment

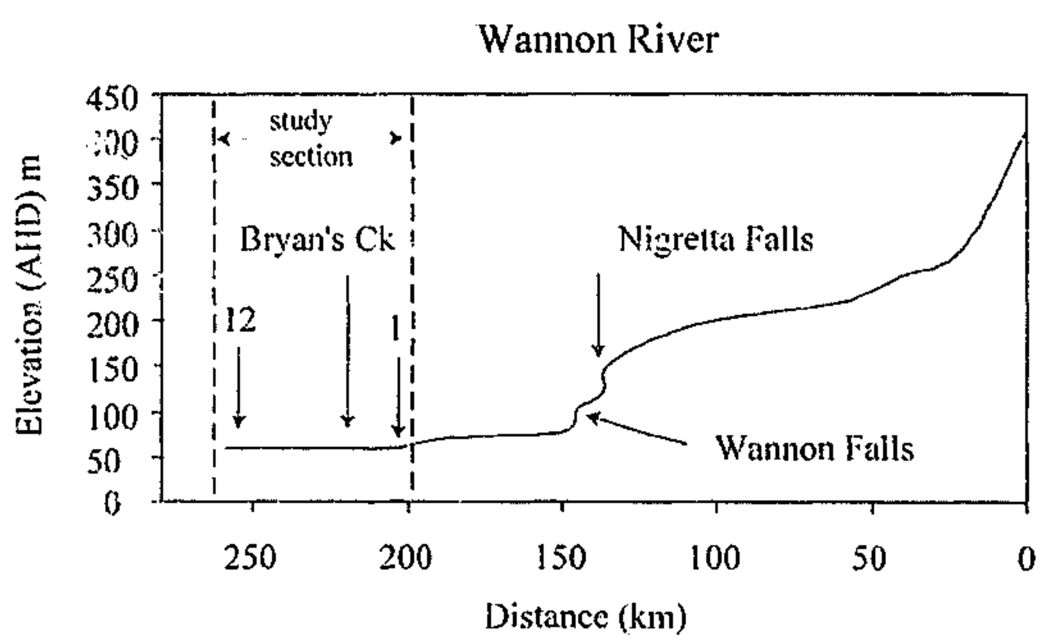


Figure 4.7: The change in elevation over the length of the Wannon River. The position of Reach 1 and 12 and the location of the tributary, Bryans Creek, is shown. (Source: 1:100, 000 Map sheets - Casterton 7122, Coleraine 7222, Hamilton 7322 and Grampians 7323)

4.4.2. Previous research findings

A number of researchers and organisations have looked into the sediment problem in the Glenelg Catchment. The Wannon River, being the largest tributary of the Glenelg, was often included in these studies. Early research by Marker (1976) looked at the incidence of soil erosion in the Dundas Tablelands surrounding the Wannon River Catchment. This research described how the streams were actively eroding in the mid 1970's, despite the re-establishment of stability to many of the eroding slopes. Thus, the erosion was considered to be a lag in the response of the stream to changes in the catchment. Subsequent research in the Wannon catchment has focused specifically on the impacts of the stream erosion, and the production of sediment that has evolved from the combination of catchment and stream erosion.

A report by I.D.&A. and others (1992) was the first report that looked specifically at stream management issues focusing on the sedimentation problems within the stream. Subsequent research by Erskine (1994a) described the 'response' of the Wannon River to increased sediment loads. In his paper, the response of the river was described in terms of a large-scale response model relating various stages that were defined as either Phase 1 'natural condition', Phase 2 'catchment degradation', Phase 3 'catchment stabilisation', or Phase 4 'new equilibrium'. Using this terminology, the reaches upstream of Bryans Creek were considered to be in Phase 1, and those downstream of Bryans Creek in Phase 2 (Erskine, 1994a).

Later research by Rutherfurd and Budahazy (1996) devised a sand management strategy for the Glenelg catchment including the Wannon River. In this study, the specific volumes of sediment were quantified and recommendations of further sediment extraction were made to ease the sediment delivery to the Wannon River. The most recent study undertaken on the Wannon River was by Sinclair Knight Merz (1997). The purpose of this study was to undertake an environmental assessment of the Wannon River to deal with issues such as sand movement, reduction of waterway capacity, and loss of stream habitat. The main findings of this report related to the management of large woody debris (LWD), and recommendations were made that no LWD be removed in the future.

Each of these studies have provided valuable background information on the history of the Wannon River. Previous knowledge of the site meant that the Wannon River was an appropriate stream to test the model of disturbance and recovery. In most aspects, the sediment slug on the Wannon River meets all the criteria of a 'classic, single injection' sediment slug, as most of the sediment is coming from Bryans Creek. In addition, the extraction of sediment from Bryans Creek means that the sediment input is declining. This will be discussed further in Section 4.4.6.

4.4.3. Geology and vegetation

The headwaters of the Wannon originate in the sandstone areas of the Grampians National Park and then flow through the Dunkeld basalts, before incising into Rhyolites and Rydacite near Nigretta Falls. Near the Wannon Falls the river flows through basalt again before reaching the Cretaceous sediments of the lower valley (I.D.&A. *et al.*, 1992). The study reaches for this research were located in the alluvial deposits of the Cretaceous sediments of the lower valley section, downstream of Wannon Falls. This section is distinguished from the upper reaches above the falls by its wide valley and floodplain morphology and relatively high sinuosity (up to 3.5) upstream of Bryans Creek junction.

The land in the Wannon River catchment was extensively cleared between 1836-1950, with exception of the headwater reaches within the Grampians National Park. The forests were replaced with grasslands to cater for the sheep and dairy industries of the time (Erskine, 1994a). The riparian vegetation remaining today is dominated by River Red Gums (*Eucalyptus Camaldulensis*). There is little understorey along the study sites, although several species of wattle (*acacia spp.*) can be found, particularly in areas that have been fenced out from stock.

4.4.4. Climate and hydrology

The lower Wannon River, between Coleraine and Casterton, has a temperate climate, with average daily temperatures between 8.3°C and 19.9°C. The rainfall mostly falls in winter and averages about 650 mm each year. There are four gauges on the Wannon River; the nearest to the study site is located at Henty (see Figure 4.6). This gauge is still operational, and has been recording flow data from 1974. A flood frequency curve was developed using the method described in Appendix A and gauge data (sourced from Thiess Environmental Services). The flood frequency curve is shown in Figure 4.8. The 1 in 2 year discharge (AEP = 50%) calculated from the flood frequency at the gauge is 87.9 m^3/s or 7590 ML/day. Other, more detailed, hydrological characteristics such as flow duration curves, annual volumetric coefficients and threshold flow analysis for the lower Wannon River were presented in Sinclair Knight Merz (1997) and are not be repeated here.

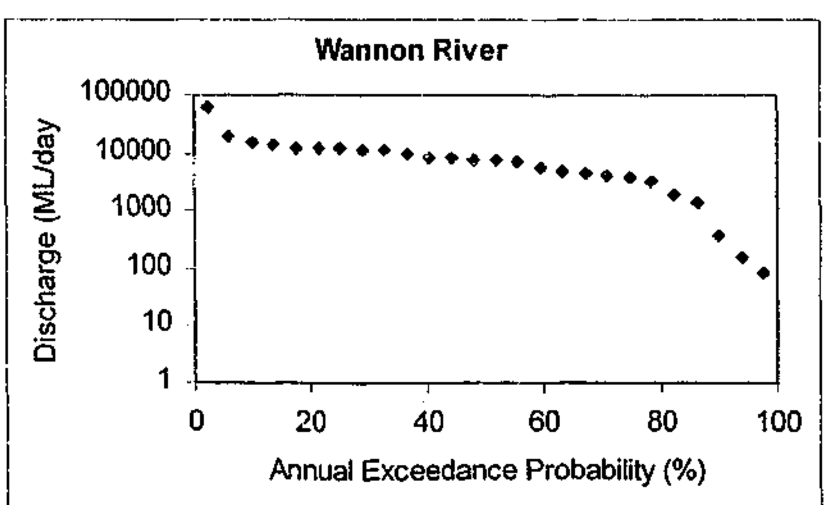


Figure 4.8: Flood Frequency curve for the Wannon River at Henty

It is appropriate to note that the summer over which the Geomorphic Variability data was collected on the lower Wannon River (Dec 99/Jan 2000) was in the driest year on record. This made measuring flow indices for determining site specific discharges difficult, however, it allowed a good view of the channel below the normally higher water levels.

4.4.5. Instream Ecology

There have been very few studies undertaken to look at the instream ecology of the Wannon River. The report carried out by Sinclair Knight Merz (1997) described the Wannon as having moderately diverse instream fauna. Surprisingly, the number of families (of macroinvertebrates) found in the upper less-disturbed sites were lower than in the downstream sandy reaches. In the downstream sections impacted by the sediment slug, there was a relatively high number of invertebrate families. This distribution of instream fauna, could possibly be related to the fact that many of the clay bed sections become anoxic in the drier parts of the year when flow is low. The sections downstream would be more frequently disturbed in the more mobile sandy sediments; however, the fauna may have adapted to the disturbance regime and thrive on the less anoxic conditions, particularly where LWD is abundant.

4.4.6. History of landuse and evolution of the sediment slug

The Glenelg River catchment (including the Wannon River) has one of the longest records of culturally accelerated soil erosion in Australia (Erskine, 1994a). The land was settled around the 1838, originally by squatters for wool production, and erosion has been occurring since this period. Perhaps the first documented reference to the severity of erosion, occurring in a letter sent from an early farmer John Robertson to Governor La Trobe in 1853, expressing his dismay with the degrading environment in the area (Erskine, 1994). Amongst other problems, he referred to

> *"The clay is left perfectly bare in summer. The strong clay cracks; the winter rain washes out the clay; now mostly every little gully has a deep rut; when rain falls it runs off the hard ground; rushes down these ruts, runs into the larger creeks, and is carrying earth, trees, and all before it..."* (Bride, 1898 in Erskine, 1994a).

High soil erosion rates were thought to have continued up until the 1950's (Marker, 1976), when large soil conservation works were implemented. Since then, soil erosion rates, sediment yields, and run-off have decreased. The effects of almost 60 years of severe soil erosion is, however, still evident in many of the streams that received the eroded material.

De-snagging of large trees from many streams in the Glenelg catchment was also a common stream management activity up until the 1980's. The large quantities of LWD in the channel were considered to increase the incidence of flooding, and therefore removed. In 1977 a grant was given to Dundas Shire to remove 30% of the obstructions from 9 km of the lower Wannon (I.D.&A. *et al.*, 1992). Fortunately, today the LWD is considered as an important habitat and is not removed (Sinclair Knight Merz, 1997).

<u>*Bryans Creek*</u>

Bryans Creek is the main source of sediment and largest tributary in the study reach. It was once a 'chain of ponds' that began to incise last century, and then filled with sand from gully and catchment erosion (Rutherfurd and Budahazy, 1996). Many of the reports undertaken on the sediment problem in this area, recommended sediment extraction as a method for restoring the channel. Since the 1960s, more than 415,000 m^2 (official estimate) or 90% of the sand extracted from the Glenelg catchment has taken place in Bryans Creek (Rutherfurd and Budahazy, 1996). Hence, the natural progression of the sediment down Bryans Creek has been accelerated by the extraction of sand along several sections. As a result, the channel is incising with many sections having no more sand in the upper reaches. Clay is now discontinuously exposed in the bed of Bryans Creek with surveying showing degradation progressing downstream (Erskine, 1994a).

<u>*Evolution of the sediment slug*</u>

The Wannon River has been effectively dammed by Bryans creek. Upstream of the junction of the two rivers, the Wannon River is ponded for a couple of kilometres. The sedimentation is confined to the downstream section of the junction with Bryans Creek. The amount of sediment that has been estimated to be in the Wannon River is 280,000 m^3 (Rutherfurd and Budahazy, 1996). Estimates of sand volumes were made by dividing the streams into reaches, and extrapolating channel dimensions and sand volumes surveyed at cross-sections in those reaches (Rutherfurd and Budahazy, 1996).

The extraction of sediment from Bryans Creek (eg. Plate 4.5) has had the effect of reducing sediment loads to the Wannon River. Erskine (1994a) suggested that there has been no major sedimentation in the Wannon (from Bryans Creek) since 1957. This evidence came from the fact that there were no major changes in bed level or bank position (using long term bridge cross-sections).

Plate 4.5: Sand extraction from Bryans Creek

Time scales associated with the sediment slug in the Wannon River

To determine the period of time over which the Wannon River has been undergoing recovery, historic data, including aerial photo's, were assessed. Aerial photos from 1947 were the earliest available for the area between Coleraine and Casterton; they clearly show sediment coming out of Bryans Creek into the Wannon River. However, bridge cross-sectional data (described in Erskine, 1994a) suggest that there has not been continued sedimentation into the Wannon River since 1957. Examination of subsequent aerial photos (in 1967, 1975 and 1985) support the view that the Wannon River downstream of Bryans Creek junction has degraded to its former bed level, and that it has been stable for approximately 25 years. This area would still receive sediment from Bryans Creek in very large flow events, however, due to sand mining activities, very little sediment is stored in this area directly downstream of the junction.

Visual description of the Wannon River

The lower Wannon River has been divided into four distinct sections (two impact sections) to correspond with the three phases of the Geomorphic Recovery Model described in Section 3.6.2. To provide a visual image of each section, a series of photos taken from a range of sites along the length of the study section are presented.

Plate 4.6 was taken during data collection on Reach 2. This pool was over 2 m deep and representative of the pool depths in each of the control reaches. Plate 4.7 was taken immediately downstream of the junction of the Wannon River and Bryans Creek. Remaining sand deposits in this section (Reach 4) are only small (~ 2 cm thick); in most parts, the bed is beginning to incise leaving a flat clay substrate. Plate 4.8 was taken at Reach 9 and shows a typical impacted reach. Plate 4.10 was taken downstream of Reach 8 showing sediment delivery from Henty Creek into the Wannon River. Finally Plate 4.10, taken at Reach 11, shows the relative height of the banks and evidence of over-bank deposition.

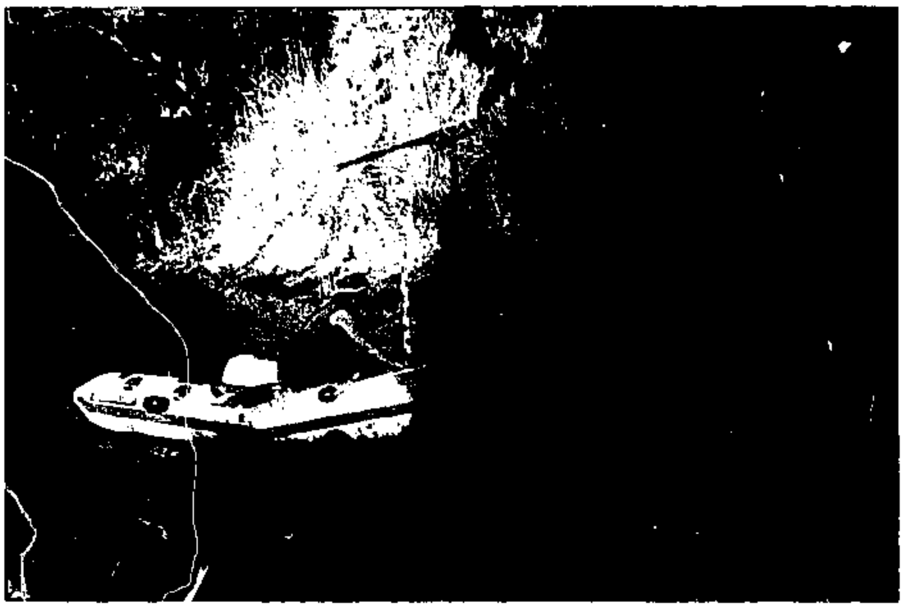


Plate 4.6: The deep pools in Reach 2 (control reach) required measurements to be made from a boat.

Plate 4.7: Reach 4 is a recovering reach downstream of junction with Bryans Creek. The alternate bars are the only remaining areas of sand, and these are only a few centimetres thick. Most of the bed is clay in this area.

Plate 4.8: Reach 9 is an impacted reach with large flat sheets of sand. Water depths are only ~5-10 cm.

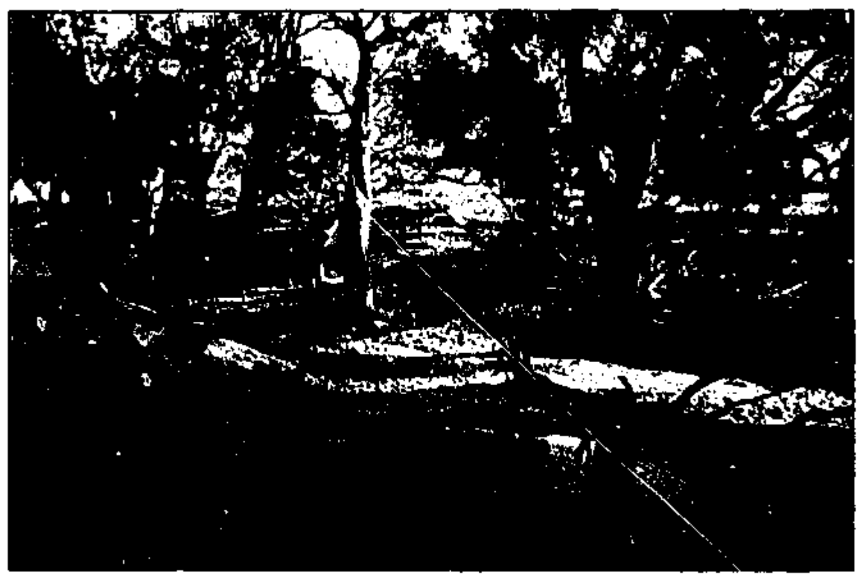


Plate 4.9: Downstream of Reach 8, Henty Creek is delivering sediment to the Wannon River

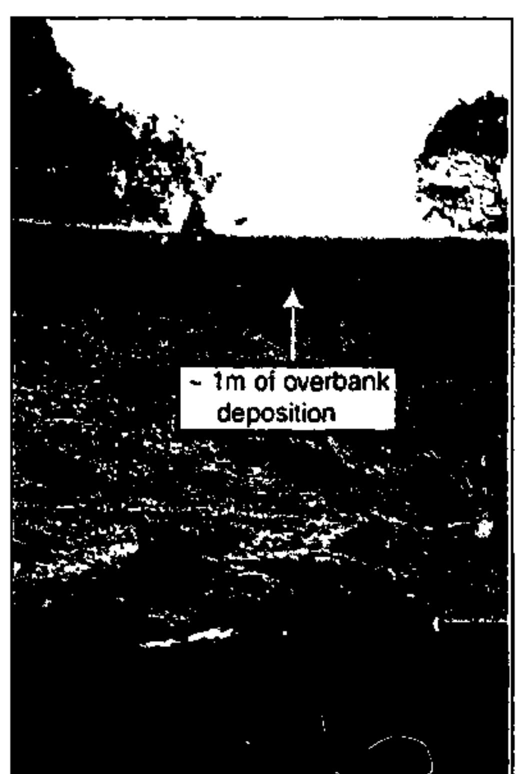


Plate 4.10: Evidence of over-bank deposition and the relative height of banks on the Wannon River (Reach 11).

4.4.7. Summary

The Wannon River met most of the criteria outlined in Section 4.2.1, and provided a different type of case study to Creightons Creek. The main difference is that the Wannon River is a much larger stream (in terms of width, depth and catchment area), and the injection of sediment into the Wannon was primarily from a single source. The main difficulties with using the Wannon River is that there has been considerable (illegal) sediment extraction at various sections along the river. This activity has the potential to distort the results if it is assumed that natural sediment transport has occurred, when in fact sediment has been artificially removed. For this study, given the unknown volumes, illegal extraction was ignored.

Another difference between Creightons Creek and the Wannon River is that the front of the slug on the Wannon River is not easily defined. Some reports have suggested that the Wannon River is a dominant source of sediment to the Glenelg River (Erskine, 1994a; I.D.&A. *et al.*, 1992); other reports have shown that the main slug has not yet reached the junction with the Glenelg (Rutherfurd and Budahazy, 1996). This difference maybe a result of the different sampling periods and methodologies. There is some evidence that there has been extraction of sediment on the lower Wannon, although the location and dates are not specified (I.D.&A. *et al.*, 1992). The investigation undertaken in this study suggests that sediment may reach the Glenelg River when in suspension; however, the main bulk of the slug (bedload) is still slowly moving its way through the lower reaches near Reach 11 (see Plate 4.10). This was determined by probing the bed sediments along the length of the study reach, and is discussed further in Chapters 5 and 9.

4.5 Ringarooma River

4.5.1. Physiographic setting

The third site, the Ringarooma River, is a naturally gravel bed river in north east Tasmania. This river presents a case where the sediment slug has been the result of extensive tin mining. The town of Derby (147^0 47' E and 41^0 09' S) being the site of the largest mine in the catchment (see Figure 4.9 and Figure 4.12). The Ringarooma has a catchment area of 912 km^2, and the river flows from south to north, into Bass Straight (Figure 4.9).

The river rises in the southern slopes of Mount Maurice at a height of over 1000 m, falling to 250 m at the junction with the Maurice River (Knighton, 1987c). The change in relief is shown in Figure 4.10 and the relative locations of the Maurice River and Reaches 1, 6 and 10 are shown for comparison with Figure 4.9. The Ringarooma River is approximately 110 km long with at least 70 km of the river having been aisturbed by mining at some stage.

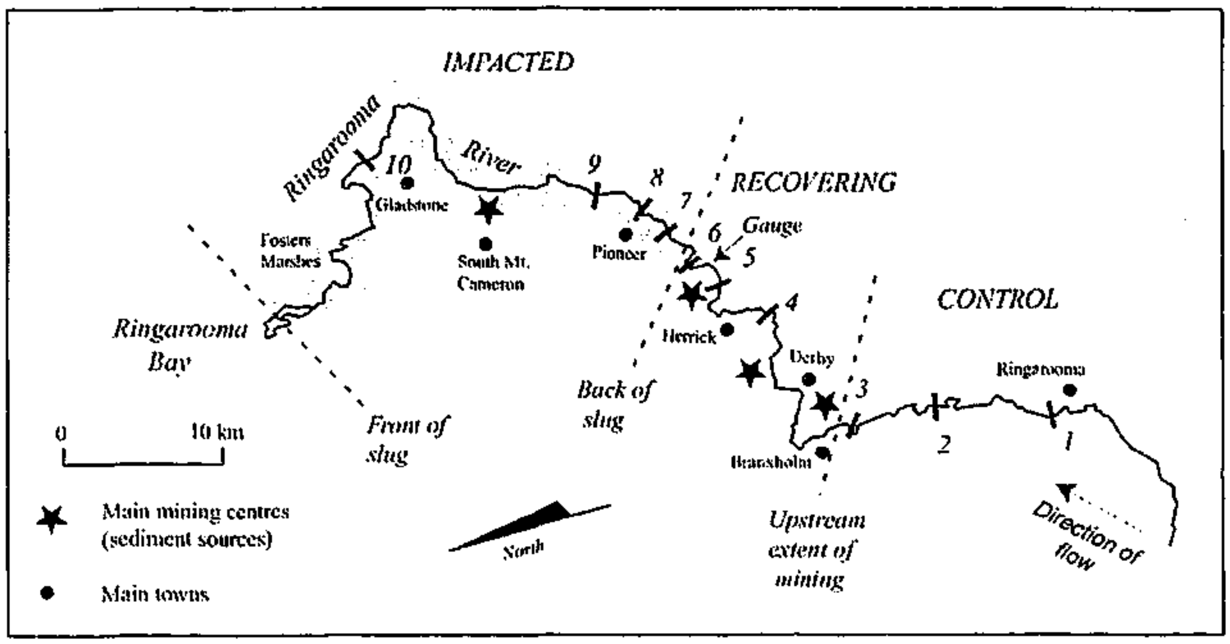


Figure 4.9: Site map of the Ringarooma River showing the location of the study reaches, the Moorina gauging station and the location of the sediment slug.

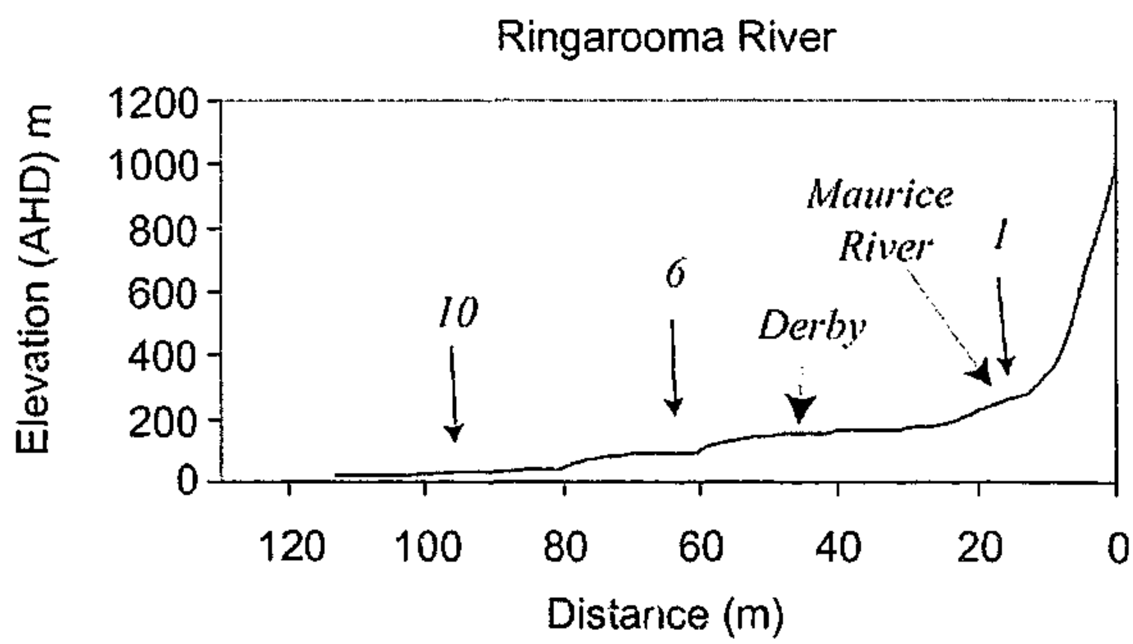


Figure 4.10: Longitudinal profile of the Ringarooma River (Source: 1:100,000 map sheets - Forester, Swan Island and Cape Portland)

The river above the town of Ringarooma is generally steep, with sharply dissected relief, and well vegetated. Between Ringarooma and South Mount Cameron, the river varies between steep dissected relief, narrow valley gorge, with steep sides and sections of wide floodplain. Most of this area is still well vegetated with some areas being cleared for dairying and forestry. Downstream of South Mount Cameron, much of the river has a low relief with multiple channels and wetlands.

The current location of the sediment slug reflects the source of the sediment, but also the general geomorphic characteristics of the stream. Between Derby and Herrick, the sediment has generally been flushed through the steep gorge sections and has spread out on the broad floodplain reaches. The main floodplain areas are found downstream of Moorina Bridge at Herrick (Reach 6), up and downstream of Pioneer, sections near South Mt Cameron, and the open flats near Ogilvies and Bells Bridge (near Reach 10).

4.5.2. Suitability of site and previous research conducted

The bulk of the previous research conducted on the Ringarooma River was carried out by Dr David Knighton, who undertook an extensive study of the history of mining and the production, distribution and large scale movement of the sediment slug in the Ringarooma River. His research has provided an integral basis from which to test the concepts of disturbance and recovery at a smaller scale.

Knighton published six papers that described the sediment history and hydrology of the Ringarooma River (Knighton, 1987a; 1987b; 1987c; 1989; 1991; 1999) The main outcomes of Knighton's work were:

- regional flood frequency and hydraulic geometry relationships for stream's in north east Tasmania, including the Ringarooma River (Knighton, 1987a; 1987b)
- a history of the sediment supply source's and volume's delivered to the Ringarooma River from tin mining. This was based on records from 53 mines throughout the catchment (Knighton, 1987c);
- the development of a mass-conversion model to reconstruct the main pattern of sediment movement through the disturbed reaches. Using this model, peak storage estimates can be determined for the lower reaches (Knighton, 1989);
- the process of aggradation and incision, documented for the length of the stream (Knighton, 1991); and finally
- a description of the gravel-sand transition associated with the incision process (Knighton, 1999).

In addition to Knighton's extensive research, there is a large amount of historical information documenting the history of the Ringarooma catchment and in particular, the tin mining. The relevant contents of the historical documents are given in subsequent sections of this thesis. The area around Derby and the workings of the largest of the tin mines, the Breseis Mine, will be given the most attention.

The most recent report to have been undertaken on the Ringarooma River is the 'State of the Rivers Report for the Ringarooma Catchment' (Bobbi et al., 1999) published by the Department of Primary Industries, Water and Environment (DPIWE), Tasmania. This report covers a range of issues, including water quality, hydrology and aquatic ecology and then provides an overall index of river condition. The overall rating of river condition proposed for the Ringarooma River varies between being 'slightly modified' and in 'natural condition'. This is an interesting finding, considering that 40 million m^3 of mining waste has been supplied to this stream! I would suggest that some of the results may have been different if Knighton's work had been consulted more thoroughly.

4.5.3. Geology of the Ringarooma Catchment

Due to the tin mining that occurred in the Ringarooma Catchment, the geology has been extensively documented (eg. Blake, 1928; Braithwaite, 1964; Groves *et al.*, 1977; Keid, 1952; Montgomery, 1891); however, only a brief summary of the geology relating specifically to the geomorphology of the river will be given here.

Considerable bedrock is visible along most of the river between the headwaters and South Mount Cameron. Most of this is either granite, or ancient sedimentary slates and sandstones of probably Lower Silurian age (Montgomery, 1891). The granites, compromised of various forms, intruded the Mathina beds of the Blue Tier Batholith (Groves et al., 1977). Tertiary basalts can also be found at several points along the stream, particularly in and around the Derby area.

The formation of the tin deposits within the Ringarooma catchment are closely linked with paleogeological record of the Ringarooma River. Montgomery (1891) suggested that there was a previous river channel running at least 70 feet (21 m) below the present river. This ancient channel slowly filled up with fine quartz gravel which contained the tin ore, until the surface of the gravels was roughly 100ft (30.5 m) above the present river level. The gravels then became covered in volcanic ash and basalt from lava flows. The existing river then cut its way down through these deposits to its present position. As Ringarooma excavated its present valley, it left behind various terraces of gravel that represented the old river flats (Montgomery, 1891). Many of these ancient river terraces probably no longer exist along many sections of the river as they have been re-worked during the various methods of tin mining.

4.5.4. Climate, hydrology and vegetation

The Ringarooma River has a cool temperate climate with a mean annual rainfall of approximately 980 mm. The rainfall falls mainly is winter and is highly variable. The mean daily minimum temperatures is 6.8^0C and maximum temperature 16.5^0C.

The hydrology of the Ringarooma River has been considerably altered over the last century mainly through the development of water races for the hydraulic sluicing for the tin mining. The most notable of these is the 56 km long Ringarooma race which delivered water from the Maurice River to the Briseis Tin Mine at Derby (Bobbi et al., 1999).

The other major hydrological disturbance in the catchment include the presence of at least seven dams, built primarily for mining operations. The Ringarooma River itself is un-regulated, with the two largest dams, the Cascade and Frome Dam, being located on large tributaries. Both dams still exist, and are used for agricultural irrigation around Derby.

Flow records for the Ringarooma catchment date back as far as 1921 (Bobbi et al., 1999); however, the most complete data set is based on the present gauge located on the Ringarooma River at Moorina (Figure 4.9). The Moorina gauge has been recording flows since 1977 to the present. The annual median flow is 5.9 m^3/s and the 1 in 2 year event (AEP = 50%) at the gauge is approximately 8250 ML/day or 95.5 m^3/s. The largest gauged flow recorded on the river was approximately 4.83 m with a flow of 182 m^3/s. However on the 25th of July 1988 the river level rose to 7.2 m which was estimated from flood frequency analysis to be approximately 485 m^3/s. Such a flow would have a recurrence interval of a 1 in 10,000 year event (Bobbi et al., 1999). Historical records also refer to at least two large floods, one in 1929, which resulted in the Cascade Dam bursting, killing 14 people, and the other in 1936, an even bigger event which caused the river to overflow into the mine workings (McKeown, 1938).

A flood frequency curve (Figure 4.11) for the Ringarooma River was developed using the method in Appendix A. As there were 13 more years of flow data since Knighton calculated the flood frequency curve (Knighton, 1987a; 1987b), the Q_2 (1 in 2 year event) was re-calculated. Due to the relative short flow record (for the gauge) the flow estimated for the 25th of July 1988 was considered as an extreme event (outlier) and left out of the analysis.

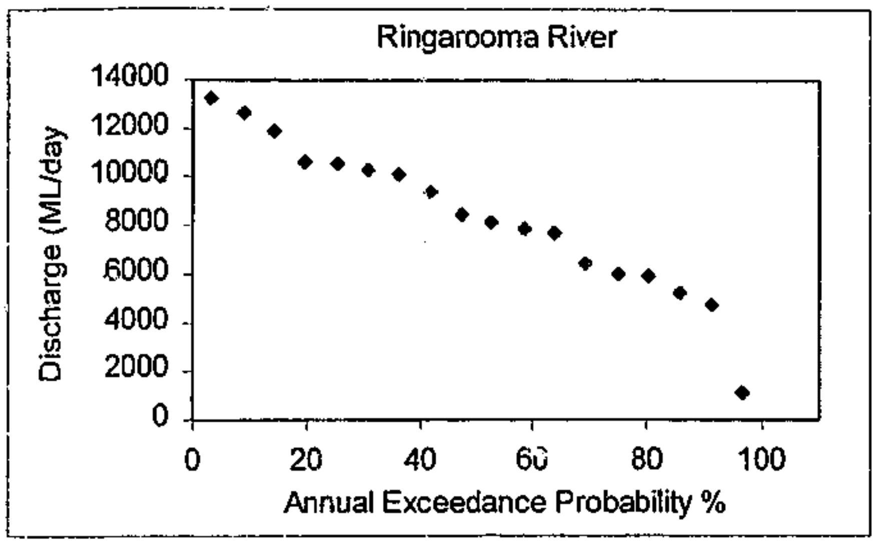


Figure 4.11: Flood frequency curve for the Ringarooma River at the Moorina Gauge

Vegetation

The quality and quantity of stream side vegetation is quite high along most of the Ringarooma River. Apart from some cleared riparian zone in the dairy country around the town of Ringarooma, much of the riparian zone is intact. Even areas that would have once been extensively cleared for mining have revegetated and many areas of the stream are difficult to access, even on foot. The vegetation is dominated by native species of *Eucalypts* and *Acacia's* with stands of sassafras, pine and myrtle. In some places the vegetation is typical of temperate rainforest particularly in the upper reaches. In many parts, weeds such as blackberry are common. In comparison to the previous study sites, the Ringarooma River catchment is extremely well vegetated.

4.5.5. Instream Ecology

A comprehensive study of the aquatic ecology of the Ringarooma River has been carried out by DPIWE and presented in Bobbi (1999). This report describes the general state of the aquatic fauna, the endangered species, the macroinvertebrate community along the main channel and tributaries, and the various condition and types of algae found along the river. There are a number of species that occur within the Ringarooma catchment, that are considered as vulnerable or rare. These include at least one frog species, two fish species and two aquatic species of snail.

To determine the health of the macroinvertebrate community along the stream, the biological monitoring package AUSRIVAS (Australian River Assessment System) was used. A total of 12 sites were sampled between 1994 and 1997 in the Ringarooma Catchment, however, only three of these sites were located on the main trunk of the Ringarooma and these were all upstream of Moorina. It is not clear why samples were not collected downstream, although the absence of riffle structures would present methodological problems for this assessment technique. The overall health rating determined the Ringarooma River and its tributaries to be in 'good health'. Again, it is not certain that this would be the result if the whole stream, including the impacted sections below Herrick, had been included in the analysis.

4.5.6. History of landuse

The area around the Ringarooma River was settled around 1859; tin was first discovered around 1873 (Loone, 1928). Tin mining occurred along the alluvial tin deposits of the Ringarooma River for 110 years, reaching a peak around 1905-9; operations had ceased by 1981 (Knighton, 1987c). There were at least 53 individual mines in the Ringarooma valley which covered 75 km, producing approximately 40 million m^3 of material with an average sediment size of 5 mm. The quantity of sediment is considerably greater than the natural bedload (although no pre-mining data is available). The large number and extent of the mines meant that distribution of sediment input to the river was spatially and temporally diffuse. There were 22 main supply points, of which 10 were from mines less than 0.5 km from the Ringarooma (Knighton, 1989). The large number of sediment supply points meant that the history of the Ringarooma was quite different to other mining areas (eg Gilbert, 1917; James, 1989) in which the input occurred from a more concentrated, single source.

During the mining period, more than 40 000 tonnes of tin were produced in the Ringarooma basin, with four mines producing over 75% of the total: the Arba mine at Branxholm, Briseis mine at Derby, Pioneer mine at Pioneer and Endurance mine at South Mt Cameron (Figure 4.12) (Knighton, 1987c). The Briseis mine dominated sediment supply, particularly in the early days of mining and peak sediment production tended to become greater moving downstream through time (Knighton, 1989).

The main methods used to extract the tin were hydraulic sluicing and dredging, directly on the river bed. Sluicing involved blasting the tertiary tin deposits with high pressure water (Plate 4.11). The tin was then separated from the parent material by a series of sluice boxes (Anon, 1948). During the sluicing operations, particularly around the Breseis Mine, the overburden material was stacked on land, and anything smaller than 2 inches (5 cm) dumped into the river (Parker, 1937; Steane, 1972). Steane (1972) estimated that 335,500 m^3 was fed to the river from the Breseis Mine each year. The maximum height of the overburden pile at Breseis was estimated to be 1021 feet (311 m) (Dunkin, 1946), and can still be seen at Derby today.

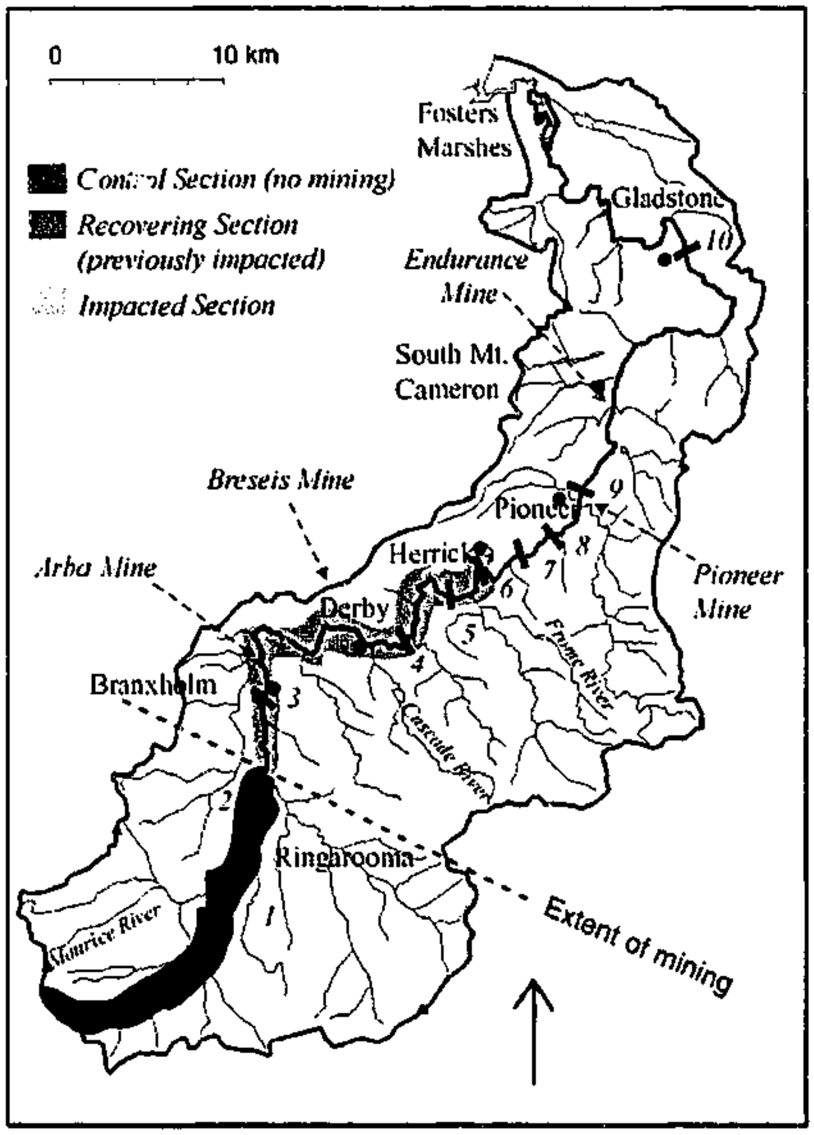


Figure 4.12: Distribution of sediment and position of mines within the catchment

Plate 4.11: An example of the sluicing operations on the Ringarooma River (Source: St Helen's historic library)

To access the alluvial lead lying beneath the current river, the river at Derby was diverted three times between 1914 and 1924 (McKeown, 1938). In many cases the diversion made the river wider at some sections, thereby reducing the velocity and the capacity of the stream to carry away the overburden (Smith, 1899) (Plate 4.12).

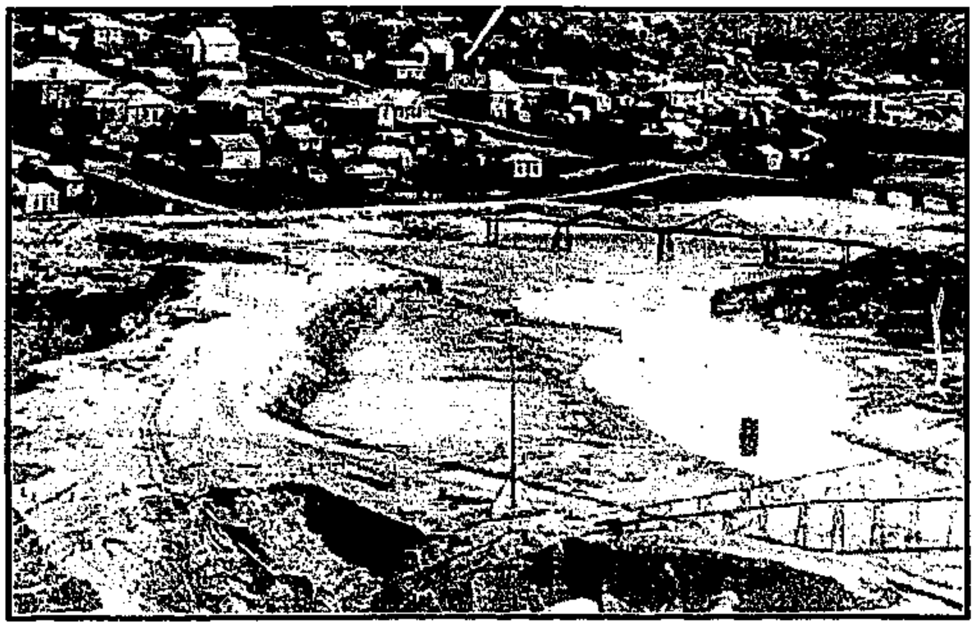


Plate 4.12: The Ringarooma River at Derby pre 1930. Note the deep mine workings in the foreground and left side of the picture (Beswick et al., 1987). It was not possible to take a photo from the same point in the year 2000 as the river has since cut a new coarse and there was extensive revegetation in the area.

Dredging, which involved direct mining of the river bed, was also used to recover tin; this method was used more in the downstream reaches in the period following World War II (WW2) (Knighton, 1989). The dredge, described as a ship or floating tin mine, weighed around 1,000 tons (Beswick et al., 1987). The Dorset Tin Dredge was the larger of two dredges that operated along the Ringarooma River (Plate 4.13). The dredge occupied the area between Pioneer and South Mount Cameron between 1944 and 1969 (Beswick et al., 1987). This machine essentially chewed along the bed and banks of the river, recovering alluvial tin and gold deposits in the sediments. It often dug down to depths of up to 50 feet (15 m) below the water-line to recover material, and involved altering the course of the river in some sections. The river at South Mount Cameron has multiple braided morphology, probably as much a result of the workings of the dredge as it is the increased sediment supply.

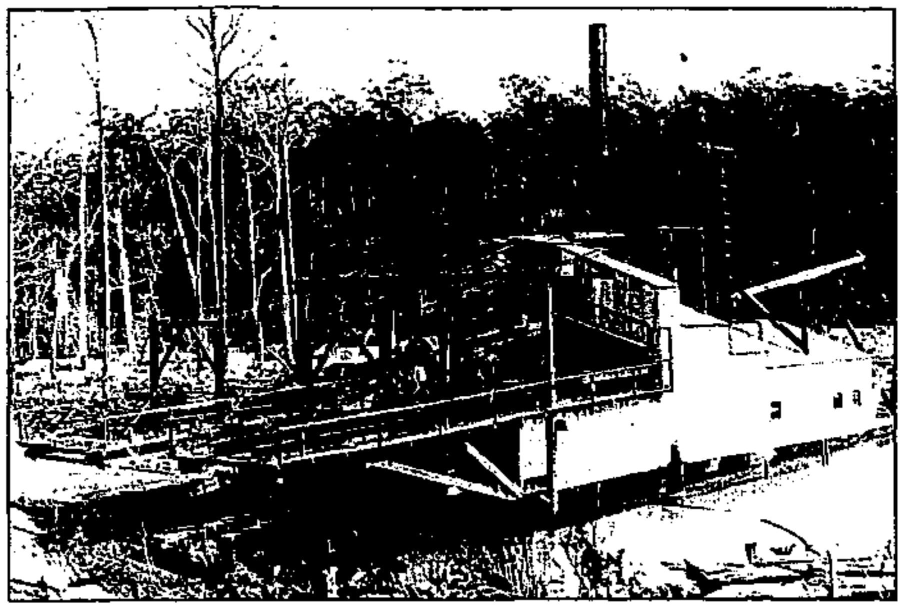


Plate 4.13: The dredge that worked the bed of the Ringarooma around South Mount Cameron (Beswick et al., 1987).

Pre-disturbance condition

There is very little detail in any of the historical documents describing the pre-mining condition of the Ringarooma River, although the report written by Steane (1972) presents some anecdotal evidence:

> "the accountant for the Dorset Tin Mining Dredge, aged about 50, remembers 40 years ago that there were three water-falls, each six to eight feet high, in a stretch of river between South Mount Cameron and Gladstone. This stretch of the river is now as flat as any - an average rise of bed level of 6 inches per year for 40 years"

This suggests that the lower reaches were once bedrock controlled until the channel began filling early in the 1900's. The only other evidence describing the pre-mining condition related to the destruction and re-construction of various bridges along the river. Although this provides useful evidence of bed level changes, it does not provide any descriptions of the morphological characteristics of the river. More recent work by Knighton (1999) suggests that the sediment as the river mouth should be around 22-25 mm, which is much coarser than the sandy based material that is at the mouth of the Ringarooma River today.

4.5.7. Evolution of the sediment slug

The most upstream extent of the mining on the Ringarooma River was around Branxholm (although there is some evidence of small scale workings around Ringarooma), with the Breseis Mine supplying the greatest amount of sediment to the river. The area between Branxholm and Herrick have been considerably impacted by the mining tailings, and the bed level has fluctuated considerably between these areas. The area between Branxholm and Pioneer has narrowed on average by 25% (Knighton, 1991), and the bed of the river is back to bedrock and large gravels line the bed in the reaches upstream of Herrick.

The Herrick reach could be considered as the 'back end' of the slug. The bed is close to its former level, and has re-exposed old tree stumps and its former gravel bed. This reach has degraded over 7 m, with at least 2.5 m being in the last 14 years, with a maximum rate of 0.5 m yr^{-1} (Knighton, 1991). Further downstream, between Pioneer and South Mount Cameron, the bed is still considerably above its original level. Knighton (1991) suggests that this area reached its maximum bed height in 1970, approximately 40 years after the Herrick reach did. Evidence has shown that during the 1970's when the bed fell at Herrick, the bed rose at Pioneer, suggesting that the upstream reaches are a direct source of sediment (Knighton, 1991). Knighton (1991) also determined that the amount of annual degradation is reasonably well correlated with annual flow conditions, suggesting that high discharges can remove the surface armour and continue to degrade actively.

The lower reaches near Gladstone are different from upstream reaches as the bed is still aggrading (Knighton, 1991). This area is much wider, and has a braided appearance. The survey data show that the bed has fluctuated only 0.3 m from 1973-85, suggesting that a series of waves are passing through the reach (Knighton, 1991). The bed is not expected to lower for some time, as there is still considerable sediment supply coming in from upstream reaches.

Many parts of the Ringarooma have a braided morphology, particularly in the downstream reaches with high sediment volumes. In these unconfined areas, the river has increased in width by up to 300% (Knighton, 1989). There are also many central and lateral bars in reaches downstream. In some cases, particularly near South Mt Cameron, the stream forms two dominant channels, divided by mid-channel bars that have become well vegetated. This was possibly a direct result of the dredging activities discussed in the previous section. As a result of the rapid incision, many terraces have also formed along parts of the Ringarooma between Branxholm and Pioneer.

Inspections of the 1970 and 1971 aerial photos by Steane (1972) show that the sediment from the Ringarooma River has been carried at least one mile (1.6 km) out to sea. The mouth of the Ringarooma was once one of the most active ports in north east Tasmania, and was the main access ports for ships transporting tin from Australia for use in WW2. The deposition of sediment, still continuing, is being aggravated by the mobile and unstable dune systems at the mouth of the river. The combination of sediment sources means that the mouth of the river will continue to build up and flooding of the lower marshes will increase.

Bed level change and time scales associated with the sediment slug

Knighton (1987c) used data from published and un-published mine records to estimate the supply of sediment to the Ringarooma over the mining period. He then developed a model for sediment transport for fifteen, 5 km river reaches over 4 year periods, and modelled the downstream movement of the sediment load. The details of the development and results of the model are explained in Knighton (1989) and summarised in Figure 4.13.

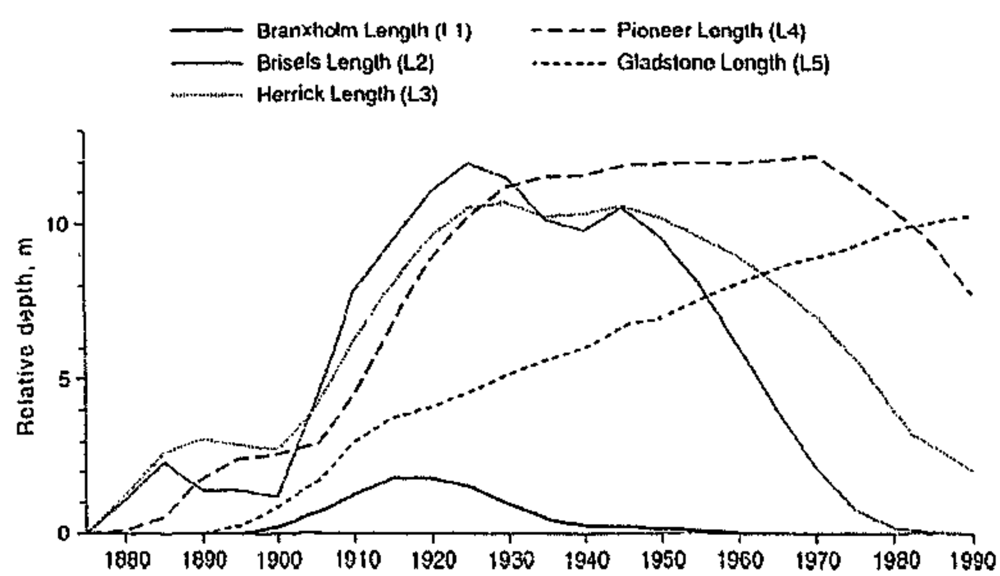


Figure 4.13: Relative sediment depths at the main mining areas as predicted by Knighton (1991).

Knighton (1989) estimated the relative bed heights by dividing the predicted sediment load in each reach by stream width, obtained from aerial photos over a period of 30 years (years 1949-1982). The sediment depths near the Briseis mine was near 12 m between 1920-30 (Figure 4.13); the bed is now back to its original level.

The process of changing from aggradation to degradation will also bring about a change in the bed material. In the case of the Ringarooma, one would expect to see the sand sized fraction replaced with the native gravels. This gravel-sand transition was discussed by Knighton (1999), and is evident in many sections upstream of Herrick where thick armour layers can be found. The formation of the armour layer will considerably slow the incision process. There will, however, be a residual sediment load of mining tailings for some time as sediment will continue to be mobilised during high flood events from the many bench and bar features, as well as incising and draining tributaries.

The area upstream of Herrick (and downstream of Branxholm) could now be described as the 'recovering' area as nearly all of the mining sediment has evacuated the bed of the stream. There are still considerable amounts of sediment stored in lateral bench systems; however, the re-armouring of the bed and re-exposure of LWD in many sections suggest that the bed level has returned to pre-disturbance levels. The time scale over which this process has occurred varies for the specific reaches. Using Figure 4.13, Knighton estimated that the pre-mining bed level had returned at Branxholm by 1960, at Derby (Breseis) by 1985 and at Herrick by 2000. As the three 'recovering reaches' are located between Derby and Herrick, the time scale applied to the recovery period would between 0 and 40 years, averaging around 18 years.

Visual description of the Ringarooma River

As with the two previous study sites, the reaches used for data collection were chosen based on the different depths of sediment in the bed. Reaches that were determined to have had very little disturbance were described as 'control' sites, those that were severely impacted as 'impacted sites' and those where the sediment had moved out of the system as 'recovering' reaches. To provide an idea of the current state of the Ringarooma River, a number of photos were taken of the various reach types.

Plate 4.15 was taken at Reach 3, just upstream of Branxholm. This was the upstream most extent of the mining activities. The gravel bar is well armoured and there are well structured pool-riffle sequences along the bed. This is considered to be one of least disturbed or control reaches. Plate 4.16 (Reach 5) is a 'recovering' reach which is located approximately eight river kilometres downstream from Derby. It is situated in a gorge section, with steep side walls and bedrock on the bed of the river. All of the river tailings produced by the Arba and Breseis Mines would have passed through this section. The well vegetated benches of sandy material that line the river in some sections are now the only remaining evidence of mining in this area.

Plate 4.16 and Plate 4.17 were taken at the Herrick Reach (Reach 6). This is another recovering reach located in the floodplain section where the sediment was able to expand laterally. The massive benches that line this area (and areas further upstream) are evidence for the rapid degradation of the bed. The benches are presently being stabilised by various stands of vegetation; however, any significant flood could re-mobilise these sediments. It is also possible to see the re-exposed trees and logs (Plate 4.16 and Plate 4.17).

Plate 4.18, was taken from the Garibaldi bridge, just downstream of the junction with the Wyniford River, Reach 9. This section is considered to be in the body of the slug and is therefore classified as an impacted reach. Plate 4.19 was taken between South Mount Cameron and Pioneer, and shows only one section of a multiple channel sequence. The total width of the sediment in this section is approximately 180 m. The Dorset dredge operated extensively in this area and was possibly the cause of the over-wide sections. The final photo (Plate 4.20) was taken at the mouth of the Ringarooma River.

Plate 4.14: This photo was taken at Reach 3 (control reach) in an area that had not undergone any obvious mining activity.

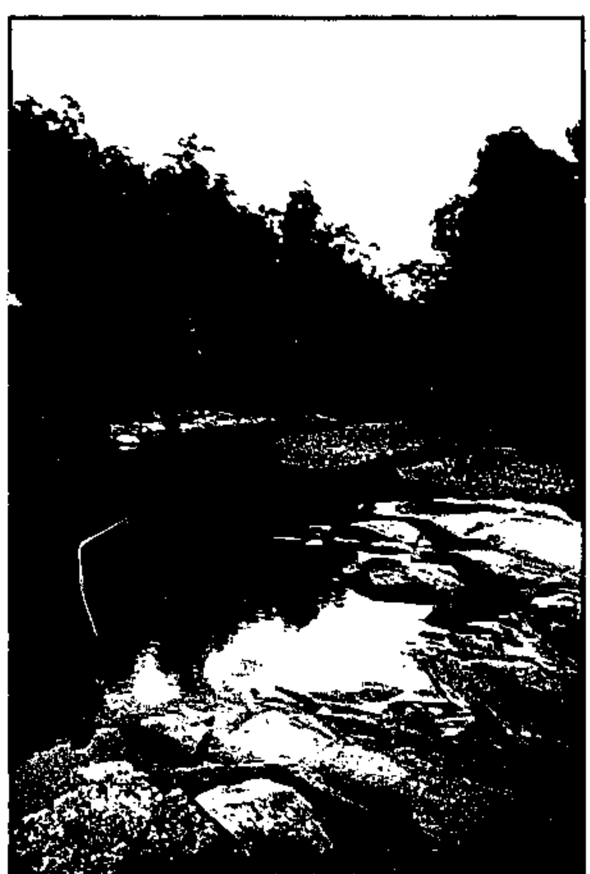


Plate 4.15: Reach 5 is a recovering reach approximately 8 km downstream of Derby. Note the armoured gravel bar in the background and exposed bedrock in the foreground.

Plate 4.16: Reach 6 is a recovering reach located at the Herrick which is the first floodplain section downstream of Derby.

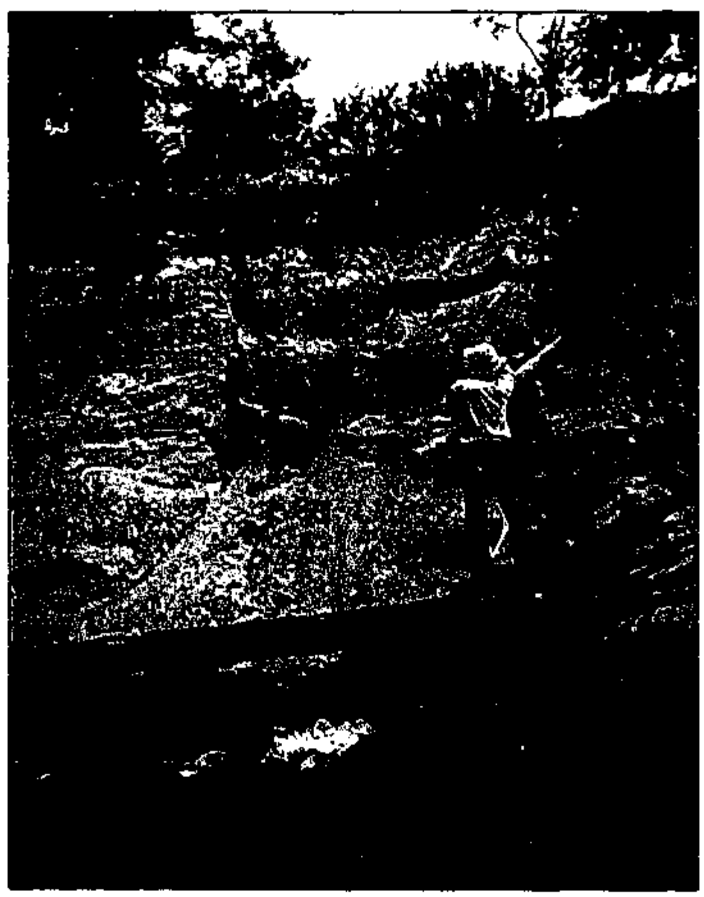


Plate 4.17: Reach 6 is a recovering reaches and there are benches on both sides of the river that have been left behind following channel incision. This bench is on the left hand side of the stream and is approximately 4.5 m high.

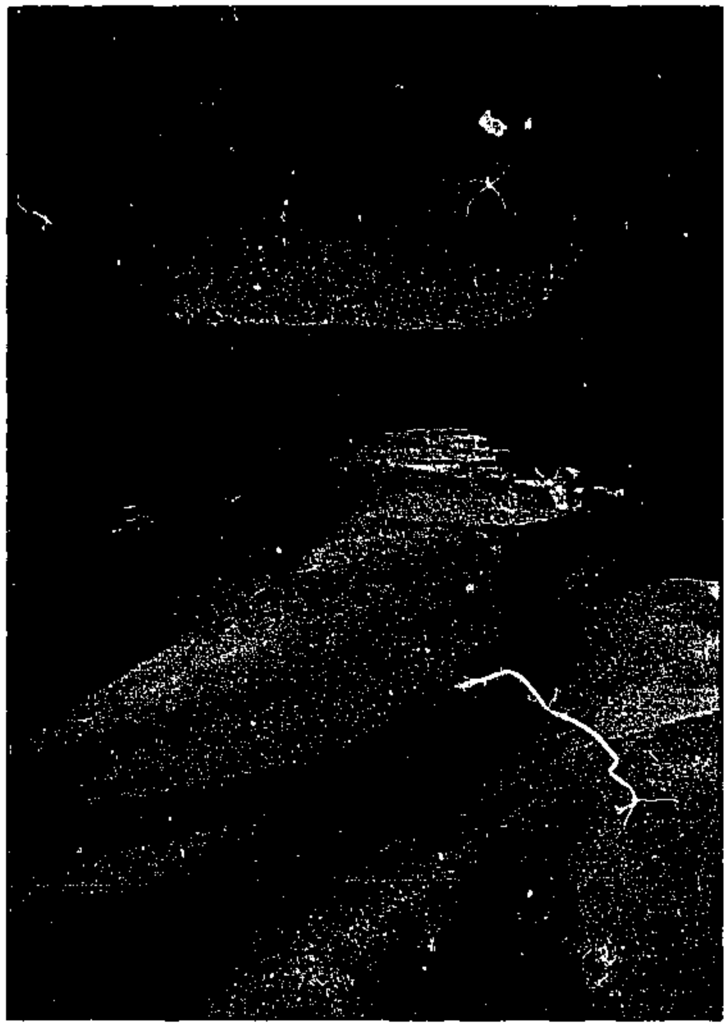


Plate 4.18: This photo of Reach 9 (impacted reach) was taken from Garibaldi Bridge at Pioneer.

Plate 4.19: This photo was taken between South Mount Cameron and Gladstone. This is just one of the multiple channels that expand this section.

Plate 4.20: Mouth of the Ringarooma River completely filled with sediment.

8.1.1. Summary

The Ringarooma is by far the most severely impacted of the three study sites described in this chapter. It has undergone extensive changes, not only indirect changes as a result of the sediment slug, but also direct manipulation to the stream in the form of channel diversions and dredging. The impact caused by the direct alteration of the stream was taken into consideration; no survey reaches were located in sections that had undergone channel diversion or dredging. The selection of study reaches is discussed further in the Chapter 5.

Despite the multiple sediment sources, the sediment slug in the downstream reaches now appears to be moving as a single 'wave'; hence, the Ringarooma presents a unique case study as the sediment was from a purely exogenous source. The Ringarooma is a gravel bed and bedrock controlled channel, which provided a different morphology to assess the recovery process.

8.2 Summary

This chapter presented the field sites that were chosen to test the recovery model. The initial part of this chapter described the selection criteria for choosing the three study sites. At least 20 streams that were assessed as potential study sites for this project. The selection criteria narrowed the number of suitable sites down to three streams: Creightons Creek, the Wannon River and the Ringarooma River. The remainder of the chapter described the physical and cultural mechanisms that lead to development of the sediment slug in each stream. The following is a summary of the main characteristics of the selected field sites:

Creightons Creek:

- The sediment slug in Creightons Creek was a result of channel incision in the upper catchment. The incision was caused by channelisation and clearing over the last two centuries;
- The estimated volume of sediment in Creightons Creek is 240,000 m^3;
- Historical evidence suggests that most of Creightons Creek was once a chain of ponds sequence. The natural bed material along Creightons Creek is silt/clay with some sand fractions.
- Both historical and geomorphic evidence shows that the bed level has returned to near predisturbance levels in many areas upstream of the Hume Highway. This was initiated at least 25 years ago.

Wannon River:

- The sediment slug in the Wannon River has been delivered primarily from a single source, Bryans Creek. The sediment in Bryans Creek is a result of severe catchment erosion due to vegetation clearing;
- The estimated volume of sediment that has been delivered to the Wannon River from Bryans Creek is 280,000 m^3;
- Historical evidence suggests that most of the lower Wannon had an irregular pool morphology, similar to the chain of ponds sequences. The natural bed material along the Wannon is silt/clay;
- The area immediately downstream of Bryans Creek has not had large quantities of sediment delivered to it from Bryans Creek since 1957. This is supported by bridge surveys and channel cross-sections. Thus, the bed level and recovery process has been at its present level for at least 25 years.

Ringarooma River:

- The Ringarooma River was severely impacted by tin mining for 110 years;
- The total volume of sediment forming the slug has been estimated at 40 million m^3. The river has also been altered through channel diversions and dredging.
- In the absence of the mining, it is expected that the natural morphology of the stream would have been a gravel bed river with considerable bedrock outcrops along the entire length of the stream;
- Historical evidence using bridge cross-sections and other lines of evidence show that the bed level has returned to pre-disturbance conditions between Branxholm and Herrick. The bed level has been at this position for approximately 18 years.

The historical description presented in this chapter has provided a number of key pieces of information for understanding sediment slug impact and recovery:

- estimates of the source and type of sediments in the sediment slug;
- volumes of sediment in the slug;
- time scales for the initiation of bed level recovery.

This historical information provides the basis for further quantitative research presented in the following chapters. Chapter 5 outlines the specific field work techniques used to collect data on each of the three study sites described in this chapter.

Chapter 5

Experimental design, data collection and preliminary data analysis

5. Chapter 5 - Experimental design, data collection and preliminary data analysis

5.1 Introduction

The previous chapter introduced the field sites used in this study. The suitability, particular characteristics and history of disturbance for the three field sites were discussed. This chapter will now describe the methods used to collect data from each stream. Some initial data analysis procedures are also presented.

As discussed in Chapter 2, the process of determining if a stream has been disturbed, and then (with time) has recovered from that disturbance, requires some objective measurement of physical change. The term Geomorphic Variability was proposed to describe the physical state of the stream. Any significant changes in the level of Geomorphic Variability along a stream can then be used to describe the disturbance and recovery process within a stream. This can then be used to evaluate the Geomorphic Recovery Model presented in Chapter 3.

The first part of this chapter (Section 5.2) describes the experimental design for the collection of data. The use of representative reaches and the statistical basis of the field survey is also described. Section 5.3 then briefly outlines the specific variables used to quantify Geomorphic Variability. Sections 5.4-5.6 then outline the theoretical background and specific data collection methods used to measure the thalweg, cross-sections, sediment size data and sediment stability, respectively. The various methods for identifying bankfull on each stream are also presented in Section 5.5. The tools for measuring the dependent variables (sediment depth, LWD and flow data) are presented in Section 5.7. Section 5.8 then summarises the main outcomes of the chapter.

5.2 Experimental design

5.2.1. Framework for data collection

The framework for the collection of data in this chapter relates specifically to testing the Geomorphic Recovery Model presented in Chapter 3. As described in Section 3.7, the Geomorphic Recovery Model has three phases which correspond to control or un-impacted stream sections, severely impacted sections and recovering sections. Each of these phases represent the different stages of disturbance according to the principles of ergodic theory (Section 3.6.1). The model then uses 'Geomorphic Variability' to measure any changes resulting from sediment slug impact.

To quantify the Geomorphic Variability of each of these sections, a rigorous sampling design needed to be developed. Fluvial geomorphologists and stream managers do not traditionally undertake rigorous statistically based sampling designs. This is often due to the large spatial scales and slow temporal scales over which disturbances can occur. In this study, however, an attempt is made to include rigorous sampling design (where ever possible), thus increasing the reliability of the results.

Maher *et al.* (1994) outlined 3 types of sampling used in fieldwork studies:

1. *Systematic sampling*: where samples are collected at regular intervals in space or time. This is the most practical of methods; however, it has the risk of falling in line with the natural sequencing (eg. pool-riffle pattern) of the stream.
2. *Randomly spaced sampling*: Strata do not need to be of equal size and the number of samples is usually in proportion to the variance of the strata. This is a more statistically significant way of testing; however, the number of cross-sections needs to be significantly large to ensure that the full range of parameters are measured.
3. *Stratified sampling*: is judgmental in that prior information is used to choose strata, but probably the best compromise between random and systematic sampling, as it is relatively free of personal judgement and reduces replication needs. Sampling precision is improved because uncertainty arises from variations within the strata not differences between the strata.

A combination of random and stratified sampling has been chosen for this study. The random component satisfies the assumptions for statistical analysis, whilst the stratified component is used in the allocation of data collection sites (see Figure 5.1).

It is not physically possible to quantify the Geomorphic Variability of the entire length of each stream, therefore the 'reach' unit is used as a representative sample of different stream 'sections' or 'phases'. It should be noted, however, that there will always be some differences between the information obtained from measurements of the small part of the environment that has been sampled, in relation to what actually exists in the total environment (Norris et al., 1992). The remainder of this section outlines the reach concept and the statistical design associated with the data collection.

5.2.2. The 'reach' concept and study design

Each of the study streams were broken up into sections of river that represented the different levels of disturbance (control, impacted and recovering); these sections corresponded directly with the three different three phases of disturbance described in the Recovery Model in Section 3.7. Then within each of these sections, a series of sample reaches were set up to represent the state of the stream. The 'reach' is considered the most appropriate scale to observe changes following disturbance because the initial response of the sediment regime is at the reach scale.

It is difficult to quantitatively differentiate between the different reach types; however, for streams impacted by sediment slugs, sediment depth is a useful indicator. Table 5.1 describes the sedimentary characteristics that differentiate between the different reach types.

Table 5.1: Sediment characteristics within each reach type

Reach type	Sediment depth characteristics
Control	Sediment depth matches the natural bedload for that channel;
Impacted	Sediment depth is >1/5 mean bank height and is either stable or increasing;
Recovering	Sediment depth <1/5 mean bank height and is declining.

Attempts were made to evenly space the reaches along the stream, simulating the natural gradient of change, however, primary consideration was given to the following criteria:

- Presence or absence of the sediment slug;
- Position along the stream and representativeness of the reach to characterise the processes occurring along the stream (ie. impact, control or recovering reach);
- Access to the site;
- Record of historical change;
- Consideration of previous research sites along the stream.

Once the reaches were identified, and divided into 'control', 'impact' and 'recovering', it was possible to place them in an ergodic time series (as discussed in Section 3.6.1), which corresponds to the Recovery Model proposed in Section 3.7.

Using control or reference reaches

Fundamental to the scientific method is the use of controls or control conditions against which results obtained under test conditions are compared (Reynoldson et al., 1997). Green (1979) also suggests that impacts can only be demonstrated by comparison with a control; however, it is difficult to achieve 'pure' control sites, due the natural processes of change that occur continually along a stream. Hughes *et al.* (1986) describes control sites for field assessments as an 'unbiased estimate of attainable conditions, or minimally disturbed sites that are representative of the sites for which they are controls'.

Some authors have made a clear distinction between control and reference sites, suggesting that reference sites are areas that have the desired conditions for restoration, but are not necessarily located on the same stream or within the same catchment (Chapman and Underwood, 2000; Hughes et al., 1986). For each of the streams in this study, the areas that have not been impacted by the sediment slug can act as both 'control' sites, with respect to the experimental design, and 'reference' sites, in terms of any potential restoration. For the remainder of this thesis, however, they will be called 'control' sites.

For all of the sites, conditions such as geology, morphological structure, hydrological and vegetation characteristics were as similar as possible. It is acknowledged, however, that there will be differences in the magnitude of features (eg. pool-riffle sequence) between the different sections, and this has the potential to influence the results. Chapter 7 is devoted to determining how the different data sets vary according to their position in the catchment.

Determining reach length

It is common in fluvial studies to use a reach length that corresponds to two pool-riffle sequences (Gordon et al., 1992). In this study, pool-riffle sequences did not naturally occur in each stream system; where they did occur, they were usually covered with sediment. As pool-riffle spacing has been shown to be approximately proportional to channel width (5-7 times the channel width) (Keller and Melhorn, 1978), channel width was used as an alternative measure for defining the reach length.

A reach length of approximately 10 times bankfull width, or 12-15 times base-flow water surface width of the control sites, was considered as an appropriate determinate of reach length (after Shields *et al.*, 1998). Wharton (1995) also recommends that a reach length of at least five channel widths as the minimum for measuring channel geometry. For the purpose of comparing the data between reaches, the reach length remained the same for each stream (although it differed between streams). It was also important to consider the concept of spatial auto-correlation (after Underwood, 1996) which states that sites/samples that are close together in space will be more similar than sites that are far apart. Thus, to prevent pseudo-replication and auto-correlation between sites, all reaches were selected to be a minimum of one reach length apart (pers. comm Dr Barbara Downs, University of Melbourne).

Determining the number of reaches required at each site

Without considerable existing data on the morphological characteristics of the study streams, it is difficult to determine the number of reaches that should be measured within each reach (control, impact, recovering). Keough and Mapstone (1995) suggest that multiple control and impact locations are the best option, yet the exact number of locations required is not clear. It is suggested that confidence in the results will increase approximately as the square root of the number of locations, and where appropriate statistical 'Power Analysis' should be used to determine the number of sites (Keough and Mapstone, 1995).

Statistical Power is the probability of getting a statistically significant result given that there is an effect in the process or population being studied. If a test is not statistically significant, it may be due to the fact that (a) there is no effect, or (b) that the study design did not pick up the effect due to small sample sizes (Thomas and Krebs, 1997). Power analysis makes it possible to distinguish between (a) and (b). In statistical terms, power is inversely related to the probability of making a Type II error. A Type II error is made when a study concludes that there is no real/significant impact when, in fact, an impact occurred (Fairweather, 1991).

Power Analysis was initially considered in the design of a sampling program; it was important to determine the number of reaches required so that the true effect was detected. However, at this stage in the research it was not possible to determine the 'Effect Size' (ES) for a given impact on such a large scale (ie. reach scale). Under these conditions, Mapstone (1995) proposes that the research should be seen as exploratory, suggesting that it is not yet possible to apply rigorous statistical analysis at the reach scale. However, there is potential to apply statistical techniques to data collected 'within' each reach. This is dealt with further in Section 5.5.3, where Power Analysis is used to estimate the appropriate number of cross-sections required.

Study Design

Compromise was therefore needed to balance the number of study reaches, with the amount of data collected within each reach. Hence, an arbitrary minimum value of three reaches (within each impact section) was chosen. The number of control, impact and recovering reaches varied for each stream, based on the length of each impact zone, size of the channel and access to sites. An example of the study design showing the section divisions and reach allocation is shown in Figure 5.1. The specific location of the sample reaches for each of the three study sites was shown in Chapter 4.

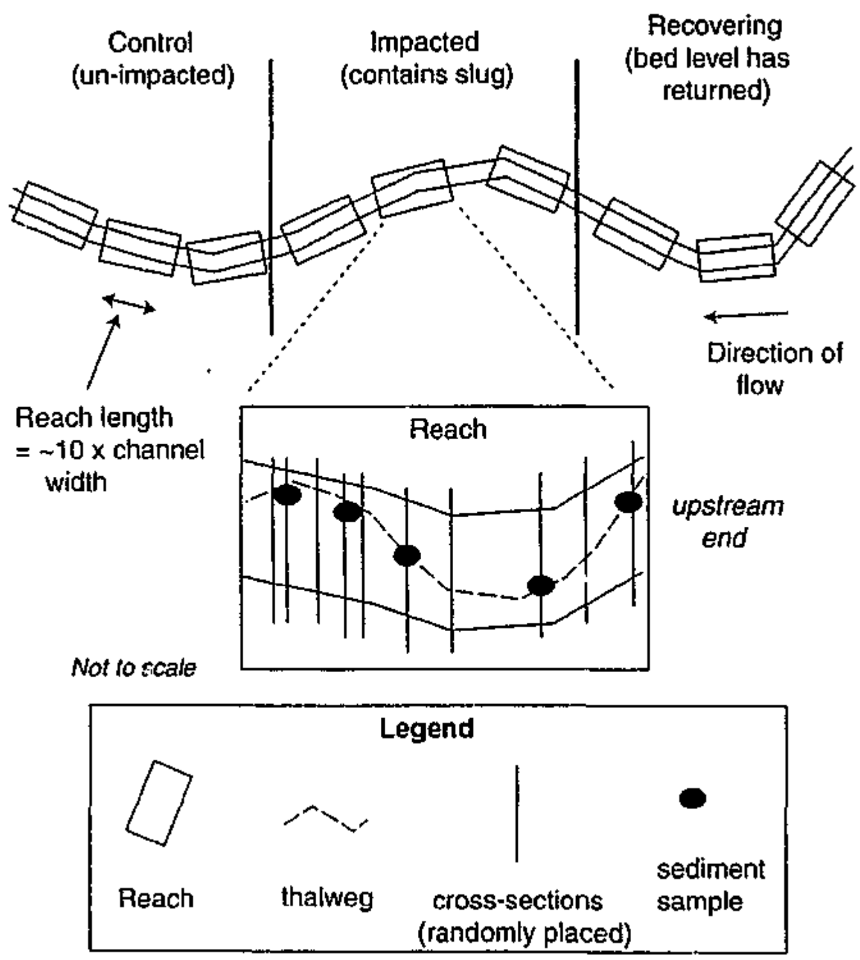


Figure 5.1: An example of the sampling design used in this study. Each stream was broken up into 3 sections (control, impacted and recovering) and sample reaches were located within each section. Note that the recovering reaches for both the Wannon and Ringarooma Rivers were located upstream of the disturbance (ie. they would be on the right hand side in this figure).

Table 5.2 presents the number of each reach type, and the length and average distance between each reach, for each stream (note that reaches were not evenly spaced). Both Creightons Creek and the Ringarooma River had one impact, one recovering and one control section; each with at least three reaches. The Wannon River had the same structure with an additional impact group which represented a different level of disturbance (as discussed in Section 4.4.1).

Table 5.2: Number and length of each reach type on each stream

Reach type	Creightons Creek	Wannon River	Ringarooma River
Control	4	3	3
Impacted	6	3	4
Impacted (group 2)	-	3	-
Recovering	4	3	3
Reach length	100 m	300 m	300 m
Average distance between reaches	~2.5 km	~3 km	~7 km

5.2.3. Statistical design

The main purpose of the experimental framework was to set up a data collection program that can be analysed using both Analysis of Variance (ANOVA) and multivariate techniques. Therefore, where possible, all of the data were set up to meet the assumptions of ANOVA designs. For example, all of the cross-sections were randomly spaced within each reach and the reaches were adequately spaced to prevent pseudo-replication and increase the 'independence' of the data set from each reach. The specific statistical techniques used to determine if there is a significant difference between the reaches are outlined in the appropriate sections in Chapters 7 and 8.

5.3 The factors used to measure Geomorphic Variability

As described in Section 2.6.1, the main variables that were considered important for quantifying Geomorphic Variability are:

- thalweg variability;
- cross-sectional shape variability;
- sediment size variation; and
- sediment stability (or % time sediment is entrained over the flow record).

Each of the variables essentially provide a measure of a different spatial scale; together, they provide a three-dimensional view of a river reach. The variables also represent different types of data, which will have an influence on the way in which they are collected and analysed. Table 5.3 describes the type of data each variable represents.

Table 5.3: The type of data that each of the variables making up Geomorphic Variability represent.

Variable	Data format
Thalweg	The thalweg data is a spatial series which is analogous to a time series, but through space.
Cross-section	Cross-section data is a unique kind of space series as it has an underlying parabolic shape.
Sediment size (variability)	Sediment size data represents a distribution, and the variability indicators quantify the range of sizes within the distribution.
Sediment stability	Sediment stability data is a combination of spatial data as it uses the sediment size characteristics, and temporal data as the stability is related to flow duration curve.

In addition to the main variables that were measured to quantify Geomorphic Variability, three other variables were measured:

- Depth of sediment;
- LWD in each reach;
- Velocity measurements (for calculating discharge).

These last three variables are not considered as key (first order) indicators of Geomorphic Variability. They do, however, have an important influence on the amount of Geomorphic Variability that is found in any one reach. Essentially, these indicators, in particular the sediment depth and LWD, are dependent variables upon which the independent variables (thalweg, cross-sections, sediment variability, sediment stability) depend. The next sections outline the significance, data collection interval and field work procedures for collecting each of the four key variables that make up Geomorphic Variability.

5.4 Theoretical and practical considerations for measuring the thalweg

5.4.1 Significance of the thalweg

The thalweg is made up of a series of topographic undulations, which, in many stream systems, form pools and riffles. These are the characteristic macro-scale bedforms of river channels. The thalweg, or deepest path of water within a reach, is the best scale to observe and measure the change in the longitudinal heterogeneity, and pool-riffle sequence in a stream. Alternating pools and riffles are now recognised as a fundamental morphological characteristic (O'Neill and Abrahams, 1984), and an important habitat feature of stream channels. For example, Jungwirth (1993) quantified habitat heterogeneity in a stream by the variance of the thalweg depth and showed that there are significant correlations with the number and diversity of fish species. As a result, the measurement of pools and riffles is commonly used to assess river condition, and thus recovery, following disturbance (eg. Lisle, 1995; Madej, 1999; Poulin, 1991).

In Australia, many streams are either alluvial clay systems that do not have the structured pool-riffle sequence of gravel bed or headwater streams, or bedrock controlled with random bed-form configurations. In streams without distinct pool-riffle sequences, such as large alluvial rivers or the 'chain of ponds' type morphologies once present in many Australian streams (Eyles, 1977), the presence of depressions (areas of scour) and elevated areas (areas of deposition) are still important, yet the methods used to assess them are not necessarily the same as for pools and riffles. In Australia's variable climate, a small scour hole, not large enough to be objectively identified as a pool, may be crucial refugia for organisms in drought times. It is therefore considered important to measure the full spectrum of longitudinal variability, and not just pools and riffles. Hence, thalweg variability in this study represents the small scale changes in bed elevation (not water level) along the length of each reach.

5.4.2. Determining appropriate data collection interval

There is no one single data collection interval that is considered appropriate for measuring thalweg variability as it is dependent on the bed-form features of interest. In this study, the macro-scale bedforms, which include features such pools, riffles, runs etc are of most interest. Freely formed pools and riffles can be characterised by an average pool-riffle spacing of 5-7 channel widths (Keller, 1972); however, it is also acknowledged that pools can also be 'forced' by features such as LWD, significantly reducing the length of pool features (Montgomery et al., 1995). For this reason, the bed elevation was measured along the thalweg at 2 m intervals (after Lisle, 1995) for all reaches on each stream. A two metre measurement interval was considered an appropriate and practical scale to describe the longitudinal bed variation. It is also relevant for the statistical analysis of the data, for at least fifty observations in each reach are required to apply time series estimates (Box and Jenkins, 1976).

5.4.3. Procedure and equipment

A surveying level and staff were used to determine the bed-level elevations (using arbitrary height datum) and the distance along the deepest thread of water in each reach was measured with a tape. Water surface elevations were also recorded. No previous thalweg elevations had been surveyed on these streams (to the authors knowledge); therefore it was not possible to compare measurements with historical data or existing bench marks. The thalweg was also used to estimate the slope of each reach. The slopes were calculated using least-squares regression (after Harvey and Schumm, 1987).

Plate 5.1: Surveying the thalweg along the Ringarooma River (Reach 2).

8.1.1. Removing the trend from the thalweg profiles

Prior to any analysis of the thalweg data, the slope (or trend) was removed from the profiles. This was an important step as the slope often changes dramatically depending on its position in the catchment. In a given spatial series such as a thalweg profile, there are three components: a trend, which is generally the long term change in mean level, a cyclic (or periodic) effect (generally a series of cyclic oscillations that do not necessarily have a fixed period), and a random element. Each of these components are described using Equation 5.1.

$$X_t = m_t + C_t + \varepsilon_t \qquad \text{Equation 5.1}$$

Where, at a given time t, m_t represents a trend (or slope) in the series, C_t is the cycle or periodicity and ε_t denotes the random component (Chatfield, 1996). Essentially, the trend is affected by catchment area and discharge relationships, and removal of this factor is important to allow comparison of thalweg profiles from various parts of the catchment.

There are many sophisticated time series methods that are suitable for trend removal in a spatial series (eg. moving averages, loess, smoothing etc), however, most of these techniques serve to smooth out the profile and reduce the variability of the series so that more obvious patterns can be detected. In this analysis, however, the variability is important, therefore the more sophisticated techniques are not useful. The easiest way to remove the slope from the thalweg profiles (without changing the variability of the series) was to fit a regression line to each thalweg profile and calculate the slope of the entire reach. The slope is then removed from the profile by multiplying the slope of the profile by the horizontal distance (eg. 0, 2, 4...) and subtracting it from the original elevation value. Removal of the slope (trend) in the data then allows comparison of reaches from different parts of the catchment.

5.5 *Theoretical and practical considerations for measuring cross-sections*

5.5.1. Significance of cross-sections

Cross-sections are the fundamental measurement unit with which river channel form is described. Cross-sections are traditionally composed of distance and elevation measurements between left and right banks, based on a nominated discharge, usually bankfull (described further in Section 5.5.5). Cross-sectional measurements are needed to provide data on both direct and indirect measures such as width, depth, channel area, discharge, hydraulic radius, velocity and sediment transport capacity. Hence, in measuring the variability of the cross-sectional morphology of a channel, it is also possible to infer details about the channel conditions mentioned above. For example, a high width-depth ratio is associated with a large bedload (Schumm, 1969); conversely, streams carrying a high suspended load (eg. Creightons Creek and the Wannon River) will tend to be deeper and narrower under natural conditions.

Cross-sections are used in this study as their gross morphology is considered to be sensitive to changes in boundary conditions such as increased sediment load. In addition, the small scale features within a cross-section provide important habitat for aquatic flora and fauna. Cross-sections can be used to identify distinct habitat features (eg. edgewater habitats, riffles, macrophyte beds), or alternatively, the variability of the entire cross-section can be used to estimate the morphological diversity across the stream. Methods for calculating cross-sectional variability are presented in Chapter 8.

5.5.2. Determining appropriate data collection interval

It is traditional for cross-sectional data to be measured at 'significant breaks of slope' (Harrelson et al., 1994) across the stream. However, due the data analysis techniques used in this study (see Chapter 8), it is important to keep a consistent measurement interval for each cross-section. A measurement interval of 50 cm was chosen as this was rigorous enough to pick up most significant changes in slope and sufficient enough to define the morphological diversity of the cross-section.

Recent biological studies looking at quantifying fish habitat have recommended that for streams 6–10 m wide, approximately 20 cross-sections spaced at 2 mean stream widths (MSW) are required to estimate values within 5% of the true mean (Simonson et al., 1994). However, these estimates are based on using non-random spacing of cross sections using a single reach in each stream and require a reach length of 35-40 MSW.

As this study collected data from between 10-14 reaches on each stream (rather than a single reach on each stream), the number of cross-sections within each reach was limited to ten. This allowed a compromise between the amount of data collected over the length of the river, versus the length of the reach. In this study, the cross-sections were placed randomly within each reach by using a random number generator, starting from the up-stream end of the reach.

5.5.3. Determining the appropriate number of cross-sections to be measured

To confirm that ten cross-sections are sufficient for characterising the cross-sectional variability of a reach, post-hoc Power Analysis was applied to Creightons Creek, as this was the first site at which data was collected. The standard deviation (SD) of the bankfull depths of each cross-section were used as an initial estimate of the amount of cross-sectional variability in each reach. The analysis used the SD of three control and three impact reaches on Creightons Creek, as this represented the extreme values in terms of stream variability.

The calculations were carried out using GPOWER (Faul and Erdfelder, 1992), a statistical analysis package, using an *a priori*, two tailed t-test. The effect size is computed as [mean 2 - mean 1]/[Standard deviation of control site means], and the critical t value or alpha (α) was set as 0.05.

The SD of the control sites was used to compute the effect size as this represents the least disturbed state of the stream (and therefore greatest variability). The 'power' of the test was set to 0.8 as this is considered as the minimum acceptable value for such analysis (Fairweather, 1991; Keough and Mapstone, 1995). The preliminary results suggested that a sample size of 5 cross-sections in each reach would be sufficient to characterise the cross-sectional variability of a reach on Creightons Creek. This result was also supported by other statistical methods outlined in Eckblad (1991). Therefore, the measurement of ten cross-sections appears to easily provide enough detail and reliability in further statistical analysis. Creightons Creek was the first study site sampled, and the sampling design appeared sound; therefore, the number of cross-sections remained at 10 for both the Wannon and Ringarooma Rivers.

8.1.1. Procedure and equipment

To measure the cross-sections on each stream, two different techniques were employed. On Creightons Creek, standard surveying apparatus (ie. level and staff) were used to link the ten cross-sections with the thalweg on each reach. The level, (model *Leica NA820*), was always tested for accuracy before use. The Wannon River and the Ringarooma River were much larger streams with bank heights commonly greater than 3 m above the bed height, making standard surveying difficult.

To allow for more rapid surveying on the Wannon and Ringarooma Rivers, a new surveying apparatus was constructed in the fashion of a large inclinometer (similar to the 'A' frame instrument developed by Riley, 1969). It measured the angle of the ground at increments of 50 cm, and with the aid of a range of trigonometric spreadsheet calculations, it transformed the angles into depth and elevation data. The apparatus was affectionately named 'Trigmaster 2000' and it was constructed using two Polycast® Magnetic Protractors (Empire Series, Patent number 4125490) mounted onto two aluminium poles placed exactly 50 cm apart (see Plate 5.2).

Plate 5.2: Application of 'Trigmaster 2000' for measuring cross-sections

The 'Trigmaster' was tested by surveying the same cross-section with both the Trigmaster and a dumpy level, and the resulting profiles looked almost identical. There was less than a 0.5% difference between the cross-sectional areas of the two profiles; this was considered an appropriate error margin, and probably equivalent to (or less than) the operator error using the dumpy level alone. Using Trigmaster, the cross-sections were linked to the thalweg by surveying in the tops of the cross-sections and recording the exact point it crossed on the thalweg. On the cross-sections where the water was too deep, the Trigmaster was used to measure the bank shape, and a boat and staff were used to record the water depths.

5.5.5. Determining an equivalent stage along the length of each stream

Prior to any analysis of any cross-sectional data, a consistent value for the discharge at which the upper limits of the cross-section is defined, is required (Thorne, 1992). It is well recognised that for most stream systems, stage increases with both discharge and catchment area. This section describes the methods for identifying an equivalent stage along a stream. Consistency is needed for the cross-sectional analysis, so that reaches on the same river can be compared. This study uses two different stages to characterise the cross-sections:

- Bankfull; and
- Low flow or channel maintenance flow.

Both these levels are considered important from a geomorphic perspective; however, the dominant flow influencing channel form is the bankfull discharge (Church, 1992; Harvey, 1969; Leopold et al., 1964; Petts et al., 1995). Both flow stages will be taken into consideration, although the bankfull stage will be given more attention.

5.5.5.1. Background - calculating bankfull discharge at each reach

The bankfull level in any reach is often identified according to the average recurrence interval (ARI) of a nominated flow; this usually corresponds to the morphological bankfull conditions. The ARI of bankfull conditions typically averages between 1 and 3 years (Harvey, 1969), although it can vary considerably between streams ranging from between 1.01 to 32 years (Leopold et al., 1964). The ARI of the bankfull discharge in this study was set as the 1 in 2 year event or Q_2. For the remainder of this thesis, bankfull stage will refer specifically to the 1 in 2 year event (Q_2), unless stated otherwise.

Bankfull discharge is the flow which fills the channel without over-topping the banks, and is considered the critical or dominant discharge in natural rivers (Richards, 1982). It has also been demonstrated that sediment transport is partially controlled by the geometry of over-bank discharges (Leopold and Maddock, 1953), which suggests that in alluvial channels, the maximum competence of the stream is normally associated with bankfull conditions (Harvey, 1969). This is why bankfull discharge is associated with, and interchangeably described as, the 'dominant discharge'.

Williams (1978) described 16 different ways of calculating bankfull discharge, ranging from using vegetation lines, to the height of the valley flat and also flow based indices. In many studies, it is common to use morphological features to define the bankfull stage when in the field. However, Gordon *et al.* (1992) highlighted that identifying bankfull is difficult in the following situations: (1) where bank tops are not at the same elevation, (2) in braided streams, (3) where the break between the channel banks and floodplain is not obvious, and (4) at complex cross-sections where benches or terraces are present. Woodyer (1968) also discussed the difficulty of identifying bankfull in Australia, because of the evidence suggesting that many streams may have incised their floodplains at mid-latitudes.

For these reasons, a more quantitative approach is required for reaches where it is not possible to determine bankfull stage from field observation alone. The method for determining bankfull stage varied for each of the field sites according to the morphological planform of the river and the available data from previous studies. Each of the methods is described below.

Estimating the discharge at each reach

To estimate the bankfull width and depth for each reach, an estimate of the discharge (Q_2) is needed. To determine the Q_2 for each reach on each stream, a flood frequency curve was first developed using the gauge data. [The flood frequency curves for Creightons Creek, the Wannon River and the Ringarooma River were presented in Chapter 4]. From the flood frequency curves, the Q_2 of the bankfull event at the gauge site was calculated. The contributing catchment area of each reach was calculated using a planimeter. The next step was to estimate the Q_2 for the reaches remote from the gauge.

The method described in Grayson *et al.* (1996) for extending flow records to ungauged catchments was adapted and used to determine the relationship between catchment area and bankfull stage (Equation 5.2). In this analysis, the higher flows are assumed to be equal to the ratio of the catchment area to the power of b. The exponent value, b, varies widely, ranging from 0.5 to 0.85 (eg. Alexander, 1972), however, use of a median value of 0.7 is considered appropriate (Grayson et al., 1996).

$$Q_2 = XC^b \quad \Rightarrow \quad Q_2 = XC^{0.7}$$ Equation 5.2

Where Q_2 is the bankfull discharge at the gauge, X is the scaling parameter and C is the catchment area at the gauge. To determine the equivalent discharge at other (un-gauged) cross-sections, the scaling parameter is simply multiplied by the catchment area of each un-gauged cross-section to determine the bankfull discharge at that site. The catchment area and discharge calculated for each reach on each stream are given in Chapter 6.

8.1.1.1. Calculating bankfull on Creightons Creek

Creightons Creek has two quite different physiographic areas as described in Section 4.3.1. The area below the Hume Highway (Reaches 1-7) is characterised by a meandering channel within an easily distinguishable floodplain. In these reaches, bankfull is obvious due to the distinct change in slope between the channel and the floodplain (**Plate**).

Plate 5.3: Bankfull versus base-flow stage for a typical survey reach on Creightons Creek (Reach 7). Bankfull was identified by change in slope at the top of the bank on streams with an obvious floodplain.

The reaches upstream of the Hume Highway (Reaches 8-14) are steeper, and the channel is confined within bench and terrace formations. Reach 8 is just below the highway, however, it was included in this analysis due to variable bank heights. As well as the geomorphic structure of the channel being different, most of the reaches upstream of the Hume highway are incised to some degree. These factors combine to make determining bankfull difficult. For this analysis, bankfull in Reaches 1-7 were determined by placing the pegs at the point where bank slope became small (slope< 5%) compared to the steepest part of the bank (after Western *et al.*, 1997) (Plate 5.3). For Reaches 8-14, bankfull stages were determined from calculations outlined below.

Application of Manning's Equation for calculating bankfull

To determine the equivalent stage corresponding to the scaled discharge in Reaches 8-14, adaptations of Manning's equation were used. This method was described in Williams (1978), and was given some criticism, mainly due to problems estimating values of Manning's *n* (roughness); however, it was also presented as the only method suitable for estimating bankfull at non-gauged sites, and it was therefore used.

In this method a relationship between hydraulic depth ($\bar{y}$) and $AR^{2/3}$ was established for a representative cross-section in each reach, where A is cross-sectional area and R is hydraulic radius. In each reach, the cross-section with the highest bank elevation data for both banks and the most uniform cross-section was used. The cross-sectional data for each reach including the mean velocity and hydraulic radius is given in Appendix E. Using the observed velocity and depth recordings taken at each cross-section (as described in Section 5.7.3) manipulations of Manning's equation (Equation 5.3) can be used to determine the value of $s^{1/2}/n$.

$$v = \frac{s^{1/2}}{n} R^{2/3} \quad \Rightarrow \quad \frac{s^{1/2}}{n} = \frac{v}{R^{2/3}}$$ Equation 5.3

where v is the average velocity at each cross-section, s is slope, and n is Manning's n. Then substituting the value of $v/R^{2/3}$ for $s^{1/2}/n$ into Equation 5.4, it is possible to obtain a value of $AR^{2/3}$ (where R = area/wetted perimeter). Then by plotting depth ($\bar{y}$) against $AR^{2/3}$, a power function can be fit to the curve to determine the depth that corresponds to the bankfull discharge (Q_2). A more detailed example of these calculations are presented in Appendix B.

$$Q_2 = \left(\frac{s^{1/2}}{n}\right) AR^{2/3}$$ Equation 5.4

The mean bankfull depths for the reaches downstream (1-7) and upstream (8-14) on Creightons Creek are given in Chapter 6. It is acknowledged that this method is somewhat crude, and does not involve any backwater analysis; this was considered too difficult, given that not all reaches had a downstream control point. Nonetheless, this method is more rigorous than estimating bankfull by eye. It is also important to note that the bankfull position determined in this analysis represents the relative bank-full level (calculated using Mannings equation) as a function of the geometry of the channel in its current bed position, not original pre-disturbance bed position.

5.5.5.3. Calculating bankfull on the Wannon River

The Wannon River was the easiest study site for determining bankfull widths and depths, as it has a distinct floodplain, and it was easy to identify the change in slope at the top of the bank. In the Wannon reaches, the method for determining bankfull was the same as for the lower reaches of Creightons Creek; ie. pegs were placed at the point where bank slope became small (slope< 5%) compared to the steepest part of the bank. There were very few sites where there was not an obvious floodplain on both banks. In the few cases where the banks were un-even, the lower bank was used to indicate bankfull. The mean bankfull depths for each reach on the Wannon River are given in Chapter 6.

5.5.5.4. Calculating bankfull on the Ringarooma River

Determining bankfull on the Ringarooma River was more complicated than on the Wannon; there are few reaches that have a distinguishable floodplain, and much of the river is confined to a bedrock gorge with steep banks. Initially, a more empirical approach to estimating bankfull was applied. This was essentially an adaptation of Manning's equation similar to that used for Creightons Creek. However, following an analysis using this approach, it was determined that this method consistently under-estimated the bankfull widths. This is because it was using a hydraulic prediction which estimates the width and depth by putting a scaled volume of water through each cross-section. In reality, the Ringarooma River has experienced massive changes to channel form as a result of the slug, and the channel widths are much greater than predicted using Manning's equation.

To reflect the true morphology of the stream, the bankfull width and depths were determined using physical evidence in the field. In most cases, the cross-sections were determined by setting the bankfull width as either the point on the channel boundary that showed an obvious change in bed material (eg. sand to loam or bedrock), or the lowest bench height. The bankfull depth was then read off the cross-section for the nominated width. The results of the original analysis using Manning's equation were also taken into consideration, and used as a check for unusual estimates of width or depth. Overall, this method provides a more accurate estimate of the state of the channel. The mean widths and depths for each of the ten reaches are given in Chapter 6.

Comparison of observed and expected bankfull estimates

An extra analysis procedure was carried out on the Ringarooma River, as Knighton (1987b) had undertaken a study of the hydraulic geometry and stream-flow characteristics of the streams of north east Tasmania. This enabled a comparison of the current observed bankfull conditions, with the expected bankfull conditions estimated using hydraulic geometry. It is important to note that when Knighton (1987a; 1987b) developed his hydraulic geometry relationships he included both the Ringarooma and the Georges Rivers into the analysis; both of these rivers have been severely impacted by mining tailings (these rivers represented two out of eight rivers used in his analysis). Thus, the final empirical relationships produced are not necessarily characteristic of un-disturbed streams. Nonetheless, the gauges used were not necessarily located in highly disturbed areas, and the analysis provided a useful insight into the expected hydraulic geometry conditions. This analysis was unique to the Ringarooma River as the other two study sites had not been subject to a regional hydraulic geometry analysis.

Hydraulic geometry was first introduced by Leopold and Maddock (1953) and it provides a set of relationships that describe river behaviour in terms of discharge (Q) and the dependent variables width (w), mean depth ($\bar{y}$) and mean velocity (v). Q and w, d and v are related by the power functions described in Equation 5.5, Equation 5.6 and Equation 5.7. In these equations, discharge is considered as the dominant independent variable to which the independent variables adjust (Knighton, 1977).

$$w = aQ^b \qquad \text{Equation 5.5}$$

$$\bar{y} = cQ^f \qquad \text{Equation 5.6}$$

$$v = kQ^m \qquad \text{Equation 5.7}$$

Where b, f and m are the rates of change of the dependent variables and a, c and k are the corresponding intercept values at unit discharge. These equations must then satisfy the continuity equation given in Equation 5.8.

$$Q = w.\bar{y}.v \qquad \text{Equation 5.8}$$

Thus, the exponents and intercept values should sum and multiply respectively to equal one, as in Equation 5.9 and Equation 5.10.

$$b + f + m = 1 \qquad \text{Equation 5.9}$$

$$a.c.k = 1 \qquad \text{Equation 5.10}$$

Although hydraulic geometry has been criticised in the literature (eg. Bates, 1990; Huang and Warner, 1995; Knighton, 1977; Park, 1977b; Richards, 1982), there have also been many successful applications (eg. Hey and Thorne, 1987; Newbury and Gaboury, 1993; Singh and Broeren, 1989).

Knighton (1987b) determined the 'downstream hydraulic geometry' relationships for the streams in North East Tasmania, including the Ringarooma, using a bankfull recurrence interval of 2 years. The relationships between Q_2, width, depth, cross-sectional area and velocity are shown in Table 5.4 including the constant and exponent values, and the correlation co-efficient and standard error for each relationship.

Table 5.4: Downstream hydraulic relations from Knighton (1987b)

Discharge	Hydraulic Geometry	Correlation Co-efficient	Standard error of estimate
Q_2	$w = 3.8Q^{0.49}$	0.93	0.16
	$\bar{y} = 0.32Q^{0.43}$	0.98	0.08
	$A = 1.22Q^{0.92}$	0.99	0.11
	$v = 0.82Q^{0.08}$	0.55	0.12

To determine the expected bankfull width and depth, the discharge for each reach was determined using the method described in Section 5.5.5.1. The discharge for each reach was then substituted into the equations for width and depth in Table 5.4. This produced an 'expected', or pre-disturbance width and depth for each reach. The results of this analysis are presented in Chapter 6.

5.5.5.5. *Calculating the base-flow discharge or active channel*

As described in Section 5.5.5.1, the base-flow discharge is considered important for the aquatic flora and fauna in a stream. The base-flow or active channel is defined as the part of the channel that is active under low to moderate flow conditions (Wharton, 1995). The base-flow is commonly identified by changes in sediment and vegetation characteristics between the bed and the banks (Gordon et al., 1992). The base flow zone is the area where sediment and water scour the channel, and vegetation is unable to grow. For this study, the low flow zone was identified by using the vegetation line, as well as changes in the bank material. Bank material was a useful indicator in streams impacted by sediment slugs, as the banks were very different from the sand dominated bed material. Plate 5.3 showed the difference between bankfull and base-flow on Creightons Creek.

5.6 Theoretical and practical considerations for measuring sediments (sediment variability and sediment stability)

5.6.1. Significance of measuring sediment size variability and stability

The size of a sedimentary grain is a result of many factors - its mineralogy, its structure and its history of weathering. These factors combine to produce particles of different sizes (Briggs, 1977). The effect of changing the size and character of indigenous sediment load was described in Section 3.4, and is not repeated here. In summary, however, the dominant reason for using sediment data as a variable to describe Geomorphic Variability is that changes in the sediment load, and/or type, usually have complex long-lasting physical and biological consequences (ASCE, 1992).

The main properties of the sediment that are of interest in this study are the changes in grain size along the stream, the heterogeneity of the surface bed material, and the stability of the sediment. The grain size properties are important for determining each of these variables, as well as determining how much the introduced sediment has changed from its indigenous load.

It is of interest to note that almost all studies that have looked at the impact of sediment have specifically looked at the impact of fine sediments on coarser grained sediments such as gravels. In this study, however, two out of three study sites involve coarser grained sediments impacting on naturally clay or fine grained channels.

The main requirements for measuring both sediment variability and sediment stability is knowledge of the sediment size. The following section is divided into two parts:

- procedures used for collecting and analysing the sediment size data (Sections 5.6.2 and 5.6.3) ; and
- methods for quantifying the stability of the sediments collected in each reach (Section 5.6.4).

The specific tools for quantifying the 'variability' of the sediment data are described in Chapter 8.

5.6.2. Procedure for collecting sediment samples

One of the main purposes for collecting sediment samples was to assess if the median grain size as well as composition of sediment (heterogeneity) had changed. Bulk sampling (after Church *et al.*, 1987) was therefore considered appropriate. Sediment samples were taken from the thalweg in each reach. This method was used for a number of reasons:

- It is the wetted area that is subject to sediment movement and thus disturbance;
- The wetted area is considered important in terms of aquatic habitat;
- It allowed for consistent sampling between reaches as not all sites had sedimentary bars to sample from.

The samples were collected using a 10 cm diameter down-pipe which acted as a sediment grab (after Goudie, 1981) to a depth of no greater than 20 cm from the surface. Approximately 1kg of sediment was collected from the thalweg in the first, third, fifth and seventh cross-sections in each reach, therefore representing a random, yet representative sample of the sediment (as shown in Figure 5.1). The five samples were bagged and returned to the lab for analysis of grain size distribution (Appendix C).

The Ringarooma River has a naturally gravel bed; hence, the bulk samples taken were subject to size discrimination in which sediment sizes greater than 16 mm were excluded. This prevented the samples being skewed by heavy particles (Kellerhals and Bray, 1971), and allowed for an assessment of the size structure and heterogeneity of the matrix of the sediment, as well as the degree of armouring in the upper reaches.

In addition to a bulk sediment sample taken on the Ringarooma River, a Wolman pebble count was carried out (after Wolman, 1954). The b-axis of 100 stones were measured on the largest exposed bar in each reach. One hundred stones is considered to be sufficient as it is free of operator error at the 95% significance level (Hey and Thorne, 1987). The D_{50} for reaches 1-6 were determined from the Wolman pebble count as gravels dominated the bed material, whereas the bulk samples were used to estimate the D_{50} of the impacted reaches (7-10) as sand dominated here. Although gravels are defined as sediments greater than 2 mm (Briggs, 1977), the minimum size of sediment for the Wolman pebble count was 16 mm. Sediments less than 16 mm were included and assessed in the bulk sieve analysis as this then provided a true estimate of the variability of the sediment sizes.

5.6.3. Sediment size analysis

The representation of a grain size distribution should be restricted to that proportion of the total size that has been sampled representatively; and the sample should be truncated before the sample size at which non-representative proportions appear (Church et al., 1987). For both Creightons Creek and the Wannon River, the upper limit for sieve analysis was set at 8mm. For the Ringarooma River, the upper size limit was set at 16 mm (inclusive). The bulk samples were analysed based on the method by Church *et al.* (1987), whereby the weight of the largest particle should not exceed 1% of the total sample weight.

The specific procedure for analysing the grain size distribution of each sediment sample was conducted according to Australian Standards (1289 SAA AS 1289 1991), as outlined in Appendix C.

Calculating the median grain size (D_{50})

The median grain size or D_{50} was calculated based on the cumulative percentage frequency curve developed for each sediment sample. The initial step was to measure the percentage of the sample in each size class (as described by the methods in Appendix C). From this data, the cumulative percentage of the sample coarser than each sieve was calculated (y-axis) and plotted against the appropriate sieve sizes (x-axis) (after Briggs, 1977). The D_{50} was then calculated by interpolating the 50th percentile value in the data set and checked against the cumulative percentage graph for accuracy. All calculations for the sediment size analysis were conducted in Excel™ (1997).

5.6.4. Measuring Sediment Stability: Incipient motion of sediment within a reach

The incipient motion, or the point at which the surface bed sediments start to move is important for determining the rate at which the bed is disturbed (as discussed in Section 3.4.2). This section outlines a technique for determining how often the bed is disturbed; this is done by estimating the flow at which the mean grain size is entrained, and then calculating how often this flow occurs (over the gauged flow record period). It is expected that the reaches that have been disturbed by the sediment slug will be less stable that the control reaches.

Unfortunately, calculating the point at which sediment transport is initiated is not a simple process, particularly due to the range of sediment sizes and diverse conditions found in the three surveyed streams. It is well known that predicting sediment transport (and its initiation) is fraught with difficulty; no two equations provide the same answer. Nakato

(1990) indicated that sediment transport equations are site specific, and that an equation that works well on one river may give poor results for the next river. Despite sediment transport equations being notoriously unreliable, they are still widely used in sediment studies (Higgins et al., 1987).

For this study, due to the difficulty and poor reliability of sediment transport equations, the full spectrum of sediment transport was not estimated. Only the initial process of sediment movement was calculated to provide an indication of the rate of disturbance for any given sediment size for a nominated flow event. This requires some estimate of the critical shear stress or incipient motion needed to move a sediment particle from the bed of the river.

A number of methods have been devised to apply critical shear stress techniques (eg. Milhous, 1982); however, many of these applications looked at the impact of fines on gravel bed rivers. There appear to have been few studies that have looked at the impact of coarse sediments on naturally fine/clay bed rivers. Likewise, the relative bed stability (RBS) method described by Jowett (1989; in Gordon *et al.*, 1992) is a suitable method for quantifying the stability of the bed; however, it was developed for sediment sizes greater than 1 mm. This is clearly not suitable for the clay/silt beds found on Creightons Creek and the Wannon River.

The simplest and most common method for estimating the critical shear stress (or tractive force or incipient motion) required to set a particle in motion is Shield's method (Shields, 1936). This method has had some criticism (eg. Yang, 1996), as it does not explicitly consider the physics of particle movement (Marsh *et al.*, 2001- In press). However, for the purposes of this research, Shield's method is considered the most appropriate. It is also one of the few techniques that enable a range of sediment sizes to be used.

Shield's method uses five dimensionless parameters to describe incipient motion: (1) the difference between the density of the particle and the fluid (ρ_s and ρ) ; (2) particle diameter (d); (3) kinematic viscosity of water (ν); (4) acceleration due to gravity ($g = 9.81$); and (5) the average particle shear stress required to move sediment on a flat bed (τ_c), where the average bed shear stress (τ_0) is a function of the hydraulic radius R and energy slope s, as described using

$$\tau_0 = \rho g R s \qquad \Rightarrow \qquad R = \tau_0/(\rho g s) \qquad \text{Equation 5.11}$$

These variables are then used to define two dimensionless quantities described by Equation 5.12 and Equation 5.13.

$$\mathrm{Re}_* = d\frac{(\tau_c / \rho)^{1/2}}{\nu}$$ Equation 5.12

$$\tau_c = \theta_c g d(\rho_s - \rho)$$ Equation 5.13

Where τ_c and τ_0 are in N/m^2, Re$_*$ is the particle shear velocity Reynolds Number, s is the slope of the energy line [which, in the case of uniform flow, is equal to the bed slope], and θ_c is the dimensionless critical shear stress constant. The relationship between Re$_*$ and θ_c is often expressed using the Shield's curve (Figure 5.2).

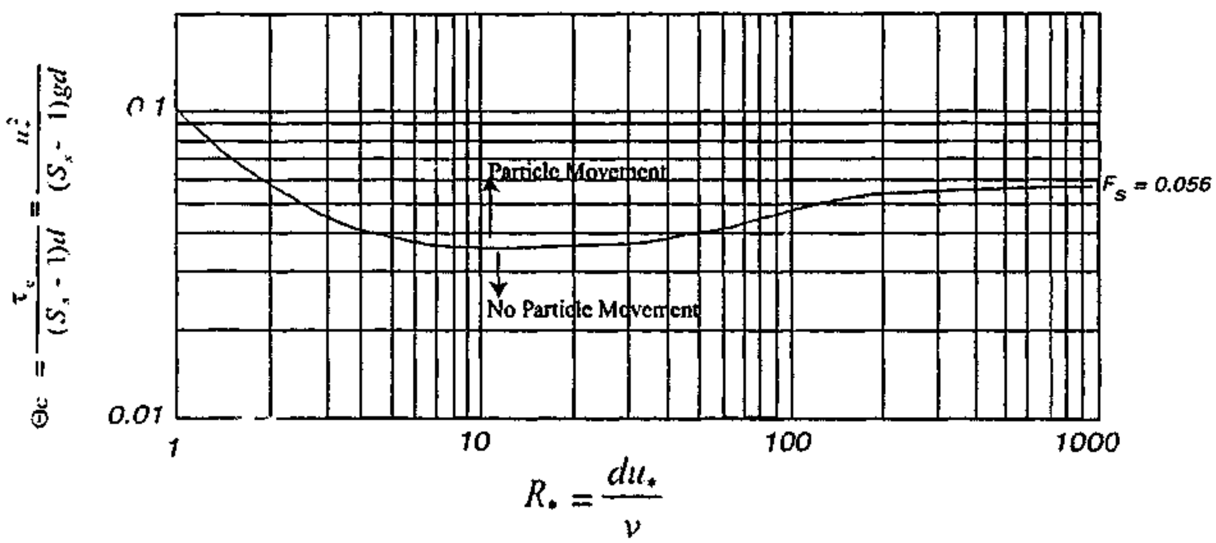


Figure 5.2: Shields curve showing the relationship between the dimensionless critical shear stress (θ_c) and Reynolds number (R_*) (adapted from French, 1985).

To calculate values of τ_c, values of θ_c need to be estimated. Essentially, θ_c represents an average value for a given sediment size, which can also be influenced by exposure, and other factors (Carson and Griffiths, 1987). It was difficult to determine the appropriate values for θ_c, as the typical values lie between 0.04 and 0.06; however, considerable scatter exists within these values. In addition, very few estimates of θ_c for cohesive sediments less than 1 mm have been published. Table 5.5 outlines a range of values for θ_c and their associated sediment sizes found in the literature. In some cases, the values of θ_c were back calculated, using known values of τ_c and Equation 5.13 for a given sediment size, or using Reynolds number and Shields diagram (Figure 5.2). In the case of sediments less than 0.063 mm, Figure 5.3 was used to determine the total shear stress rather than the dimensionless shear stress. The final values used for each reach on each stream were based on the D_{50} for the entire reach, and listed in Table 5.6. These were considered appropriate for the conditions at the time of data collection on each stream.

Table 5.5: Reported values for θ_c found in the literature.

Sediment size (mm)	Critical dimensionless shear stress, θ_c,	Source of data
~0.063 (> 25% clay)	0.1	Torfs *et al.* (1994)
0.15	0.07	Tison (1953) in Yang (1973)
0.1-0.2	0.055	Casey's data in Yang (1973)
0.5	0.038	Kramer (1935) in Yang (1973)
1.0	0.038	Tison (1953) in Yang (1973)
2.0	0.04	Grand Laboratory's data in Yang (1973)
3.0	0.048	Gilbert (1914) in Yang (1973)
4.0	0.05	Grand Laboratory's data in Yang (1973)
5.0	0.052	Grand Laboratory's data in Yang (1973)
7.0	0.02-0.25	Gilbert (1914 in Yang (1973)
Mixed bed (2-64 mm)	0.02-0.25	Gordon *et al.* (1992)
Gravel (2-64 mm)	0.002-0.12	Carson and Griffiths (1987)

Table 5.6: slope and the dimensionless and average critical shear stress values for each reach on each stream

	Creightons Creek			Wannon River			Ringarooma River		
Reach	slope	θ_c	τ_c	Slope	θ_c	τ_c	Slope	θ_c	τ_c
1	0.0046	-	10.0	0.0004	-	8.00	0.0030	0.12	102
2	0.0008	-	1.10	0.0001	-	8.00	0.0077	0.12	87.4
3	0.0033	-	1.10	0.0001	-	8.00	0.0011	0.12	126
4	0.0006	0.039	0.90	0.0004	0.039	0.26	0.0013	0.12	121
5	0.0015	0.038	0.62	0.0002	0.038	0.41	0.0024	0.08	51.8
6	0.0046	0.039	0.92	0.0004	0.039	0.55	0.0036	0.07	54.4
7	0.0009	0.039	1.10	0.0025	0.039	0.53	0.0017	0.048	2.51
8	0.0028	0.039	1.07	0.0003	0.039	0.34	0.0034	0.04	1.25
9	0.0032	0.039	0.92	0.0004	0.039	0.40	0.0012	0.048	1.96
10	0.0039	0.039	0.95	0.0002	0.039	0.28	0.0009	0.04	1.35
11	0.0027	0.047	1.72	0.0004	0.045	8.00			
12	0.0038	0.047	1.72	0.0038	0.045	0.33			
13	0.0038	0.039	1.01						
14	0.0059	0.039	1.09						

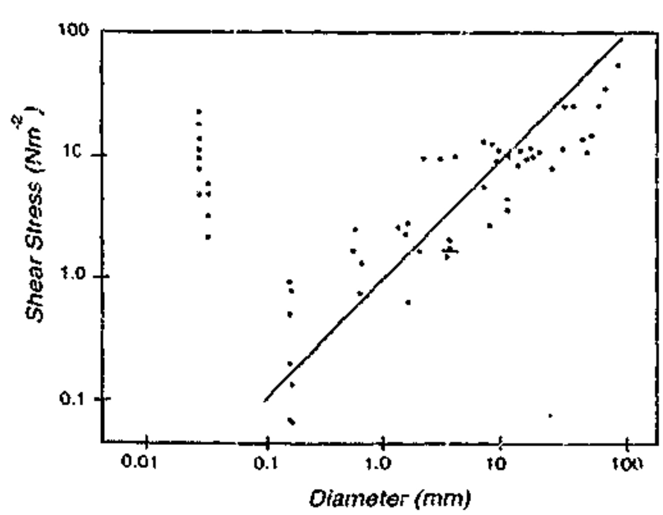


Figure 5.3: Total shear stress values for a range of sediment sizes (adapted from Petit, 1990).

To determine the critical shear stress for each reach on each stream, the median bed size (D_{50}) for each reach is used. It is then possible to link the critical shear stress τ_c to the bed shear stress τ_0, by equating $\tau_0 = \tau_c$, (after Gordon *et al.*, 1992 p 335). The final step is to use Manning's equation (Equation 5.14) to calculate the discharge at which the sediment is entrained.

$$Q = \frac{1}{n} A R^{2/3} s^{1/2}$$ Equation 5.14

where Q is the discharge (m^3/s), n is Manning's n, A is the area of the cross-section (m^2), R is the hydraulic radius and s is the energy or bed slope. As all the cross-sections are wider than 10 m, R $\approx$ mean depth ($\bar{y}$). The slope of each reach was calculated using the thalweg data (Table 5.6). Using the flow duration curve, based on the gauge data collected for each stream, it is then possible to determine the probability or frequency of the discharge that will move the D_{50}. This is calculated for each reach on each stream to determine which reaches will have the greatest frequency of sediment entrainment.

To calculate the frequency of movement for the D_{50} in each reach, the single, most uniform cross-section was chosen from each reach on each stream. The value of Manning's n was estimated using Chow (1959) and Cowan (1956), and checked against Stickler's equation (in Chow, 1959) (Equation 5.15). The Manning's n values are given in Table 5.7, and the D_{50} for each reach is presented in Chapter 6. The Manning's n values were considered to be reasonable estimates for the rivers in this study (pers. comm. Assoc. Prof. Bob Keller, Monash University).

$$n = 0.041 D_{50}^{1/6}$$ Equation 5.15

The final output is a number for each reach that represents the % probability that the D_{50} is entrained. Alternatively, this could be expressed as the proportion of time (as a %) that the flow exceeds the critical threshold for sediment transport. The flow duration curves (Appendix D) of the minimum daily flow (m^3/s) were used to determine how many days (over the entire flow record) sediment would have been entrained in each reach. This was then converted to a %.

Table 5.7: Mannings n values calculated for each reach on each stream.

Reach	Creightons Creek	Wannon River	Ringarooma River
1	0.07	0.07	0.05
2	0.07	0.07	0.05
3	0.07	0.07	0.05
4	0.05	0.03	0.05
5	0.04	0.03	0.05
6	0.04	0.04	0.05
7	0.04	0.04	0.03
8	0.04	0.03	0.03
9	0.04	0.04	0.03
10	0.04	0.04	0.03
11	0.04	0.04	-
12	0.04	0.04	-
13	0.04	-	-
14	0.04	-	-

Authors such as Cobb *et al.* (1992) described substrate stability as the percentage of stream bed paving material at incipient motion; in this case, the higher the number, the more mobile the sediments. However, to keep the scale of the methods in order with the previous techniques, it is important that the final number for each reach is described in terms of sediment stability, with a higher number representing a more stable sediments. Therefore, the final step is to use Equation 5.16 to convert the % time the D_{50} is entrained, to a sediment stability rating out of 100. Using this technique, a high value will represent high stability, and vice versa.

Sediment stability = 100 - (% time D_{50} is entrained) Equation 5.16

There are a number of assumptions used in this method:

- that the flow is uniform;
- that all particles are spherical, uniform, and have a ρ_s of 2650 kg/m^3 and the water density is 1000 kg/m^3;
- the hydraulic radius R is considered to be equal to the mean depth ($\bar{y}$);
- that there are no significant bed forms in any of the reaches (assumes $\tau_0 = \tau_c$,);
- that the D_{50} is the most appropriate grain size to use. In the case of the armoured reaches on the Ringarooma River, the D_{50} of the armoured layer (see below), rather than the sub-surface material is used;
- that the flow duration curve for each stream is applicable to all reaches within the study site.

A similar technique was described by Newbury (1984), in which he highlighted that the results should be used as only a general indicator of sediment stability, and not an exact estimate. The results of this analysis are presented in Chapter 6.

Armouring

The development of a coarse surface layer over the top of finer sediments on a river bed is described as armouring, and it is an important consideration in any study of the incipient motion of sediment. Where a bed is armoured, the sub-surface sediments cannot be mobilised until the armour layer is removed. One of the conditions required for sediments to be considered as armoured is that the $D_{95}/D_5>5$ (Knoroz, 1971 in Sutherland, 1987).

For Reaches 1-6 along the Ringarooma River there is a well developed armour layer on the bed and many bars. This armour layer will have an affect on the tractive stress levels required to entrain a particle. The science behind calculating the affect of flow on armoured beds is complicated, and will not be dealt with in this thesis. Instead, a simple calculation of the strength of the armour layer will be made for the six armoured reaches on the Ringarooma River. To calculate the strength of an armour layer, Equation 5.17 can be used (after Gordon *et al.*, 1992).

$$A = \frac{d_a}{d_{sub}} \qquad \text{Equation 5.17}$$

where d_a represents the D_{50} of the armour layer, and d_{sub} is the D_{50} of the sub-surface. Parker *et al.* (1982) suggested that typical values of A are between 1.5 and 3 in gravel bed streams; however, other authors such as Dunkerley (1990) describe values of up to 24. The value of *A* for reaches 1-6 on the Ringarooma River are presented with the results of the sediment stability analysis in Chapter 6.

5.7 *Methodology for measuring independent variables: sediment depth, LWD and flow*

The previous sections outlined the specific techniques used to collect data for the four main variables that make up Geomorphic Variability (thalweg, cross-sections, sediment size and sediment variability). As described in Section 5.3, there are also three other variables that were measured, as they were either important influences on the level of Geomorphic Variability found in a channel, or required for other data analysis procedures (eg. velocity readings for calculating bankfull discharge). This section outlines the specific techniques used to collect the sediment depth data, LWD data and flow measurements, respectively.

8.1.1. Sediment depth data

To calculate the depth of the sand in each reach, the bed of the channel was probed using a steel rod of 5 mm diameter (Plate 5.4). This is a common technique used to estimate the volume and depth of sediment in geomorphic studies (eg James, 1991; Rutherfurd and Budahazy, 1996). The sediment depth was determined by measuring the point at which the probe could no longer be penetrated into the bed. This is usually where the probe reaches a different bed material, either the original clay bed, bedrock or woody vegetation under the sand (Figure 5.4). Probe depths were taken at 1m intervals across 5 of the 10 cross-sections (alternating downstream). In each reach an average of 45 sediment depths were recorded. Sediment probing was only carried out where there was a obvious amount of sand sized fractions. In each of the control sites where there was no sand, a nominal sediment depth of 0.01 m was given to allow for some sand fractions on the bed surface.

Plate 5.4: Probing bed sediments on the Ringarooma River (Reach 9)

It is important to note that sediment probing on Creightons Creek was difficult because of the multiple clay and sand layers that were found in the bed at some sites. To overcome this problem, the probing technique remained consistent at each site by recording the sediment depth as the first resistance (clay) layer.

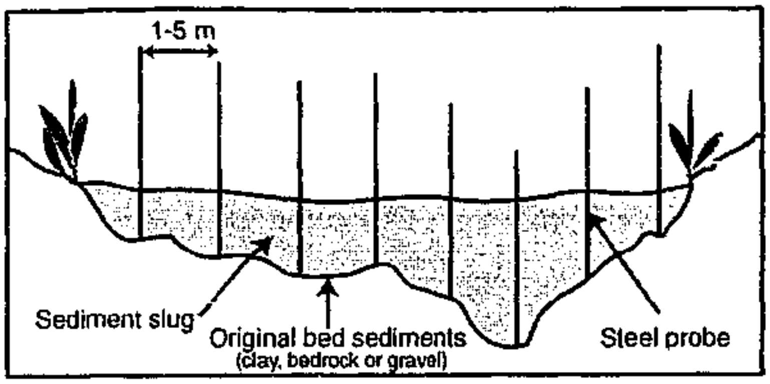


Figure 5.4: Example of probing procedure along a cross-section. Distance between probe measurements varied with cross-sectional width (between 1 m and 5 m intervals).

5.7.2. Large woody debris

Large woody debris (LWD) or large organic debris (LOD) is defined as logs, stumps, rootwads and branches with diameters of greater than 0.1 m (Hogan, 1987). No attempt was made to rigorously measure the volume, spacing or type of LWD in the channel. It is, however, recognised that vegetation, both within the channel and on the banks, has an important affect on the channel geometry and hydraulic conditions (eg. Friedman *et al.*, 1996; Hupp and Osterkamp, 1996; Shields and Smith, 1992; Wood-Smith and Swanson, 1997). Vegetation and debris located within the channel may also strongly impact both the style and amount of sediment storage, as well as the overall channel roughness. Large woody debris can provide transient storage sites for bed material, stabilise gravel bars, and provide hydraulically sheltered locations that allow fine sediment to accumulate (Montgomery and Buffington, 1993), and LWD is an important source of habitat within a stream (Keller et al., 1995).

For these reasons, the number of pieces of LWD in each survey reach was counted and recorded during the thalweg survey; only LWD within the wetted perimeter of the channel was counted. Counting LWD during the thalweg survey also allowed the submerged underwater pieces to be detected. The number of pieces of LWD found in each reach on each stream is given in Chapter 6, and its affect on the Geomorphic Variability of the streams is discussed in Chapter 10.

5.7.3. Flow measurements

The main purpose of recording flow was to estimate the discharge within each reach at the time of surveying. This data were then used to assess if there were any major inconsistencies between the measured discharge and empirically estimated discharge (as described in 5.5.5.1). The data were also useful for determining bankfull stage on Creightons Creek (Section 5.5.5.2).

The period of field work on the Wannon River coincided with the driest year on record (@ Henty Gauge, Thiess gauging records, 2000); in some reaches there was no detectable flow, making discharge calculations useless. On the Ringarooma, the massive volumes of sediment and multiple channels often found in the downstream reaches provided little consistency between sites, again providing too much error to be useful.

Nonetheless, in all reaches, attempts were made to measure the mean velocity, and thus discharge. To do this, a single cross-section in each reach was used to measure the velocity at 0.4 times the depth (0.4d) (after Gordon *et al.*, 1992). The cross-section was placed on the straightest section of the reach and velocity readings were measured at 0.5 m intervals across each stream. To calculate the velocity, a current metre (model OSS-PC1) with a 50mm diameter fan was used, and discharge (Q) was then calculated using the continuity equation in the form of Equation 5.18.

$$Q = w * \bar{y} * v \qquad \text{Equation 5.18}$$

Where w is cross-section width, $\bar{y}$ is average depth and v is measured velocity. The main stream for which the velocity data was utilised was on Creightons Creek (the relevant velocity values for each reach is presented with the cross-section data in Appendix E).

5.8 Summary

This chapter presented the theoretical background for the selection of the variables that represent Geomorphic Variability. The specific techniques and measurements procedures used to collect the data for each of these variables were then outlined.

The main points from this chapter are:

- The experimental design in this study was set up so that ANOVA and multivariate statistical techniques could be employed. There are very few geomorphic studies that incorporate this type of rigour;
- The 'reach' is the most appropriate scale from which to collect data about the Geomorphic Variability of a stream;
- Geomorphic Variability is made up of four variables: thalweg, cross-sections, sediment variability and sediment stability. These factors are also influenced by other variables, namely sediment depth and LWD.

- The method described for estimating sediment stability has not be presented in the literature before, and it provides a simple, yet useful measure of the average stability of the sediments over the flow record.
- The data collection techniques described were established to enable a relatively rapid collection of data whilst providing enough detail to obtain statistically reliable results.
- Statistical sampling frameworks for geomorphic data do not exist in the literature for the scale of this study. Thus, this study had to develop a new framework utilising designs from other disciplines, namely aquatic ecology. The sampling framework presented in this chapter presents a unique contribution to area of geomorphological research and its application to habitat scale studies.

Chapter 6 presents the data collected using the various procedures outlined in this chapter.

Chapter 6

Field data collected

6. Chapter 6 - Field data collected

6.1 Introduction

Chapter 5 outlined the various data collection techniques for measuring the four variables that make up Geomorphic Variability (thalweg, cross-sections, sediment size variation and sediment stability). This chapter now presents the data collected.

Section 6.2 provides a background to the type of data presented and outlines the graphical tools used to present the data. Section 6.3 presents the catchment area and discharge data for each of the three streams, while Sections 6.4, 6.5 and 6.6 present other data for Creightons Creek, the Wannon River and the Ringarooma River, respectively. These data include the thalweg data, cross-sectional mean widths and depths, mean sediment size values, results of the sediment stability analysis, the sediment depth and LWD data.

6.2 Background and presentation of results

The main focus of this thesis is to understand how the 'variability' of a stream is altered, and then recovers, following disturbance by sediment slugs. The data presented in this chapter have not yet been analysed for changes in variability, but represent the current 'mean' condition.

Other studies that have employed ergodic theory to analyse large scale geomorphic recovery processes (eg. Hupp, 1997; Schumm et al., 1984; Simon, 1995) have simply evaluated the response using the mean conditions. As described by Schumm et al., (1984), 'it is reasonable to assume that if downstream (or upstream) channel reaches evolved in a similar manner, and that if upstream channels are rejuvenated, their evolution will be similar'(p127). Hence, if ergodic theory was the only analysis technique to be employed in this thesis, the results presented in this chapter would be sufficient for evaluating the response of streams to disturbance by sediment slugs. However, this research identified two other important factors:

(1) the effects of scale (and thus, position in the catchment); and

(2) the use of variability, rather than mean conditions as a measure of recovery.

These factors are addressed in Chapters 7 and 8.

Presentation of results

In this chapter, of each of the data sets are presented using a variety of graphing methods. In all cases, data are presented in the same order; starting with the control, impacted, then recovering reaches. It is important to note that because of the different positions of the control reaches (ie. some upstream and some downstream of the impact), the order of the results will not necessarily be linear (ie. not always 1, 2, 3, 4, 5, 6...11, 12). Instead, the order reflects the Geomorphic Variability model proposed in Chapter 3 (presented again in Figure 6.1). Plotting the results in this manner provides consistency in interpreting the results across streams. Thus, the most downstream impacted reach is designated as the first impacted reach; the site that has been recovering for the longest time period is designated the last recovering reach. This ordering reflects the changes in both space and time.

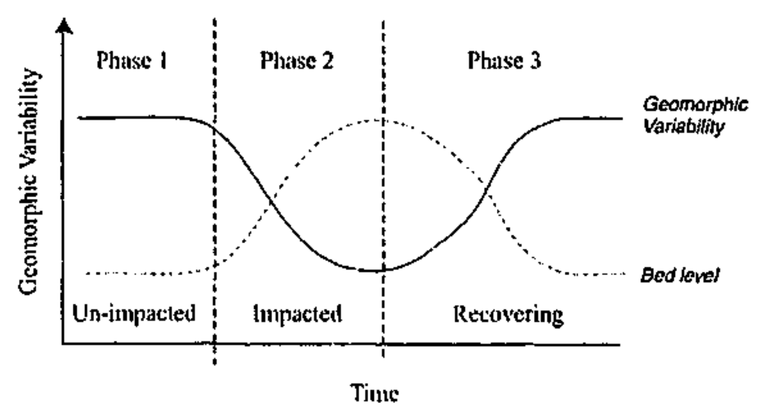


Figure 6.1: Geomorphic Recovery Model proposed in Chapter 3

Some of the data are presented as box plots, which summarise the distribution of values for each reach. An example box plot (with interpretation) is presented in Figure 6.2.

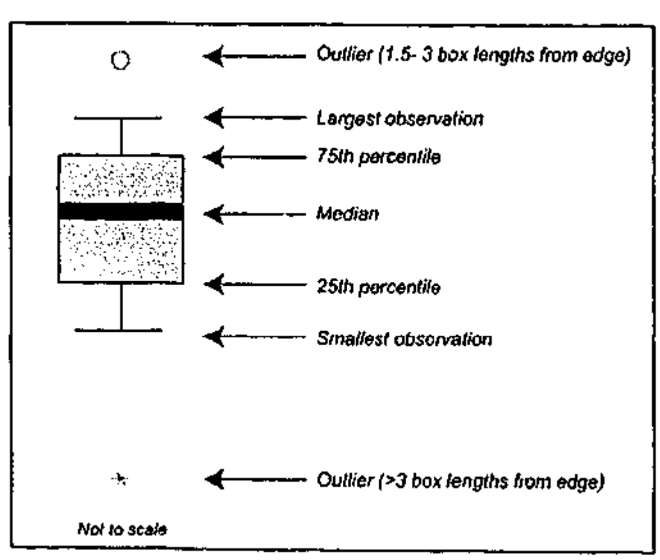


Figure 6.2: How to interpret data presented in box plots

In Figure 6.2 the median value is represented by the dark horizontal line. The upper and lower boundaries of the box are the 75th and 25th percentiles, respectively, and the smallest and largest observations are presented by the horizontal lines at the end of the box. If the distribution has any extreme scores, an asterisk (*) will represent a value that is 3 or more box lengths from the upper or lower edge of the box; a circle (o) represents a value that is 1.5-3 lengths from the edge of the box (Coakes and Steed, 1999).

6.3 *Catchment area and discharge values for each stream*

Section 5.5.5.1 described the methods for calculating the catchment area and discharge for each reach. The data from these analyses are presented in Table 6.1.

Table 6.1: Contributing catchment area and discharge for each reach on each stream

Reach	Creightons Creek		Wannon River		Ringarooma River	
	Catchment area (km^2)	Discharge Q_2 (m^3/s)	Catchment area (km^2)	Discharge Q_2 (m^3/s)	Catchment area (km^2)	Discharge Q_2 (m^3/s)
1	139	14.37	3445	77.00	53	20.36
2	138	14.30	3501	77.87	143	40.78
3	136	14.15	3507	77.97	273	64.13
4	121	13.04	4011	85.65	430	88.14
5	115	12.59	4013	85.68	466	93.24
6	105	11.81	4103	87.02	539	103.24
7	94	10.93	4124	87.33	560	106.04
8	89	10.52	4141	87.58	571	107.50
9	83	10.02	4431	91.83	647	117.32
10	73	9.16	4443	92.01	767	132.16
11	63	8.26	4449	92.10	-	-
12	57	7.70	4490	92.69	-	-
13	41	6.11	-	-	-	-
14	23	4.08	-	-	-	-

Again, it is important to note that Reach 1 represents the control reach furthest from the sediment slug. On Creightons Creek, Reach 1 is located downstream of the disturbance and on the Wannon and Ringarooma Rivers Reach 1 is upstream of the disturbance. This means that the data presented in Table 6.1 increases in value from Reaches 1 to 14 for the Wannon and Ringarooma Rivers, and decreases for Creightons Creek.

6.4 *Creightons Creek data*

Creightons Creek has the smallest catchment area of the three study sites. The upper reaches of the stream are severely incised, and present the main source of sediment fuelling the slug in lower reaches. Figure 6.3 shows the location of the study reaches along the stream to provide context for the results presented in this section.

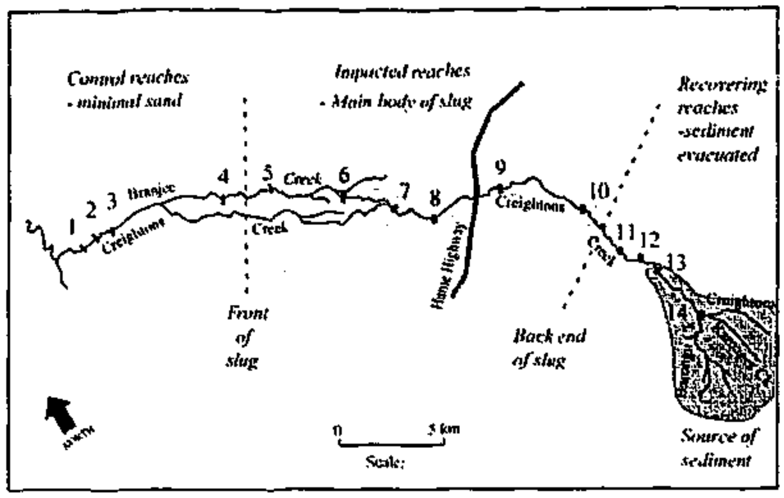


Figure 6.3: Location of reaches along Creighton's Creek

6.4.1. Thalweg

The methods for collecting and de-trending the raw thalweg data were described in Section 5.4.4, and the results are presented in Figure 6.4. The dashed lines separate the control, impacted and recovering reaches. A visual examination of this data suggests that the control reaches, 1-4, are more variable than the profiles from the impacted and recovering reaches. Further analysis of the data (described in Chapters 7 and 8) will quantify this difference.

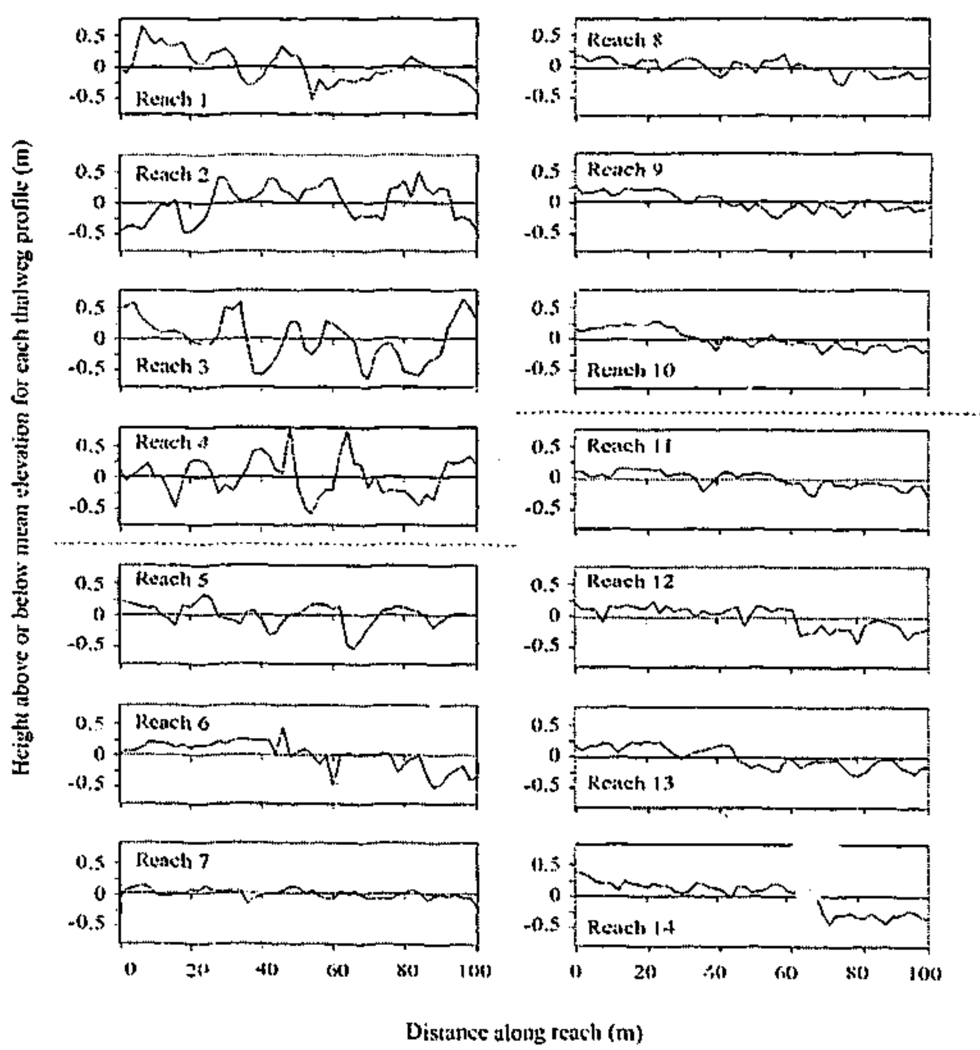


Figure 6.4: Thalweg profiles for Creightons Creek (slope has been removed). The dashed lines separate the different impact zones.

6.4.2. Cross-sectional data

The methods for measuring and defining bankfull for the cross-sections were presented in Section 5.5.5, and the width and depth data for the 130 cross-sections measured along Creightons Creek are presented in Appendix E. This section presents the average bankfull widths and depths for each reach along Creightons Creek (Table 6.2). The mean widths appear to have increased due to the impact of the sediment slug, and channel depths appear to have reduced (Figure 6.5), an observation analysed further in Chapter 7.

Table 6.2: Reach averaged bankfull widths and depths for Creightons Creek

Reach	Average width (m)	Average depth (m)
1	13.3	2.1
2	10.8	2.2
3	10.3	2.2
4	9.4	1.9
5	11.5	1.2
6	12.3	1.3
7	10.7	1.0
8	14.1	1.3
9	11.5	1.1
10	10.4	1.2
11	12.9	1.1
12	12.6	1.9
13	6.9	0.8

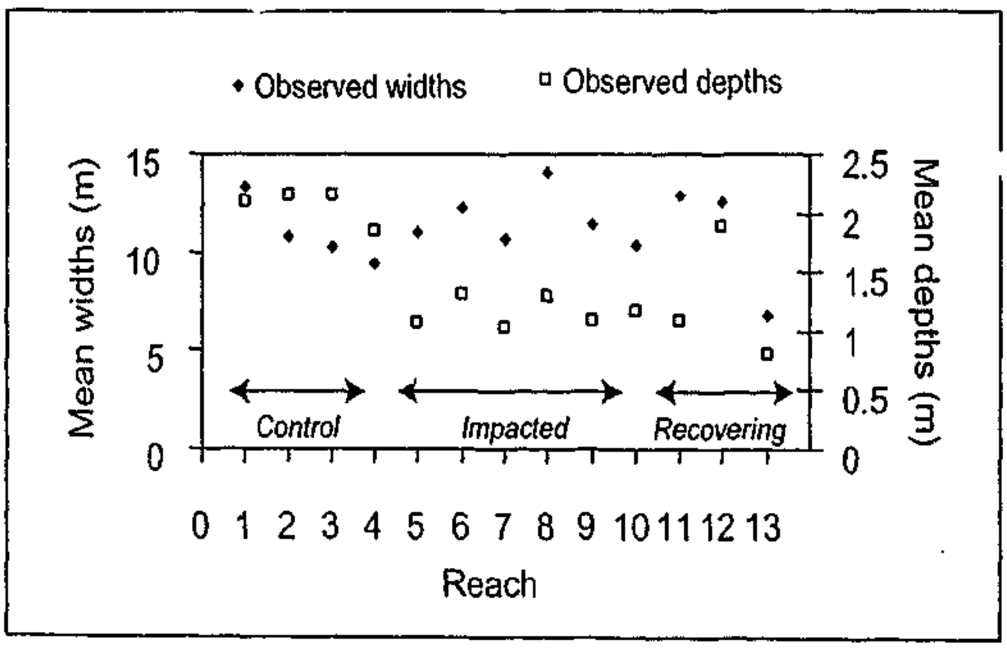


Figure 6.5: Mean widths and depths for Reaches 1-13 on Creightons Creek.

6.4.3. Sediment size

Five sediment samples were collected from each reach (totalling 70 samples); the method for calculating the median grain size (D_{50}) was discussed in Section 5.6.3. It appears that there is a considerable increase in grain size between Reaches 1-3 and all other reaches, with a slight increase from Reach 4 to 14 (Figure 6.6). There also appears to be greater variability in the median grain size for the 5 samples in the control and recovering sections (compared to the impacted reaches). This may, however, be a result of the outliers in these data sets, and further analysis is required to assess if this observation is actually a result of the sediment slug or natural conditions. Such analysis will be explored in Chapter 7.

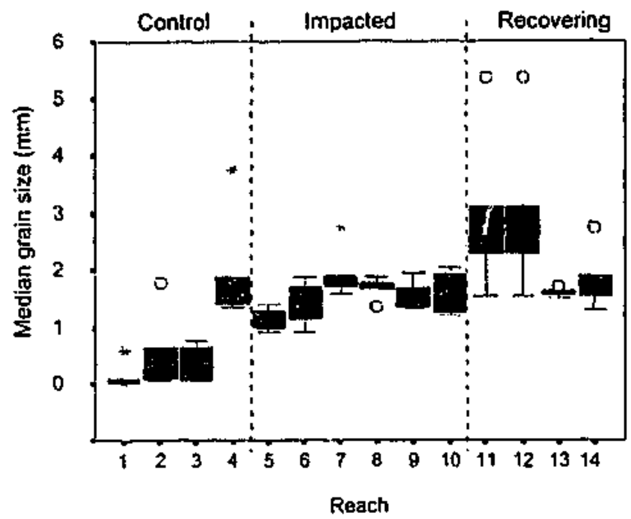


Figure 6.6: Box plot of the median grain size of the 5 samples collected from each reach on Creightons Creek.

6.4.4. Sediment stability

Sediment stability was estimated using the Shield's critical shear stress approach, described in Section 5.6.4. On average, the control reaches are more stable that either the impacted or recovering reaches (Table 6.3; Figure 6.7); this is because the clay dominated sediments in the control reaches are more difficult to transport than the sandier sediments in the impacted and recovering sections. The control reaches are stable between 7% and 75% of the time, whereas the impacted and recovering reaches are stable less than 6% of the time.

Table 6.3: Sediment stability for each reach along Creightons Creek

Reach	Discharge (m^3/s) at which D_{50} is entrained	Number of days flow is exceeded (total of 4677 days in record)	% time that the sediment is stable
1	0.315	1142	75.6
2	0.069	3239	30.8
3	0.029	4334	7.3
4	0.054	3657	21.8
5	0.005	4568	2.3
6	0.004	4575	2.2
7	0.023	4424	5.4
8	0.006	4562	2.5
9	0.004	4575	2.2
10	0.003	4579	2.1
11	0.021	4473	4.4
12	0.009	4557	2.6
13	0.004	4575	2.2
14	0.003	4589	1.9

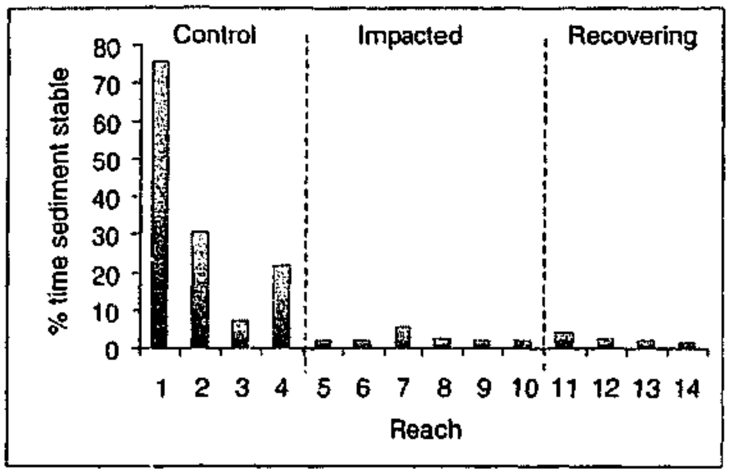


Figure 6.7: % of time sediment is stable in each reach along Creightons Creek

The overall finding for Creightons Creek is that the sediment slug has increased the rate of sediment entrainment by approximately 12 times (on average) between the reaches downstream of the slug and reaches in the slug. This result is expected to have implications for the aquatic ecology along Creightons Creek. O'Connor and Lake (1994), have shown that there is a marked decrease in the species diversity and abundance between the sandy and clay sections on Creightons Creek, particularly during high scour winter flow events. The sediment stability work presented here may provide a possible explanation for the change in fauna populations.

6.4.5. Independent Variables

As described in Chapter 5, there were a number of other data variables collected that were not directly related to the Geomorphic Variability of a stream. In this section, the sediment depth and LWD data are presented for Creightons Creek. These variables are considered to be important for understanding the impact and recovery potential of the streams disturbed by sediment slugs.

6.4.5.1. Sediment depth data

Sediment depths were measured for each reach along Creightons Creek (Figure 6.8). The results suggest that there is a wave or slug of sediment in the bed, with the front of the slug near Reach 4, the middle around Reach 7, and the tail near Reach 11. The maximum mean sediment depth measured along Creightons Creek is approximately 2.4 m (at Reach 7). These sediment depths will be discussed later in this thesis (Chapter 10) to determine if sediment depth is a key factor in controlling the changes in Geomorphic Variability along Creightons Creek.

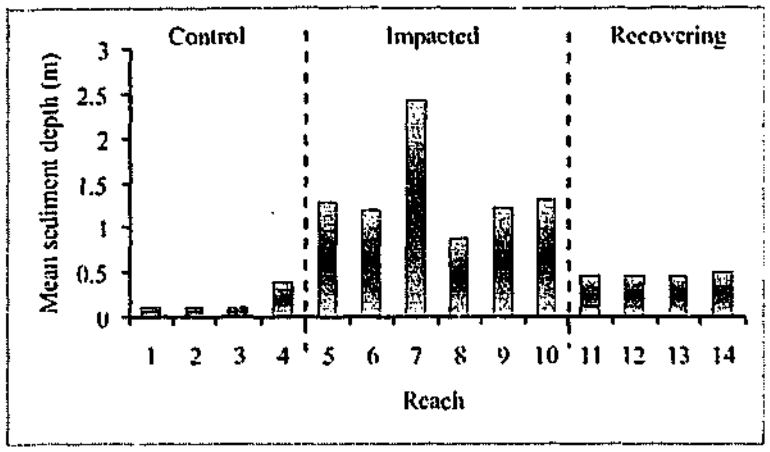


Figure 6.8: Mean sediment depths for each reach along Creightons Creek

6.4.5.2. LWD

As described in Section 5.7.2, LWD is considered to play an important role in forming and maintaining structural complexity in stream systems; hence, the number of pieces of LWD within each reach was counted (Figure 6.9). The greatest amount of LWD was in the lower reaches (1-8) downstream of the Hume Highway. The results of the LWD count will be used further to determine if LWD has a direct affect on the Geomorphic Variability of each reach (Chapter 10).

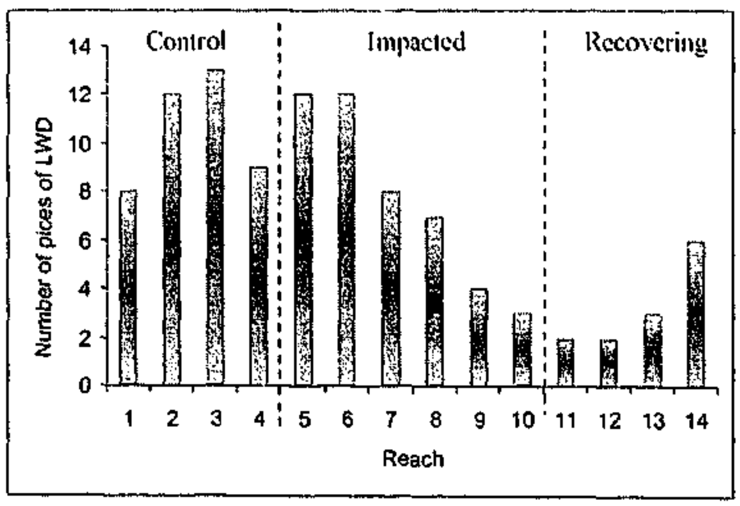


Figure 6.9: Number of pieces of LWD in each reach on Creightons Creek

6.4.6. Summary

It is difficult to make any quantitative estimates of the impact of the sediment slug on Creightons Creek based on these preliminary assessments; further analysis is required, and this is presented in Chapter 8. It is possible, however, to summarise the initial findings on Creightons Creek:

- The thalweg data suggests that there is greater thalweg variability in Reaches 1-4 (control) than in all other reaches;

- There appears to be a slight increase in channel width and a decrease in channel depth as a result of the sediment slug;
- The median grain size is much greater in the impacted and recovering reaches, compared to the control reaches;
- The overall result from the sediment stability analysis was that the sediment slug has increased the rate of sediment entrainment by approximately 12 times (on average);
- The mean sediment depths range from 1.0 m to 2.4 m in the impacted reaches, and the sediment depths have returned to roughly 0.5 m in the recovering reaches;
- There is higher amount of LWD in the lower reaches (1-8).

It appears from this preliminary data analysis that the sediment slug has had an affect on the geomorphic structure of Creightons Creek.

6.5 Wannon River data

The Wannon River has the largest catchment area of the three study streams. The area of concern in this study is the lower 60 km of the Wannon River, near its junction with Bryans Creek (Figure 6.10). The Wannon River was broken up into two impact groups for reasons described in Chapter 4. In the results, Impacted Group 1 and Impacted Group 2 are designated as 'impact 1' and 'impact 2', respectively (Figure 6.10).

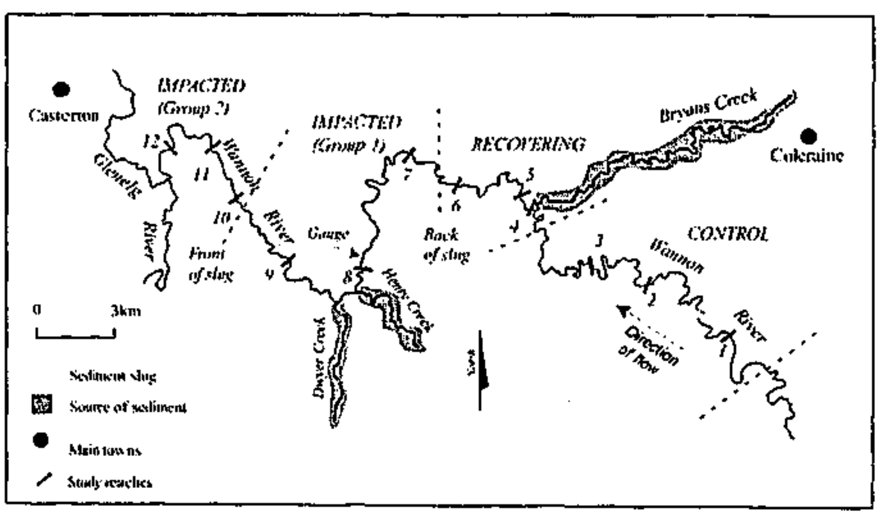


Figure 6.10: Location of study reaches along the Wannon River

6.5.1. Thalweg

Figure 6.11 presents the de-trended thalweg profiles for each reach along the Wannon River; it is difficult to detect any major differences between the thalweg profiles in the different groups. Reaches 4-6 (recovering) and Reaches 10-12 (impact 2) do appear slightly less variable than the control and impacted reaches, but further analysis of the variability of the data (Chapters 7 and 8) will be able to quantify any difference.

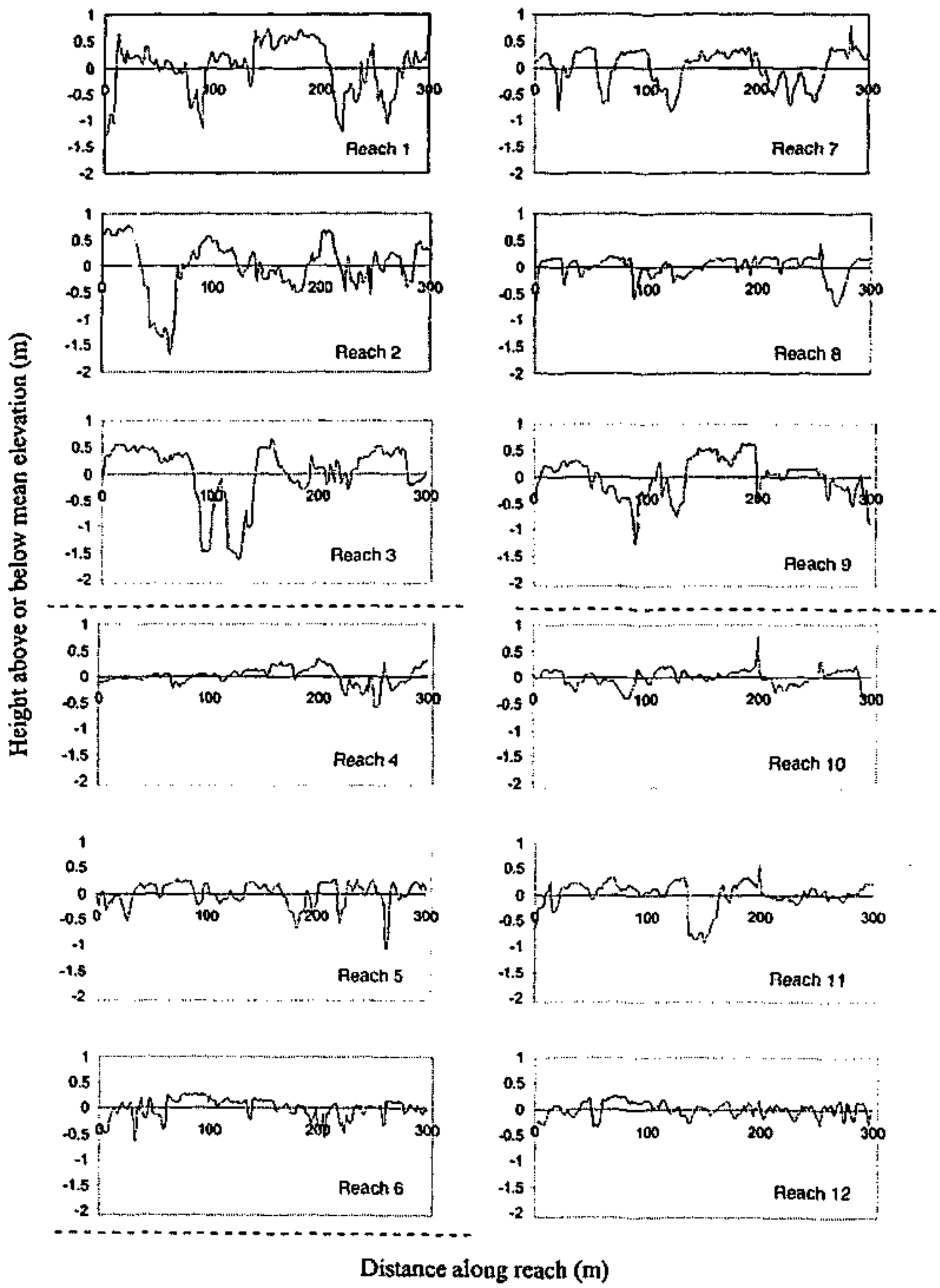


Figure 6.11: Wannon River thalweg plots. The dashed lines separate the different impact zones.

6.5.2. Cross-sectional data

Width and depth data for the 120 cross-sections measured on the Wannon River are presented in Appendix F; there does not appear to be any obvious change in pattern for either width or depth along the Wannon River (Table 6.4 and Figure 6.12). The only pattern is that there seems to be a slight increase in channel widths in the recovering reaches (Reaches 4-6). It is difficult to determine, however, if the differences between widths and depths are actually due to the sediment slug moving through the stream, or simply a function of natural variation. This will be explored further in Chapter 7.

Table 6.4: Mean bankfull widths and depths for the Wannon River

Reach	Average width (m)	Average depth (m)
1	29.7	2.2
2	29.8	5.5
3	30.8	4.1
4	34.4	2.7
5	38.2	3.7
6	36.9	3.8
7	24.6	3.7
8	29.2	4.6
9	33.2	5.4
10	38.9	6.1
11	44.3	6.5
12	38.8	6.6

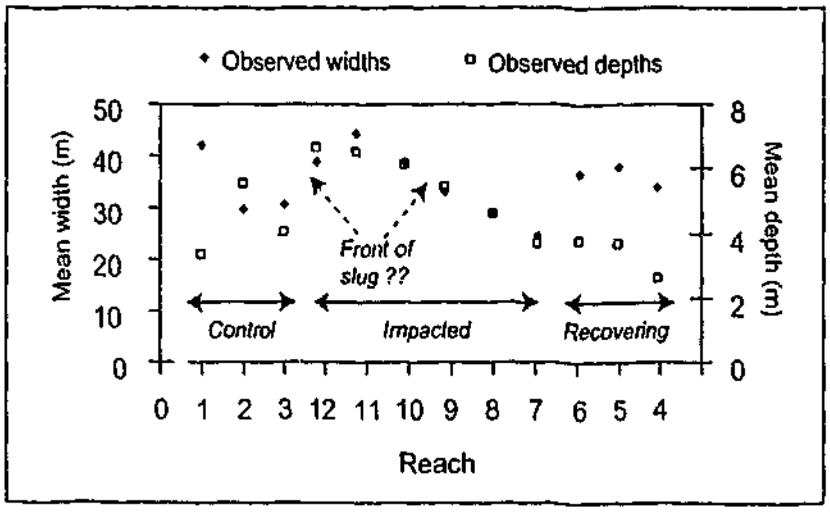


Figure 6.12: Mean widths and depths for Reaches 1-12 on the Wannon River

6.5.3. Sediment size

There were 5 sediment samples collected in each reach (totalling 60 samples); the D_{50} values for each sample are presented in Figure 6.13. It appears that there is a large increase in the median grain size (D_{50}) between the control section and both the impacted and recovering sections, with the biggest difference being between the control and recovering reaches.

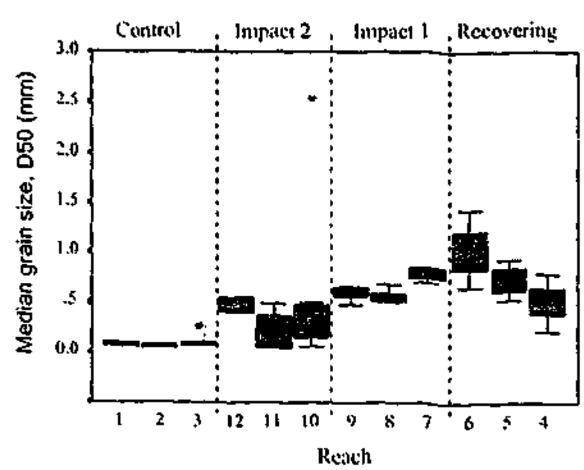


Figure 6.13: Box plot of the median grain size of the 5 samples collected from each reach on the Wannon River.

This is an unusual result, as it was expected that the sediment in the recovering reaches will return to a size similar to that in the control reaches once the sediment slug has evacuated the system. This finding is be investigated further to determine if the change in sediment size down the catchment in a function of the sediment slug or natural conditions (Chapter 7), as well as see if the change in median grain size is also reflected in the variability of the sediments (Chapter 8).

6.5.4. Sediment stability

Sediment stability was calculated according to the methods presented in Section 5.6.4. The results for the Wannon River show that the control reaches (1-3) are stable at least 99% of the time (Table 6.5 and Figure 6.14). In reality, finer sediments in these reaches would move more frequently (eg. the D_{10} or D_{20}); these estimates were based on the D_{50} size. The impacted reaches were stable between 0.4% and 16% of the time, with an exception for Reach 11; this reach is quite different from the other impacted reaches, as the main body of the sediment slug has not yet reached this area. In Reach 11 much of the bed-surface consists of 'river-rock', or consolidated clay sediments that look like bed rock from a distance, but are actually silt/clay sediments that can be broken off into small sections. There are a number of small slug fronts moving through this section (eg. Plate 6.1); however, due to the sediment sampling procedure used, it was mainly the river rock (eg. clay) sections that were sampled. The recovering reaches are slightly more stable than the downstream impacted sections due to the exposure of gravel and clay sediments as the stream begins to incise; these areas are stable between 0.45% and 45% of the time.

Table 6.5: Sediment stability values for the Wannon River

Reach	Discharge (m^3/s) at which sediment is entrained	Number of days flow is exceeded (total of 9686 days in record)	% time that the sediment is stable
1	158	3	99.97
2	141	5	99.95
3	132	6	99.94
4	0.001	9642	0.45
5	0.10	8719	9.98
6	0.721	5297	45.3
7	0.163	8120	16.2
8	0.051	9226	4.75
9	0.002	9642	0.45
10	0.007	9618	0.70
11	168	3	99.9
12	0.050	9246	4.54

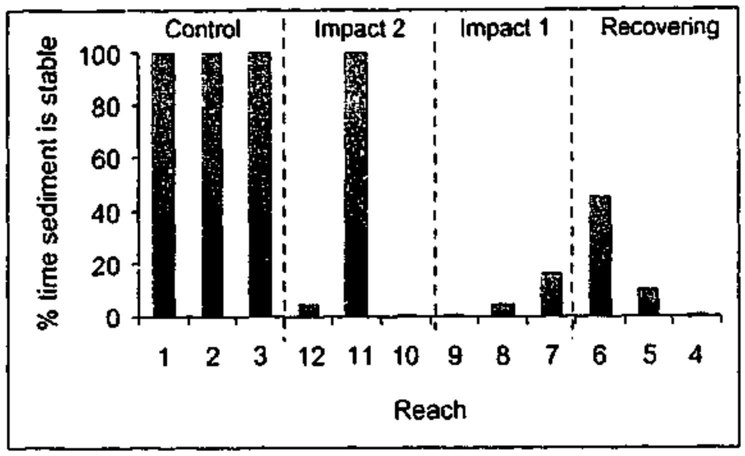


Figure 6.14: % time sediment is stable along the lower Wannon River.

Plate 6.1: Slug fronts moving through Reach 11 on the Wannon River (the water width is roughly 10 m in this photo).

Overall, there is considerable range in the level of sediment stability along the Wannon River, both within and between the different impact groups. The obvious trend, however, is that the sediment slug has reduced the level of sediment stability. On average, sediment stability has decreased approximately ten times (not including Reach 11) between the slugged and non-slugged reaches.

8.1.1. Independent Variables

As described in Chapter 5, there were a number of other data variables collected that did not represent Geomorphic Variability; however, they are considered to be important for understanding the impact and recovery potential of the streams disturbed by sediment slugs. In this section, the sediment depth and LWD are presented for Wannon River.

6.5.5.1. Sediment depth data

Mean sediment depths were measured for each reach along the Wannon River (Figure 6.15). The sediment depths form the general shape of a wave or slug, although the change in depth between the impact and recovering reaches is very gradual. The recovering reaches do appear to have higher than expected sediment depths, however, the depths conform to the definition of a recovering reach presented in Table 5.1 (ie. depth < 1/5 mean bank height and declining). The maximum mean sediment depth along the Wannon River is approximately 1.2 m.

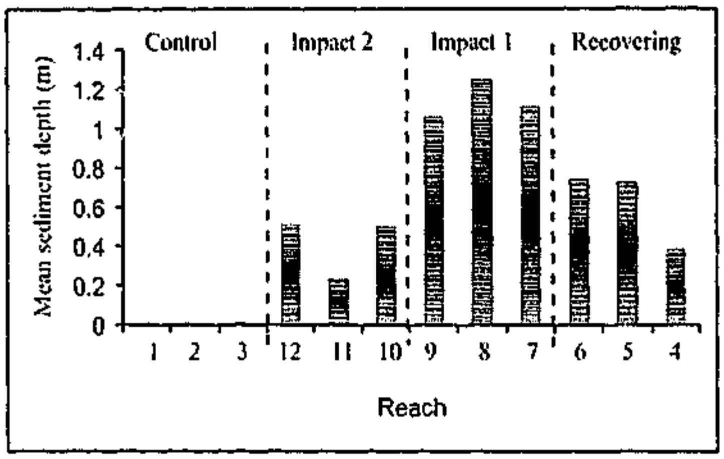


Figure 6.15: Mean sediment depths for each reach along the Wannon River

6.5.5.2. LWD

There is slightly more LWD in the control reaches; however, some of the downstream reaches (eg. Reach 9) also have considerable LWD loadings (Figure 6.16). The LWD data are used further in Chapter 9 to determine if the amount of LWD has a direct affect on the Geomorphic Variability of each reach.

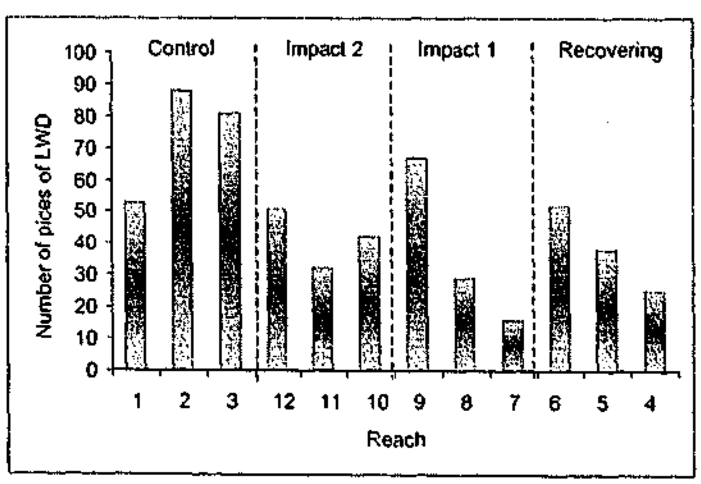


Figure 6.16: Number of pieces of LWD in each reach

6.5.6. Summary

Some of the results from the Wannon River data were not what were expected for a stream impacted by a sediment slug. The main findings for the Wannon River are summarised below:

- The thalweg data did not show any great differences between the different reach types. There appears to be a slight decrease in variability in the recovering and impact 2 groups; however, this assessment was only visual and further quantitative analysis is needed to verify this observation;
- There was no clear pattern in the trends for mean bankfull width and depth along the river; it is possible that any pattern could be confounded by natural variations in width and depth with increasing catchment area;
- There was an increase in the median grain size in both the impacted and recovering reaches when compared to the control sites, with the biggest difference being between the control and recovering reaches;
- There is a large difference in the sediment stability between the control section and all reaches along the Wannon (with exception of Reach 11). On average there is a 10 fold decrease in the sediment stability in the impacted and recovering reaches compared to the control sites;
- In the impact 1 group the sediment depths range from 1.0 - 1.2 m, and in the recovering section the sediment depths are between 0.4 and 0.75 m and are declining;
- There is a slightly higher number of pieces of LWD in the control reaches, although all other areas contained substantial quantities of LWD.

It appears from this preliminary data analysis that the sediment slug has had a mixed range of impacts for most of the variables collected. Further analysis, to determine if the sediment slug is actually the cause of the deviation in geomorphic conditions is carried out in Chapter 7. It is also necessary to determine if the change in mean conditions is analogous to a change in the Geomorphic Variability of the Wannon River.

6.6 *Ringarooma River data*

The Ringarooma has the second largest catchment of the three study sites and is by far the most impacted, with an estimated 40 million m^3 of sediment forming the sediment slug. Figure 6.17 shows the location of the ten study reaches.

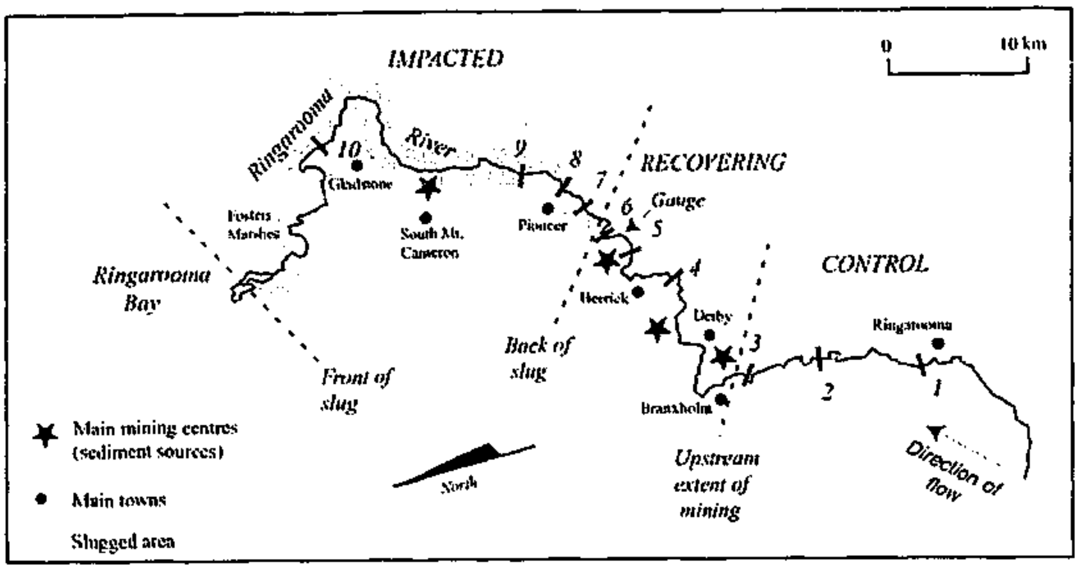


Figure 6.17: The distribution of study reaches along the Ringarooma River

6.6.1. Thalweg

The de-trended thalweg profiles for the Ringarooma River are presented in Figure 6.18. The dashed lines separate the control, recovering and impacted reaches.

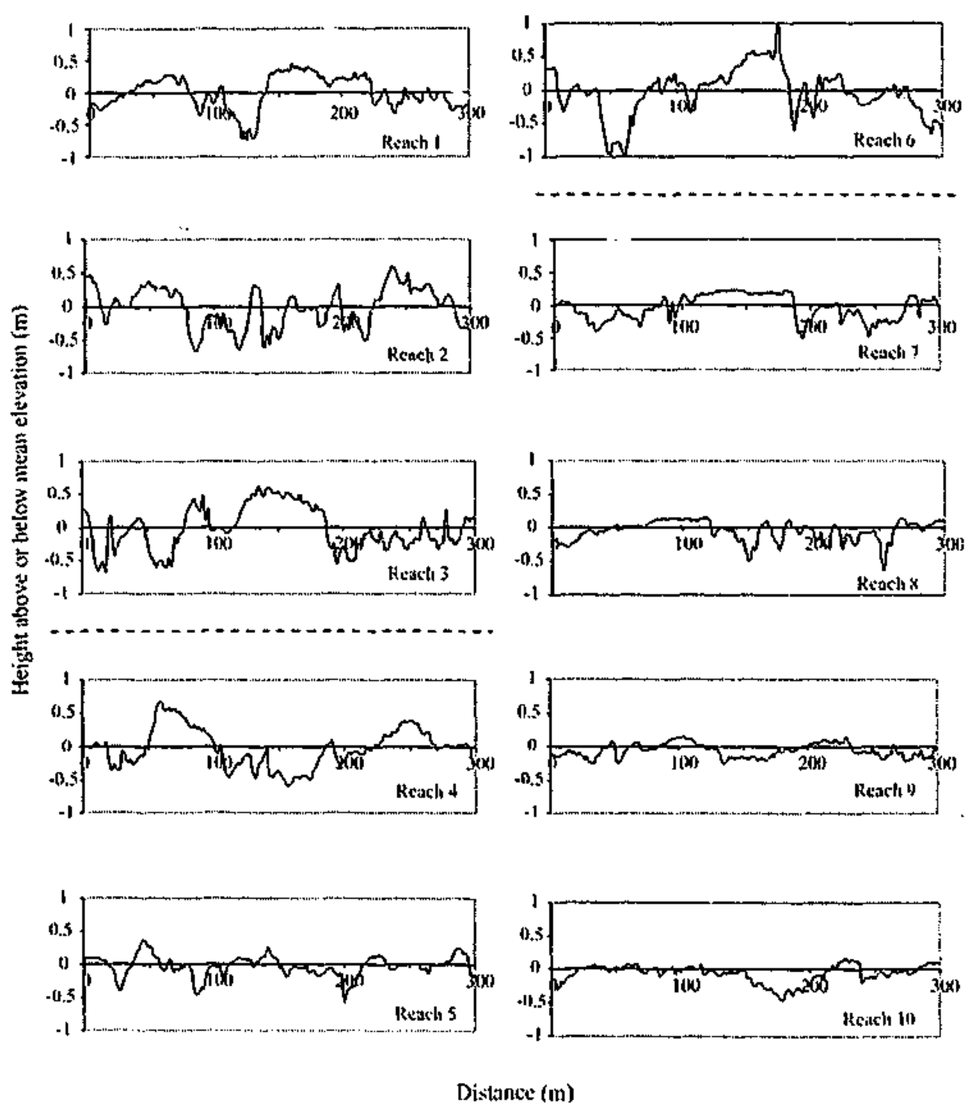


Figure 6.18: Thalweg profiles for the Ringarooma River. The dashed lines separate the different impact groups.

Visual inspection does not show any major difference in the profiles collected from both the control (1-3) and recovering reaches (4-6). There does, however, appear to be a slight decrease in variability and amplitude of the profile in the impacted reaches (7-10). The impacted reaches appear more 'flattened out' than the other profiles and may suggests a decline in thalweg variability in the areas impacted by the sediment slug. This will be investigated further in Chapter 8.

6.6.2. Cross-sectional data

The width and depth data for the 100 cross-sections collected on the Ringarooma River are given in Appendix G; average width and depth values for each reach are presented in Table 6.6 and Figure 6.19. As with the Wannon River, there is no obvious trend in the mean bankfull widths and depths along the Ringarooma River. It appears that there is a slight increase in both width and depth between the control and impacted reaches; however, this is likely to be a function of increasing catchment area and discharge in the downstream impacted reaches. The recovering reaches also appear to be adjusting to the evacuation of sediment from the area and further analysis of the data is required to assess the cause of the variation.

Table 6.6: Reach averaged 'observed' bankfull widths and depths for the Ringarooma River

Reach	Average width (m)	Average depth (m)
1	16.55	1.28
2	23.30	1.77
3	32.20	2.16
4	46.95	2.86
5	29.95	1.90
6	58.05	3.17
7	43.90	2.17
8	61.00	2.36
9	57.40	2.65
10	45.95	2.16

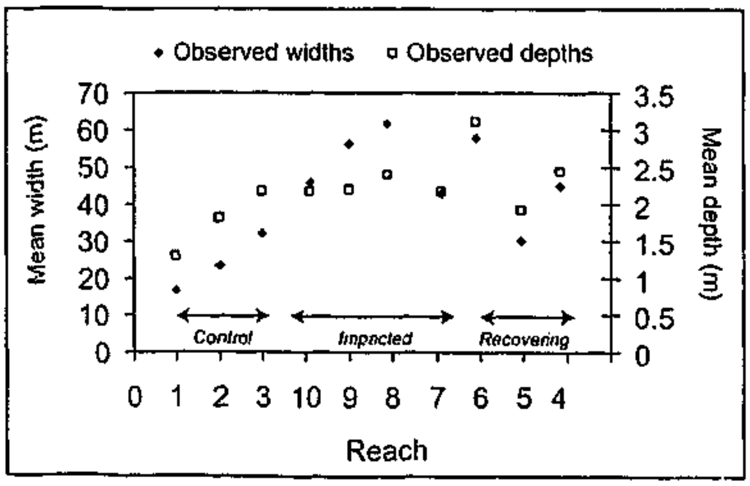


Figure 6.19: Mean widths and depths for Reaches 1-10 on the Ringarooma River

Secondary analysis using both the observed and expected data

As described in Section 5.5.5.4, the Ringarooma River data underwent a second analysis of its cross-sections using the hydraulic geometry equations developed by Knighton (1987b). In this analysis, Knighton's hydraulic geometry estimates for north east Tasmania were used to calculate the 'expected' bankfull conditions. The current conditions sampled in the year 2000 and presented in Table 6.6 and Figure 6.19 were used as the 'observed' conditions. The assumption in this analysis is the 'expected' values represent the pre-slug condition. Comparisons of the observed and expected widths and depths are presented in Figure 6.20 and Figure 6.21, respectively.

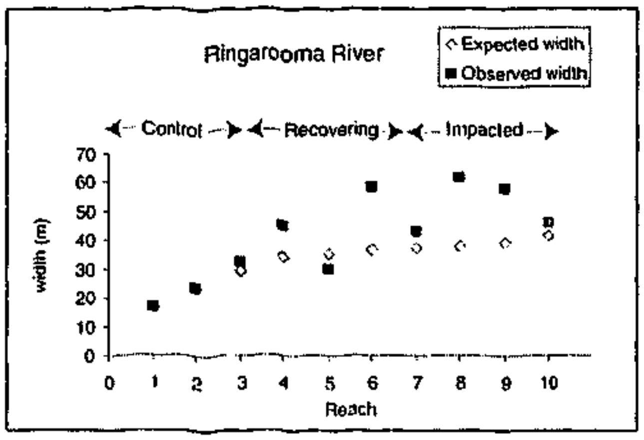


Figure 6.20: Comparison of observed versus expected bankfull widths for the Ringarooma River

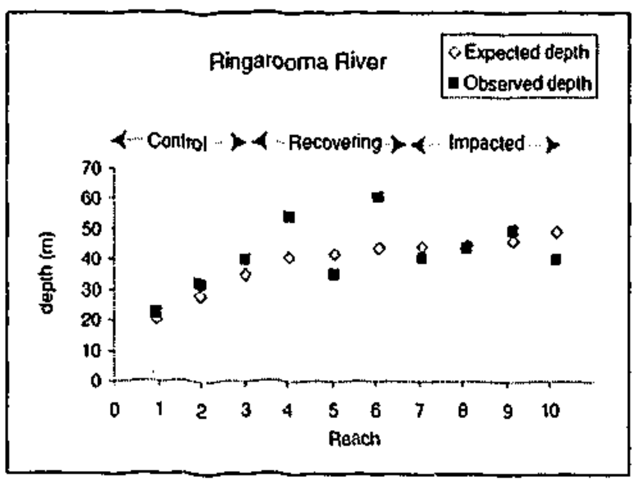


Figure 6.21: Comparison of observed versus expected bankfull depths for the Ringarooma River

These results suggest that the channel widths have been more affected by disturbance than bankfull depths. Widths have been increased by between 10%-65% in both the recovering and impacted reaches, with Reach 8 having the greatest width increase of 65%. Even in the recovering reaches, only Reach 5 has returned to near pre-disturbance widths. This is possibly only due to its confined position within a narrow valley. Knighton (1987a) estimated that there had been up to a 300% increase in width in the area around South

Mount Cameron (between Reaches 9 and 10). This was estimated by analysing aerial photos between 1952 and 1982.

The bankfull depths did not show as much difference as the width, although this could be because depths were measured to correspond to the observed widths. If pre-disturbance data was available, the bankfull depths would be much shallower today than they were prior to disturbance.

6.6.3. Sediment size

The sediment sampling procedure for the Ringarooma River was slightly different from the previous two sites due to the large size of the bed sediments in the control and recovering reaches (see Section 5.6.2). The median grain size was calculated for each reach along the river, but because the sampling strategy was different from the other streams, only the reach median is plotted in Figure 6.22 (rather than the median for all samples collected in each reach).

Figure 6.22 shows that there are large differences in the median grain size between both the control and recovering reaches, and the impacted section. The sediment slug appears to have reduced the grain size dramatically, changing it from a gravel and bed-rock controlled stream to a sand dominated bed. The similarity of the D_{50} values in the control and recovering reaches should also be noted.

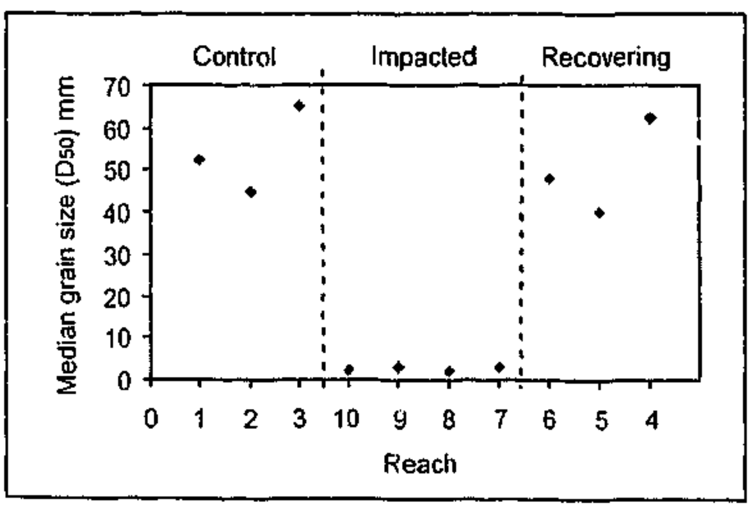


Figure 6.22: Median grain size (D_{50}) for each reach along the Ringarooma River

6.6.4. Sediment stability

Sediment stability was estimated using the Shield's critical shear stress approach as described in Section 5.6.4. The results of the analysis for the Ringarooma River are given in Table 6.7 and Figure 6.23. In addition to calculating the sediment stability, an armouring index value was calculated for Reaches 1-6; results are given in Table 6.8.

Table 6.7: Sediment stability data for the Ringarooma River

Reach	Discharge (m^3/s) at which sediment is entrained	Number of days flow is exceeded (total of 8884 days in record)	% time that the sediment is stable
1	47.9	30	99.7
2	72.9	6	99.9
3	403	0	100
4	1029	0	100
5	70.4	6	99.9
6	143	0	100
7	0.31	8340	6.1
8	0.45	8303	6.5
9	0.67	8250	7.1
10	0.01	8340	6.1

The results of the sediment stability analysis were slightly different for the Ringarooma River, when compared with the other sites. This is because Reaches 1-6 all have a large gravel content, with Reaches 1-6 being well armoured in places (Table 6.8) and unlike, the previous streams, there are no clay sediments. Hence, the critical shear stress required to entrain the D_{50} was much greater for the gravel reaches than for the downstream sandy reaches.

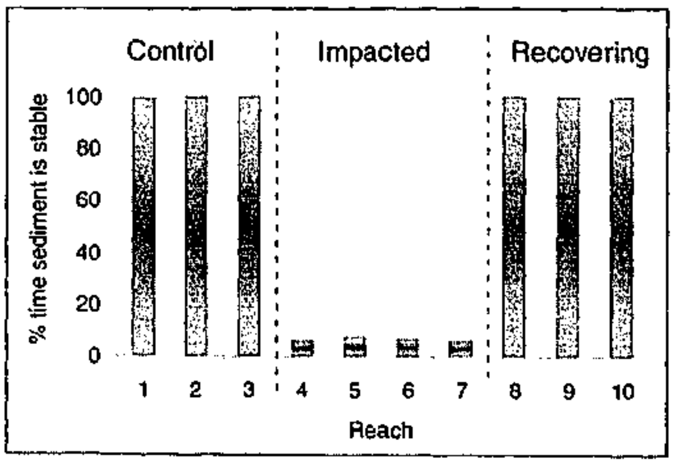


Figure 6.23: % time sediment is stable within each reach on the Ringarooma River

Both the control reaches (1-3) and recovering reaches (4-6) are stable almost 100% of time, based on minimum daily flows (Figure 6.23). This is roughly 15 times more stable than the impacted reaches. In major flood events, however, it is expected that the armoured layer in many of these reaches would be mobilised, and the finer grained sediments entrained (Plate 6.2). Table 6.8 describes the level of armour present in each of the less disturbed reaches.

Table 6.8: Index of the armour strength (A) for Reaches 1-6 on the Ringarooma River

Reach	Armour strength
1	20.65
2	17.62
3	17
4	24.34
5	13.07
6	24.8

Figure 6.23 suggests that the sediment movement in the severely impacted reaches is fairly constant. The continual movement of the sand sized sediment, in the form of small 'waves' or 'dunes', was observed during data collection in the downstream reaches (7-10) (Plate 6.3). In reality, there is still a considerable amount of sandy material on top of the gravel armour layers, particularly in Reaches 4-6. This finer sediment has come from the re-working of upstream tailings deposits (eg. benches). These smaller sediments (drapes) would be mobilised more frequently than the larger gravels.

Plate 6.2: Armoured gravel bar at Reach 3 showing the finer sediments underneath the coarse gravel layer; 30 cm ruler is used as the scale.

Plate 6.3: Small waves or dunes of sediment continually moving over the bed in all of the severely impacted reaches (photo taken at Reach 7).

Overall, the data show that the recovering reaches (4-6) have re-established their coarse bed surface and, in most cases, their armouring; this has increased the stability of the bed sediments. The downstream impacted reaches may, with time, recover to previous levels of sediment stability, as the finer sediments are winnowed away leaving the original gravel substrate.

6.6.5. Independent Variables

As described in Chapter 5, there were a number of other data variables collected that did not represent Geomorphic Variability; these are considered important for understanding the impact and recovery potential of the streams disturbed by sediment slugs. In this section, the sediment depth and LWD are presented for Ringarooma River.

6.6.5.1. Sediment depth data

The most downstream reach (Reach 10) has the greatest mean depth with sediment depths declining gradually upstream to Reach 7; there is rapid decline in depths between Reach 6 and 7 (Figure 6.24). The zone between Reach 6 and 7 was described as the 'gravel-sand transitional zone' by Knighton (1999), due to the sharp change in sediment size; the transition could also be attributed to a sharp change in sediment depth.

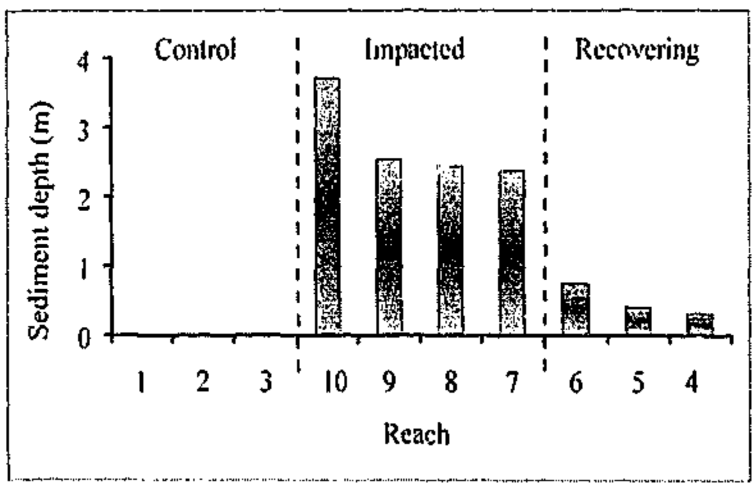


Figure 6.24: Average sediment depths (tailings/sand) for each reach along the Ringarooma River

It is not possible to accurately quantify the maximum mean sediment depths within each reach, particularly for Reaches 8, 9 and 10. This is because the maximum depth of the sediment probe used was only six metres. Previous depth measurements made at bridge sections, and cited in Knighton (1991), suggest maximum depths of up to 13 m at Bell's Bridge (Reach 10); no average sediment depths were given [and it is not certain how these estimates were made]. It is also important to note that the depths presented in Figure 6.24 are cross-sectional averages, not maximum depths. As there can be considerable error using sediment probing techniques, it is expected that the true depth values (particularly for Reach 10) are somewhere between the values in Figure 6.24, and those cited in Knighton (1989; 1991).

8.1.1.1. LWD

The number of pieces of LWD within each reach were counted (Figure 6.25). The figure shows that LWD is quite evenly spread along the length of the Ringarooma River. In many of the downstream reaches (Reaches 6-9), the main source of LWD is old tree stumps that are being re-exposed as the sediment evacuates the stream (eg. Reach 8 - Plate 6.4). The results of the LWD will be used further (Chapter 10) to determine if the amount of LWD has a direct affect on the Geomorphic Variability of each reach.

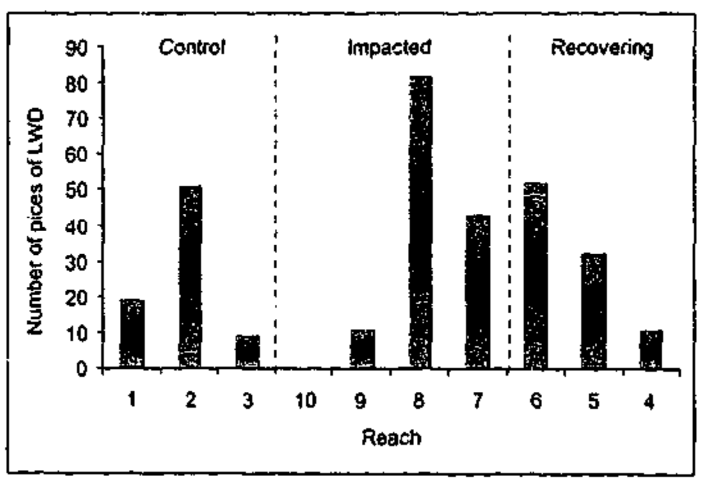


Figure 6.25: Number of pieces of LWD found in each reach on the Ringarooma River

Plate 6.4: The re-exposed trees in Reach 8 result in the high LWD count.

6.6.6. Summary

The initial field data for the Ringarooma River showed a variety of responses to the sediment slug impact, as summarised below:

- There was little detectable difference between the thalweg profiles of the control and recovering reaches. There was, however, a slight decline in thalweg variability in the impacted reaches (compared to the control and recovering sites);
- It was difficult to detect any change in the cross-sectional mean widths and depths; any slight change between the different impact groups could be attributable to an increase in catchment area with distance downstream as much as it could be a result of the sediment slug. Further analysis is required to determine the cause of any differences between reaches.
- Assessment of the observed and expected values for channel widths and depths showed that the widths have been more affected by the disturbance than depths, with widths increasing between 10-65% in the sampled reaches;
- There were dramatic differences in the D_{50} between the control and impacted reaches; however, there was little difference in the median grain size between the control and recovering sites;
- The changes in sediment stability along the Ringarooma seem to follow the same pattern as for median grain size, with much lower levels of sediment stability in the impacted areas compared to both the control and recovering reaches. The high armour strength of the control and recovering reaches were also shown to influence the sediment stability in these areas;
- The mean sediment depths in the impacted reaches of the Ringarooma River range from 2.4 m to >3.7 m, although depths of up to 13 m have been reported (see Knighton, 1991); in the recovering sections, depths are between 0.3 m and 0.75 m;
- There is no simple pattern to the distribution of LWD for the Ringarooma River, although Reach 8 has the greatest density of LWD.

6.7 *Discussion*

Four main variables were considered important for characterising the Geomorphic Variability of streams (thalweg, cross-sections, sediment size and sediment stability). Two others, sediment depth and the amount of LWD, are also considered important, as they are expected to influence the recovery process in streams disturbed by sediment slugs. This chapter presented the data from the field collection for each of the six variables.

It is important to note that only the mean condition, rather than the variability of each of the factors was presented in this chapter. Nonetheless, the data gave an important insight into how the different geomorphic elements respond to sediment slug impact, with each of the three study streams responding in slightly different ways following disturbance.

For many of the data presented in this chapter, it was difficult to determine if the differences between the reach types were actually the result of the sediment slug, or a product of natural variation due to factors such as increasing catchment area and discharge. This observation suggests that it is not appropriate to evaluate the response of each stream in the spatial dimension alone, (ie. using space for time substitution); the data need to be assessed with respect to their position in the catchment, so that the impact and recovery response can be scaled accordingly.

The next chapter (Chapter 7) presents a variety of methods for assessing the response of each stream with respect to its position along the stream, to provide a clearer indication of the true impact of the sediment slug on each river.

Chapter 7

Using scale to assess the impact of a sediment slug with respect to its position within the catchment

7. Chapter 7 - Using scale to assess the impact of a sediment slug with respect to its position within the catchment

7.1 Introduction

Chapter 5 discussed the theoretical and practical considerations relating to the collection of field data. The data collection was focused specifically towards the four factors that describe Geomorphic Variability: the thalweg, cross-sections, sediment size and sediment stability. Chapter 6 then presented the results of the field data collection for these variables for the three study streams.

The results in Chapter 6 were presented separately for each stream, and the data was presented according to the Geomorphic Recovery Model with the results divided into control, impacted and recovering reaches. Presenting the results in this manner essentially showed how the data changed through space, assuming the principles of ergodic theory, however, ignoring the factors of changing scale.

It is acknowledged, however, that there will be spatial differences in each variable (along a river), even without disturbance; this is due to differing catchment area and discharge. Therefore, it is important to assess the data and evaluate if any variation between the control, impact and recovering sites is due to the presence of the sediment slug, or simply a function of natural variation. Being able to identify when a reach is significantly different from the natural conditions expected at that point will enable the Geomorphic Recovery Model presented in Chapter 3 to be evaluated with more certainty. It is also important to have an estimate of the scale of the sediment slug impact with respect to channel size, as the size of the stream will affect the way in which it responds to sediment slug impact. Thus, this chapter highlights that it is no longer sufficient to employ the principles of ergodicy without consideration of changing spatial scales along a stream. This chapter presents a range of data analysis procedures for evaluating the effect of scale of the level of Geomorphic Variability.

This chapter can be broken into two main sections. The first part of the chapter presents a range of techniques for evaluating the response of the thalweg, cross-sections and sediment size assuming there had been no disturbance (Sections 7.2.2, 7.2.3 and 7.2.4, respectively). The sediment stability data is assessed using a different method and this is discussed in Section 7.2.5. Based on these analyses, it is then possible to determine if the current condition is a function of the sediment slug or natural change. The results for each stream are presented following the data analysis techniques.

The second half of this chapter deals with another aspect of scale: estimating the size of the sediment slug according to the size of the channel. This essentially non-dimensionalises the impact and allows a comparison of the disturbance to be assessed between reaches of varying size (Section 7.3). The results of the sediment scaling analysis are presented for Creightons Creek, the Wannon River and the Ringarooma River, respectively. A summary of the chapter findings is then presented in Section 7.4.

7.2 Determining how the geomorphic structure of a stream changes in the absence of disturbance

7.2.1. Background

Fluvial processes can operate at different scales at various points in the catchment; therefore, it is important to note that different portions of a drainage network may respond differently to a single disturbance (Montgomery and Buffington, 1993). One of the reasons for this is that the geomorphology of river channels varies systematically in the downstream direction (Brussock et al., 1985). Stream channel form changes predictively, producing characteristic patterns of flow, depth and substrate; hence, independent of disturbance, different levels of Geomorphic Variability would be found at different points in the catchment. For example, advocates of the River Continuum Concept (RCC) suggest that the greatest biological and environmental variability will be found in the mid-reaches of streams (Statzner and Higler, 1985; Vannote et al., 1980). Thus, care must be taken when attempting to compare changes that occur in different parts of the catchment.

Numerous studies on the variation of fluvial processes of the successional changes within a catchment have been produced (eg. Hooke, 1977; Leopold *et al.*, 1964; Lewin, 1977; Schumm, 1973; Schumm, 1983), and there are some well accepted relationships. Figure 7.1 shows how four characteristics (stream power, erodibility, sediment transfer and substrate size) vary with distance downstream.

The rate and pathway through which a stream re-develops its Geomorphic Variability following disturbance by sediment slugs will therefore vary depending on which area of the catchment has been disturbed. Thus, it cannot be assumed that the same conditions operate along the entire length of a stream, and as discussed in Chapter 3, the theories of space for time substitution assume that "an infinitely long record at one point has the same statistical properties as a record taken over an infinite number of spatial assemblages at a particular point in time" (Harvey, 1967). As there will naturally be differences in the statistical properties of the geomorphic variables collected at different points in the catchment, then space for time substitution cannot be rigorously applied until the issues of scale have been addressed.

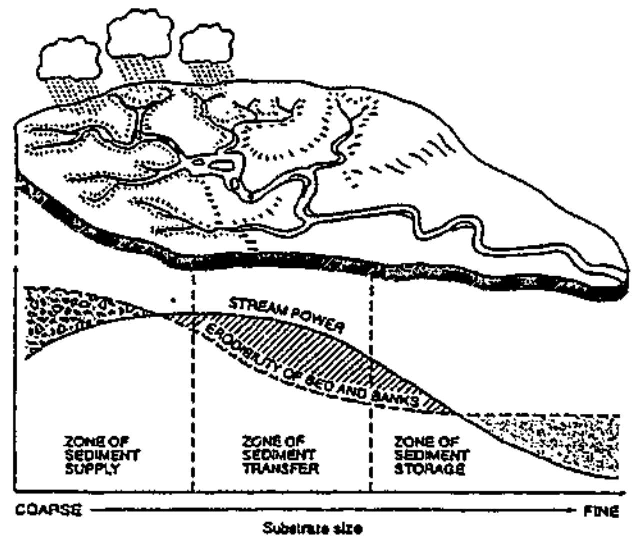


Figure 7.1: Variability in stream power, erodibility, sediment transfer and substrate size with downstream distance (Brookes and Shields, 1996).

<u>Alternative approaches to predicting the pre-disturbance condition</u>

Using space for time substitution means that the 'control' reaches are used to represent the state of the stream prior to disturbance. However, as discussed above, it is acknowledged that there will be differences in the level of variability between the control reaches and both the impacted and recovering reaches even if there had been no disturbance. Therefore it is important to evaluate the level of Geomorphic Variability in a reach, against the geomorphic condition that would be 'expected' to occur at that point in the river (if there had been no disturbance). Using an observed versus expected type approach satisfies the statistical assumptions of ergodic theory.

The most appropriate way to determine what a reach looked like prior to disturbance, would be to have pre-disturbance data. There is no pre-disturbance data for any of the field sites in this study, therefore an alternative method is required. Park (1977) suggests three approaches. The first, and most ideal method, is to monitor change through time, by setting up long term monitoring projects; for many reasons relating to funding and time, this method is often not practical. The second method proposes to use regime theory relationships (eg Schumm, 1969) to estimate the channel changes. This method is, however, dependent on understanding the magnitude and nature of change, which is not always known, and is therefore not applicable in this study. The third method, described by Park (1977), uses 'spatial interpolation', in which the well-accepted relationship between discharge (or catchment area as a surrogate) and certain morphometric features eg. width, depth, slope, sinuosity, can be predicted for various points along the stream (eg. Figure 7.1)

The following sections outline the application of the spatial interpolation approach to the three of the main variables that form Geomorphic Variability: the thalweg, cross-sections and sediment size. Spatial interpolation techniques are used to estimate the expected condition in each stream had there been no disturbance. These values are then compared to the true values measured in the field. The expected and observed values can then be compared to determine if the streams have altered in response to the sediment slug, or whether they are naturally different. Statistical and/or empirical techniques will be used to determine which reaches have been altered by the sediment slug (eg. when there is a significant difference at the 95% confidence limit). Estimating the pre-disturbance condition involved different analysis techniques for each data set, as summarised in the following sections.

7.2.2. Changes in thalweg characteristics down a catchment

This section investigates how the longitudinal bed profile (thalweg) changes with distance downstream. To do this, it is important to be able to identify a bed form feature that can be scaled between different parts of the catchment. As discussed in Chapter 5, the dominant longitudinal macro-bedforms present in the thalweg are pools and riffles. Although these are not the only bed-forms of interest in this study (as the total topographic variability of the thalweg is important), they are the most suitable feature for determining how bedforms change with distance downstream. This section attempts to derive a technique for estimating the pre-disturbance or 'expected' pool-riffle morphology or more specifically, mean pool depth (relative to pool-riffle amplitude) (see Figure 7.2).

<u>Calculating mean pool depth using catchment scale characteristics</u>

Considerable research has been carried out as to how pool characteristics alter in different parts of the catchment. Much of this research describes how pool depths change with the relative radius of meander bend curvature (eg. Apmann, 1972; Hey and Thorne, 1987; Konditerova and Popov, 1966; Thorne, 1992), with little or no attention being paid to the relationship between amplitude or mean pool depth with increasing discharge or catchment area.

Wohl *et al.* (1993) conducted a study on three gravel-bed streams in Northern California, to determine if the depth of pools (relative to the depth of riffles and runs) change with gradient downstream; 'gradient' in this study is considered as a surrogate for channel erodibility and width. The study showed that the depth of pools, as well as spacing between pools, increases with decreasing stream gradient. This work is of significance when attempting to determine how pool-riffle characteristics change in a downstream direction. Unfortunately, there is no single empirical relationship that can be taken from this study and extrapolated to other sites, as the mean depth ratio of pools and riffles does not change in a systematic fashion with stream gradient. Even if it did, each of the study sites has been disturbed; hence, the local reach gradient has changed from natural conditions.

Hey and Thorne (1987) also derived equations to predict the bankfull mean riffle depth; however, these equations are considered to hold only for gravel bed rivers under specific conditions. It is also acknowledged that gravel bed rivers have different hydraulic geometry to fine grained streams (Hey and Thorne, 1987). Consequently, this relationship was also considered inappropriate for the present study of sediment slugs.

Determining the 'Predicted' pool depth

Since there has been no specific research carried out on how mean pool depth (based on pool-riffle amplitude) changes with increasing catchment area or discharge, an adaptation of existing research relating pool depth to other scalable stream characteristics is required. Four important relationships can be used to estimate how pool depth changes downstream. The first relationship is derived from Carling and Orr (2000), who used thalweg data collected from 32.1 km of the Severn River in England. For that study, the river was divided into three reaches based on channel gradient and channel width. A bathymetric profile of the length of the stream was collected to determine how the pool-riffle sequences varied along the total length of the stream. Some 285 data points were used to provide a relationship which described how pool depth increases with pool length (Equation 7.1).

$$D_P = 0.055\,L_P^{0.71} \qquad r^2 = 0.49 \qquad \text{Equation 7.1}$$

where D_P is mean pool depth (based on pool-riffle amplitude) and L_P is pool length, as defined in Figure 7.2. Values of the co-efficient of determination (r^2) indicate the proportion of the total variance in pool depth that can be explained by pool length. In this case, the $r^2 = 0.49$, suggesting that less than 50% of the variance in pool depth can be attributed to changes in pool length. Other factors, such as the size of bed and bank material and vegetation will also play a significant role of determining pool depth. For example, Thorne (1992) has shown that depths of scour pools on meander bends increase with the erosivity of the outer bank material, and revetted bends are 10-20% deeper than free meanders. Unfortunately, the pools in this study are not confined to meander bends, and the study sites vary considerably in terms of bank material, therefore pool length (Equation 7.1) is a more suitable predictor variable than the erosivity of bank sediments.

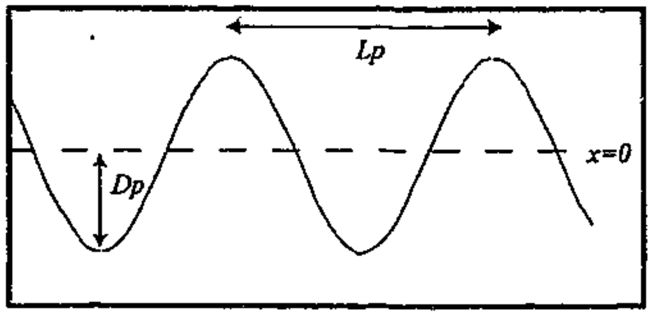


Figure 7.2: Definition of pool-riffle geometry used in this analysis (after Carling and Orr, 2000)

The second important relationship is based on the work by Keller and Melhorn (1978) with data from 251 pools in eleven different streams in the USA; they showed that pool spacing is a function of channel width, and described using Equation 7.2.

$$L_P = 5.42\, w^{1.01} \qquad r^2 = 0.83 \qquad \text{Equation 7.2}$$

where w is channel width, defined as "the width of the bed material" (ie. channel maintenance flow, not necessarily bankfull) (Keller and Melhorn, 1978) and pool length is measured as a multiple of channel widths. This relationship shows that most of the variability in pool length can be attributed to channel width ($r^2 = 0.83$), however, as the width of many streams that have been impacted by sediment slugs has also changed, another equation is required to remove width from the calculations. Thus, the third important equation needed to determine pool depth in a downstream direction is the hydraulic geometry relationship first proposed by Leopold and Maddock (1953). This relationship (discussed previously in Section 5.5.5.4) describes how channel width changes with discharge (Q) (Equation 7.3).

$$w = aQ^b \qquad \text{Equation 7.3}$$

where Q is bankfull discharge (determined from a nominated flood frequency interval), w is channel width at Q, a is the corresponding intercept value at unit discharge and b is the rate of change of the 'dependent' or 'scaling' variable Q.

Using simultaneous equations to relate Equation 7.1, Equation 7.2 and Equation 7.3, it is possible to derive a relationship, described by Equation 7.4, for the 'predicted' pool depth for varying downstream discharges, and therefore distances, downstream.

$$D_P = 0.1826\left(aQ_2{}^b\right)^{0.7171} \qquad \text{Equation 7.4}$$

Q_2 essentially represents the 'scale' factor within the equation, as pool depth is not expected to vary specifically with bankfull discharge. As a fourth and final step, it is therefore appropriate to apply the method used by Park (1977) and adopt drainage area as a measure of spatial location within the catchment as well as a surrogate for discharge. To do this a linear relationship between catchment area and bankfull discharge (Q_2) for each river was determined and used instead of discharge. The Q_2 and associated catchment area for each reach for each control reach was given in Table 6.1.

The relationship between catchment area and discharge is then substituted into Equation 7.4, producing Equation 7.5, Equation 7.6, and Equation 7.7 which represent the relationship between pool depth and distance downstream for Creightons Creek, Wannon River and Ringarooma River respectively.

$$D_{P\text{-Creightons}} = 0.183(0.086C + 2.66)^{0.72} \qquad \text{Equation 7.5}$$

$$D_{P\text{-Wannon}} = 0.183(0.015C + 25.3)^{0.72} \qquad \text{Equation 7.6}$$

$$D_{P\text{-Ringarooma}} = 0.183(0.156C + 18.3)^{0.72} \qquad \text{Equation 7.7}$$

Where C is the catchment area in km^2. To determine if Equation 7.5 - Equation 7.7 are suitable predictors of pool depth with increasing discharge for each stream, they were tested against the ten control reaches (at least three un-impacted reaches from each stream) from each of the study sites.

Defining the 'Observed' pool depth

To calculate the 'observed' pool depth for each reach, a method was required which was essentially independent of channel morphometric relationships, such as channel width and depth. This is important for two reasons, (1) to prevent circular arguments within the analysis and (2) to prevent distortion within the test, due to processes such as channel incision (eg. on Creightons Creek).

To determine the observed pool depth, the 'zero-crossing' method used by Carling and Orr (2000), and first described by Richards (1976), was applied. This is an objective way of determining pool and riffle dimensions, and is carried out by applying regression analysis to the topography of the bed profile. Based on this method, Richards (1976) described pools as areas of negative residuals, and riffles as positive residuals, around a least squares regression line. Hence, the mean pool depth can be represented as the standard error (SE) of the residuals about the thalweg (regression line). This method was criticised by O'Neill and Abrahams (1984), on the grounds that small topographic undulations would be incorrectly identified as pools or riffles; however, it is considered appropriate for this study as only the mean pool depth for each reach, and not absolute pool depths (for individual pools), is being used.

Evaluation of the relationship between the 'predicted' and 'observed' pool depths

A comparison of predicted pool depths determined using Equation 7.5 - Equation 7.7, and the actual observed pool depths, estimated by using the SE of thalweg, is given in Table 7.1 and in Figure 7.3.

Table 7.1: The predicted and observed mean pool depths for each of the control reaches.

River	Reach	Predicted pool Depth (m)	Observed pool depth (m) -
Creightons	1	1.25	0.196
	2	1.24	0.251
	3	1.23	0.308
	4	1.15	0.270
Wannon	1	4.11	0.494
	2	4.15	0.504
	3	4.15	0.564
Ringarooma	1	1.87	0.262
	2	1.89	0.304
	3	1.90	0.332

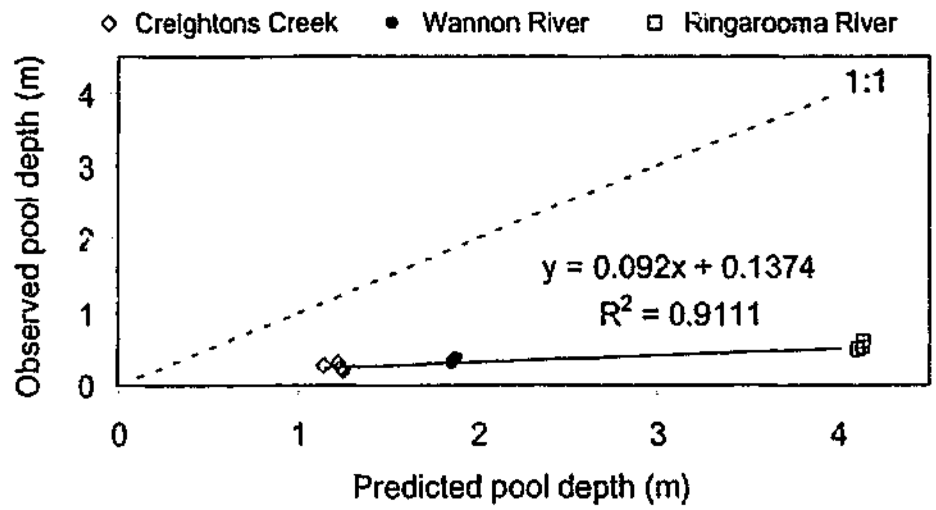


Figure 7.3: Predicted and observed pool depths using the SE method for estimating pool depth for the Control reaches.

The relationship is not directly proportional (ie. not a 1:1 relationship), probably due to the varying and inconsistent definitions of bankfull used by other authors to develop Equation 7.1, Equation 7.2, and Equation 7.3 (eg. Keller and Melhorn, 1978). Without access to bankfull conditions (if they were recorded) of each of data sets used to develop Equation 7.4, it is difficult to determine the role that bankfull played in the scale difference in this analysis. Nonetheless, the high correlation (r^2 =0.91) between the two variables means that it is possible to use this relationship to calibrate the data and determine the true 'expected' value of pool depth. Hence, Equation 7.8 can be used to derive the true expected pool depth to within 10% of the mean on the Wannon River, 20% on the Ringarooma River and 30% on Creightons Creek. Figure 7.4 shows the 'observed' and 'expected' mean pool depths for each reach on each stream.

$$D_{Exp} = 0.092D_{Pred} + 0.1374 \qquad (r^2 = 0.91) \qquad \text{Equation 7.8}$$

To determine if there was a significant difference (at the 95% significance level) between the observed and expected values in each of the control, impacted and recovering reaches, a Kruskal-Wallis Test (one-way between groups ANOVA, using Tukey's post-hoc comparison) was conducted using SPSS Version 10.0 (1999). The reaches that are represented by a filled-in black square in Figure 7.5 have significantly different observed and expected values, and the exact values are presented in Table 7.2.

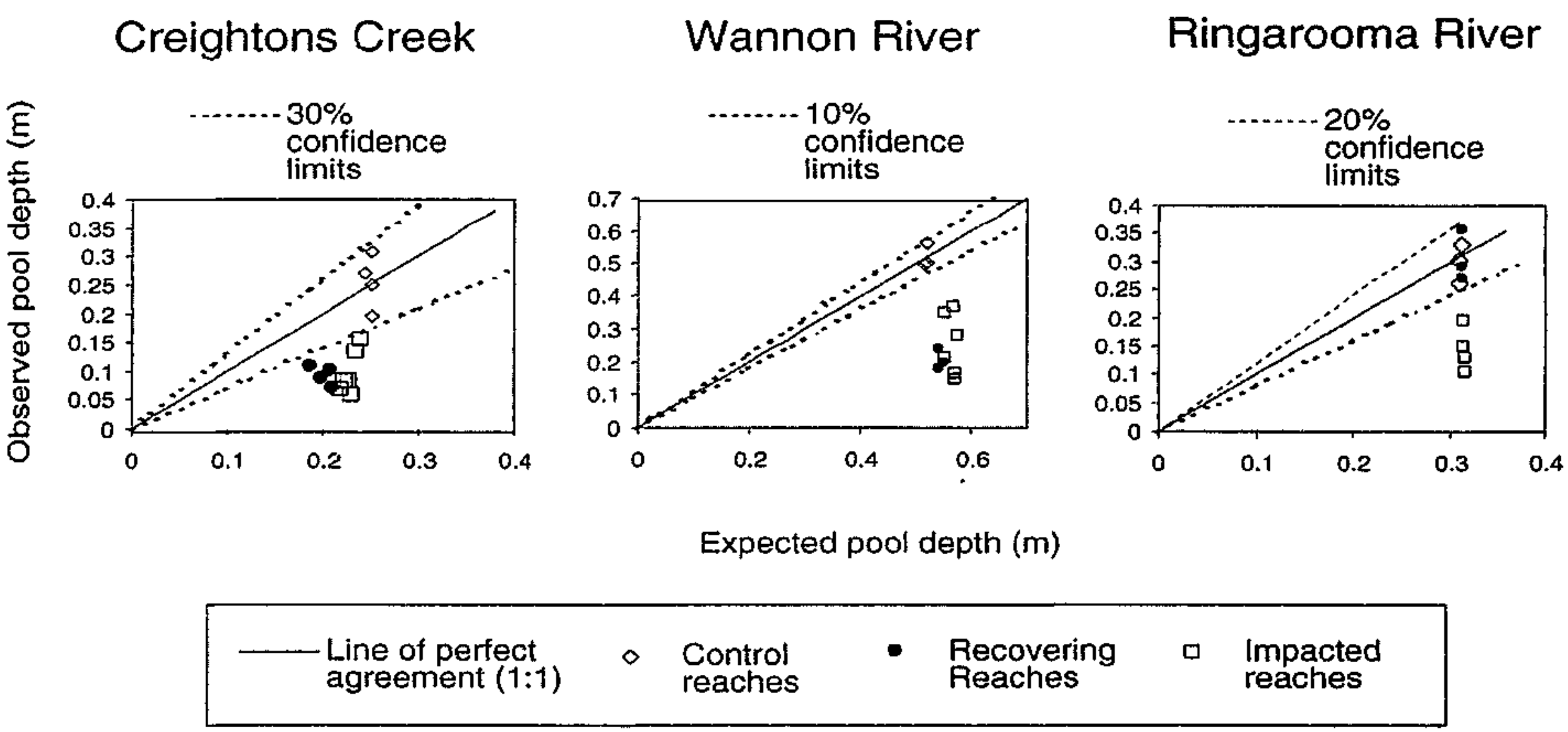


Figure 7.4: The confidence limits and position of each reach with respect to predicted pool depth.

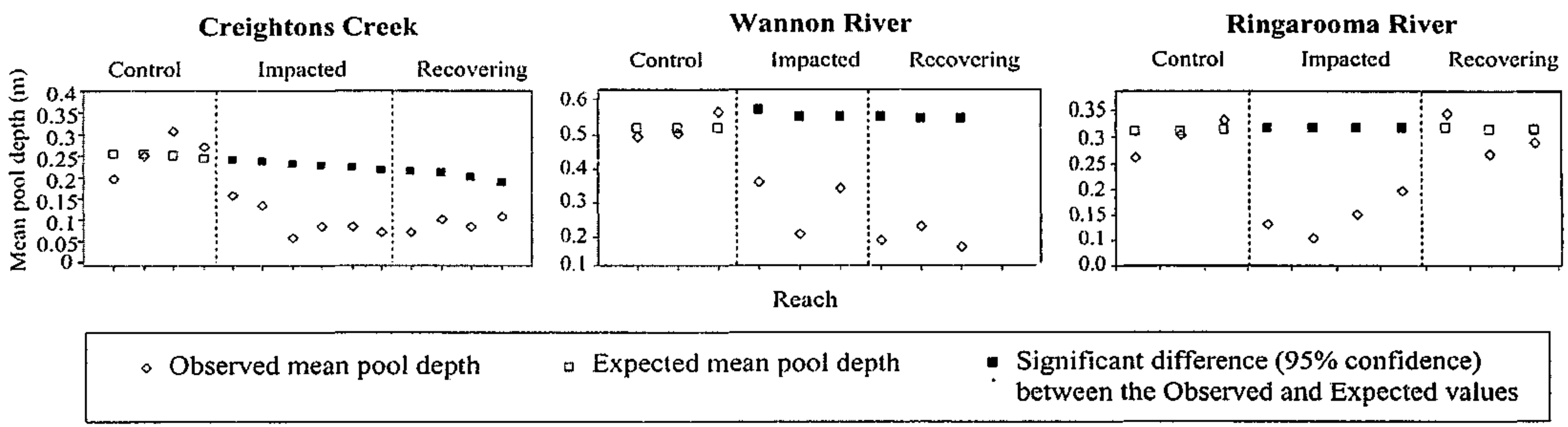


Figure 7.5: The observed and expected pool depths for each reach along each river

Table 7.2: Expected and observed pool depth values for each field site

	Creighton's Creek			Wannon River			Ringarooma River		
Reach	Exp	Obs	Reach	Exp	Obs	Reach	Exp	Obs	Reach
1	0.252	0.196	C	0.516	0.494	C	0.309	0.262	C
2	0.252	0.251	C	0.519	0.504	C	0.311	0.304	C
3	0.251	0.308	C	0.519	0.564	C	0.313	0.332	C
4	0.243	0.270	C	0.545	0.172	R*	0.314	0.290	R
5	0.240	0.155	I *	0.546	0.231	R*	0.315	0.268	R
6	0.235	0.133	I *	0.550	0.189	R*	0.315	0.355	R
7	0.230	0.057	I *	0.551	0.345	I*	0.316	0.194	I*
8	0.227	0.083	I *	0.552	0.209	I*	0.316	0.150	I*
9	0.224	0.083	I *	0.567	0.363	I*	0.316	0.103	I*
10	0.218	0.070	I *	0.567	0.166	I*	0.317	0.130	I*
11	0.213	0.070	R *	0.568	0.282	I*			
12	0.209	0.099	R *	0.570	0.142	I*			
13	0.200	0.085	R *						
14	0.188	0.106	R *						

C = control reach, I = impacted reach, R = recovering reach

*shows that there is a significant difference between the expected and observed values at the 95% confidence level.

Discussion

Figure 7.5 shows that there is a significant difference between the observed and expected values in the impacted reaches for each of the three streams. This suggests that the sediment slug has had a major impact on reducing mean pool depths along each of the streams. On Creightons Creek and the Wannon River, there is also a significant difference between the observed and expected values in the recovering reaches. This is not the case on the Ringarooma River where the recovering reaches appear to have mean pool depths similar to what would have occurred prior to disturbance. This analysis has shown that the sediment slug, rather than simply natural variation, has altered the mean pool depth, and thus, the thalweg, along each of the three streams.

Summary

The method described above predicts the mean pool depths for the un-disturbed reaches well (r^2 = 0.91), and is therefore considered an appropriate predictor of how 'expected' mean pool depths change with increasing catchment area. It is acknowledged that this method is crude, using simplified relationships between catchment area and discharge, excluding the effects of factors such channel slope, sediment size, channel roughness (including vegetation effects) and sediment transport, all of which are considered to have an important effect on pool depth. Nonetheless, in the absence of existing direct empirical analysis, this method is considered appropriate for estimating downstream changes in mean pool depth. It is encouraging that a large scale catchment characteristic such as catchment area, is one of the variables used to help predict pool depth. Other recent studies such as

Davies *et al.* (2000) have shown that large scale catchment characteristics are suitable predictors of small-scale aquatic habitat features.

Implications of these results for assessing the impact of the sediment slug

The main objective of this analysis was to determine if the differences in thalweg variability along each stream were the result of natural variation, or due to the sediment slug impact. In this analysis, the standard error of the thalweg elevations were used as a measure of mean pool depth (as a surrogate for the thalweg). The results of the analysis showed that the sediment slug had actually made a significant change to the thalweg profiles in each of the three streams. Thus, if the variability of the thalweg profiles can be quantified, then it is possible to assume that any significant differences measured between reaches will also be a function of the sediment slug and not a result of natural variation.

7.2.3. Changes in cross-sectional characteristics down a stream

One of the aims of this study is to determine whether sediment slugs reduce the cross-sectional variability of a channel. The concept of variability, in relation to habitat, has surfaced as an increasing research interest in geomorphology and hydraulics (eg Palmer and Poff, 1997; Western *et al.*, 1997). Historically, cross-sectional variability has been seen as a nuisance creating scatter in empirical equations. Therefore, there are no quantitative methods available to predict cross-sectional variability in the absence of disturbance. Without a suitable predictor for cross-sectional variability, a surrogate measure is required that also describes cross-sectional form.

This study uses the Co-efficient of Variation (CoV) of bankfull width and depth to determine if the cross-sectional shape has been altered. The CoV can be expressed using Equation 7.9. Mean width and depth data from the ten cross-sections in each reach are used to determine the CoV value for each reach. CoV is more appropriate than standard deviation or variance, as it presents a unitless measure of dispersion, allowing comparison between reaches that have naturally different morphologies.

$$CoV = \frac{\sigma}{\mu}.100\% \qquad \text{Equation 7.9}$$

where, σ is the standard deviation of depth or width for each reach, and μ is the mean. The main assumption for this analysis is that, given that no disturbance had occurred, there should be no significant difference in the CoV of width, or depth, between reaches on a stream. If there is a significant difference between the CoV for any of the experimental groups, this would show that the change in morphological condition between the reaches is a likely to be a result of the sediment slug and not simply natural variation.

Statistical analysis

The two main objectives for the cross-sectional analysis were to determine:

a) if there was a significant difference in the CoV for width and depth between the control and impacted reaches; and
b) if there was a significant difference in the CoV for width and depth between the control and recovering reaches.

It is not of any interest at this stage to look at differences between the impacted and recovering groups; this is dealt with in Chapter 9. For each reach on each stream, the width and depth data from the ten cross-sections collapsed down to a single measure of the CoV. To determine if there was any significant difference, an independent groups t-test was carried out between the control and impact groups and the control and recovering groups. A Kolmogorov-Smirnov test for normality was carried out on all the data prior to the t-test analysis. All the data were normally distributed, so there was no need for transformation. The significance level was different for each stream, as described below. In each of the following analyses, the reaches have been grouped into control, impacted and recovering reach types.

Creightons Creek

The results of the t-tests suggest that there is no significant difference ($p<0.05$) between the variation in cross-sectional width between the three impact groups along Creightons Creek (Figure 7.6). Despite there being no significant difference, there does appear to be an increase in width variability in the recovering reaches. This would be caused by the incision process in the headwater reaches and not necessarily related directly to the sediment slug (discussed further in Chapters 9 and 10). There was, however, a significant difference in the CoV for the cross-sectional depths between the three groups (Figure 7.7). In this analysis, the impacted reaches were significantly different from the control reaches ($p<0.05$), yet the recovering reaches were not significantly different from the control reaches.

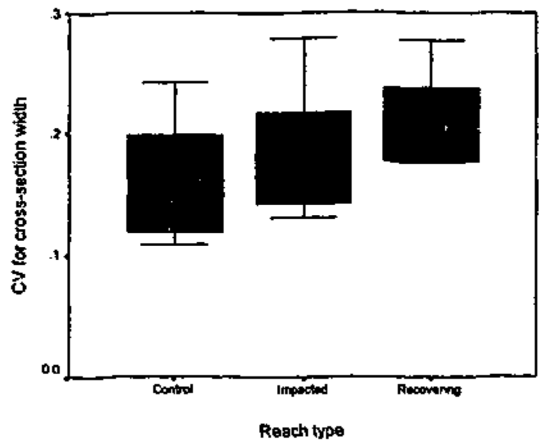


Figure 7.6: Box plot showing the difference in the Co-efficient of Variation (CoV) for the cross-section *widths* on Creightons Creek. No significant difference between any of the groups. (Each box plot contains data from at least 30 cross-sections).

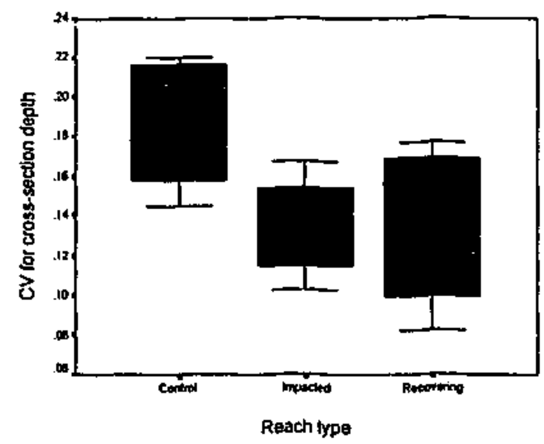


Figure 7.7: Box plot showing the difference in the Co-efficient of Variation (CoV) for the cross-section *depths* on Creightons Creek. Significant difference ($p<0.05$) between control and impacted reaches. (Each box plot contains data from at least 30 cross-sections).

Hence, the main conclusion from this statistical analysis is that the introduction of sediment into Creightons Creek has significantly reduced the cross-sectional depth variation in the stream. The channel incision and subsequent sediment slug has also caused an indirect increase in cross-sectional width variability, although this was not statistically significant.

<u>*Wannon River*</u>

The results for the Wannon River suggest that there is no statistical significance ($p<0.1$) for the CoV of widths or depths between any of the groups. The box plots showing the difference between the CoV for width and depth are given in Figure 7.8 and Figure 7.9, respectively.

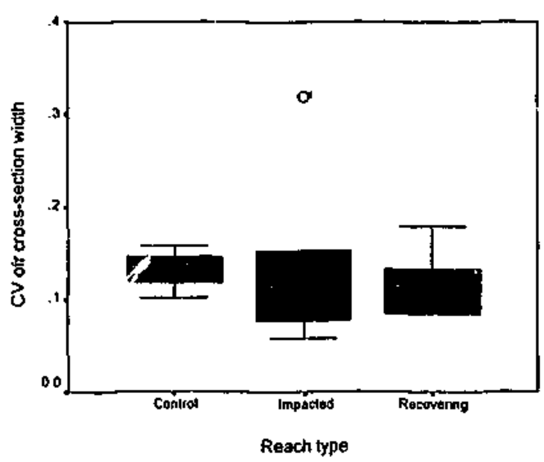


Figure 7.8: Box plot showing the difference in the Co-efficient of Variation (CoV) for the cross-section *widths* on the Wannon River. No significant difference between the reaches. (Each box plot contains data from at least 30 cross-sections).

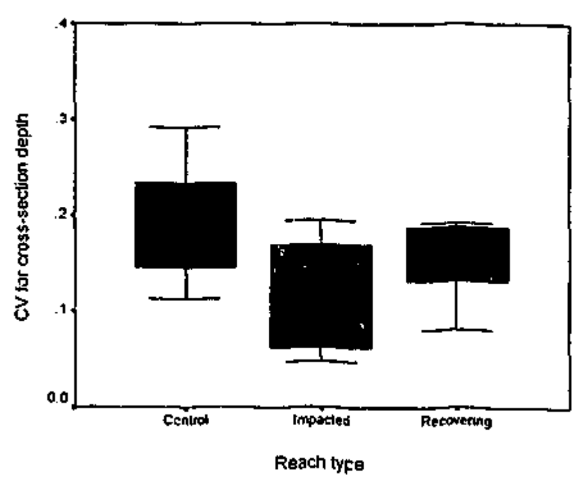


Figure 7.9: Box plot showing the difference in the Co-efficient of Variation (CoV) for the cross-section *depths* on the Wannon River. No significant difference between the reaches. (Each box plot contains data from at least 30 cross-sections).

Both the statistical and graphical results show that there is very little difference in the CoV for cross-sectional width; however, the Figure 7.9 suggests that there is a decrease in the CoV for cross-sectional depths in between the control and impacted reaches. Hence, it is possible to conclude that, although there is no statistically significant difference, there has been some alteration to the cross-sectional depth variation as a result of the sediment slug in the Wannon River.

Ringarooma River

The results for the Ringarooma River suggest that there is a significant difference in the CoV for the channel widths between control and impacted reaches ($p<0.15$), however, there is no significant difference between the control and recovering reaches (Figure 7.10). For the depth variability there is a significant difference between the control and impacted reaches ($p<0.1$) yet there is no difference between the depths of the control and recovering reaches (Figure 7.11). Overall, it is possible to conclude that the sediment slug has significantly reduced the variability of cross-sectional widths and depths.

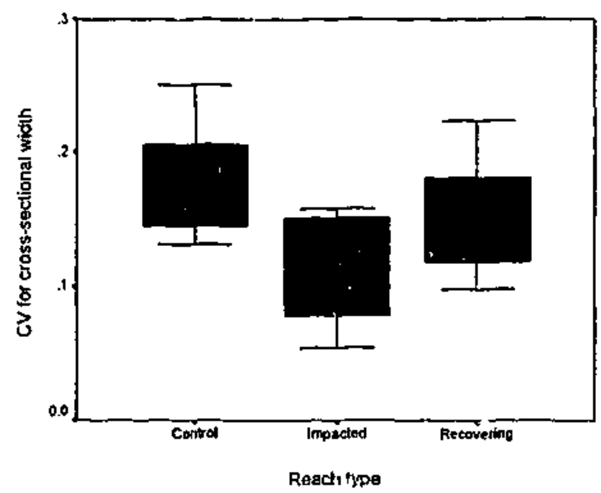


Figure 7.10: Box plot showing the difference in the Co-efficient of Variation (CoV) for the cross-section *widths* on the Ringarooma River. Significant difference between the control and impacted reaches (p<0.15). (Each box plot contains data from at least 30 cross-sections).

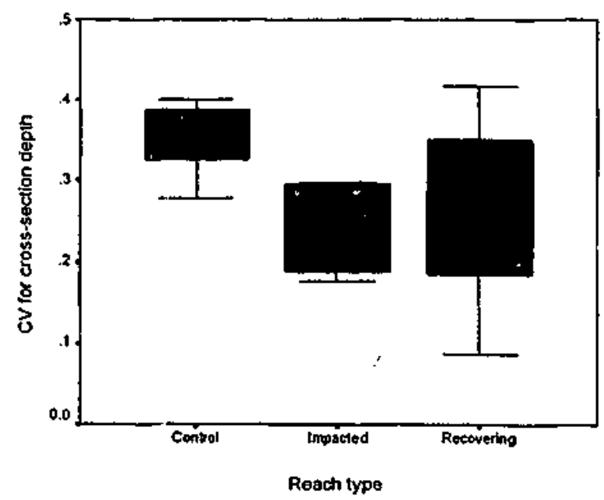


Figure 7.11: Box plot showing the difference in the Co-efficient of Variation (CoV) for the cross-section *depths* on the Ringarooma River. Significant difference between the control and impacted reaches (p<0.1). (Each box plot contains data from at least 30 cross-sections).

Summary

This is the first known study to have used a statistically rigorous approach to investigate whether there has been a change in the variation of cross-sectional characteristics as a result of a sediment slug. The results from this study suggest that depth is more sensitive to increased bedload than width. In all three case studies, there was a decrease in cross-sectional depth variation (CoV) between the control and impact reaches, although only Creightons Creek and the Ringarooma River showed that this change was statistically significant. The cross-sectional widths responded differently for each stream, with only the Ringarooma River showing a significant result. Creightons Creek appeared to increase width variability due to the slug, although this was probably a function of the incision in the upper reaches. The Wannon River appeared to have very little width variation between any of the sites, yet the Ringarooma did show that the sediment decreased the variability of the channel width, thus making the widths more uniform following impact by a sediment slug.

Implications of these results for assessing the impact of the sediment slug

This study has shown that the sediment slug has an affect on the cross-sectional characteristics of each stream; in most cases, this is through a decrease in depth cross-sectional variability. These results show that (in most cases) the difference in characteristics between reach types is a function of the sediment slug, and that differences are not simply the result of natural variation. The cross-sections have been analysed for a change in their mean conditions; it is now possible to look at the variability of each individual cross-section at a smaller scale. Based on the analysis presented here it would be reasonable to assume that any differences in the variability of the cross-sections would also be a result of the sediment slug and not simply natural variation (although there will be less certainty with the Wannon River data). Analysis techniques to quantify the variability of the cross-sections will be presented in Chapter 8.

7.2.4. Changes in sediment size characteristics down a catchment

This section outlines a method for predicting whether there has been a change in the median sediment size (D_{50}) as a result of the sediment slug impact on each stream. To determine if the sediment slug has caused a change in sediment size, it is important to have an idea of what the sediment would have been like prior to disturbance. To do this, a method is applied that allows the pre-disturbance sediment size to be estimated, based on the relationship between the grain size of other un-slugged sites and the distance along the river.

There are some well established relationships describing how sediment size changes with distance downstream in a catchment. The overall tendency is for sediment size to decrease in an exponential fashion with distance downstream. This is the result of two processes: abrasion and sorting (Knighton, 1999). Brierley and Hicken (1985) described how

Sternberg (1875) formalised abrasion and sorting processes to predict the exponential decline of particle size in gravel bed rivers (Equation 7.10).

$$W / W_0 = e^{-\lambda l}$$ Equation 7.10

where W is the weight of the particle at distance travelled, l, W_0 is the initial weight of the particle and λ is the abrasion co-efficient. Knighton (1982) used a similar equation (Equation 7.11) to express the longitudinal changes in the size of bed material on the River Noe (England).

$$D = D_0 e^{-(k_1+k_2)L_0} \quad \text{or} \quad D = D_0 e^{-\alpha L_0}$$ Equation 7.11

Where D is size of bed material (eg D_{50}), L_0 is distance downstream, D_0 is grain size at L = 0, k_1 is the coefficient of abrasion and k_2 is a coefficient of sorting. However, k_1 and k_2 are often represented by a single variable, α. Knighton (1982) found that grain size tends to decrease exponentially downstream in accordance with Equation 7.11, yet research by Brierley and Hickin (1985) found that sediment size changes with distance downstream on the Squamish River, Canada, were best represented by power rather than exponential functions. This result implies that the rate of change of particle size, with respect to channel length, declines downstream. This is also largely an expression of sediment supply and hydraulic competence, rather than abrasion forces as described by Equation 7.11.

Nonetheless, to evaluate the changes in grain size with distance downstream, the relationship described by Knighton (1982) and represented by Equation 7.11 will be used, and for two reasons. Firstly, the results obtained by Brierley and Hickin (1985) were from the Squamish River, which is represented by multiple stream forms including braided morphology. None of the field sites in this study are represented by this stream type (in their natural condition), and would not necessarily be expected to follow the same empirical relationship for sediment size. Secondly, Knighton (1999) has used Equation 7.11 in his analysis of the downstream changes in the mean sediment size on the Ringarooma River; it would therefore be appropriate to keep the analysis techniques similar for all of the field sites.

Creightons Creek

A total of 80 sediment samples were collected along the length of Creightons Creek. There were 5 samples collected from each study reach by the methods described in Section 5.6.2.

There were also two extra reaches used in this analysis: one at the very top of the catchment above the main point of incision and the other below Reach 1 in the clay section downstream. Both these sites acted as extra control points. Hence, in total, there were six control reaches (ie. 30 samples) that were considered to be free from disturbance by the sediment slug. Using the data from these six reaches, an exponential function was fitted to the data. This provided an estimate of median grain size for the impacted and recovering reaches assuming there had been no disturbance (ie. expected data values). The actual data collected and analysed from the field (observed data values) were then assessed to look at any deviations that the slug may have caused to the median grain size.

The results of this analysis, presented in Figure 7.12, show that the impacted reaches all have median grain sizes at least one standard deviation (SD) greater than the expected grain size under natural conditions. The recovering reaches also have grain sizes greater than 1 SD but, with exception of Reach 12, are much closer to the expected grain size for that reach. It is important to note that the median grain size calculated and represented by an individual data point in Figure 7.12 is the average of 5 separate sediment samples.

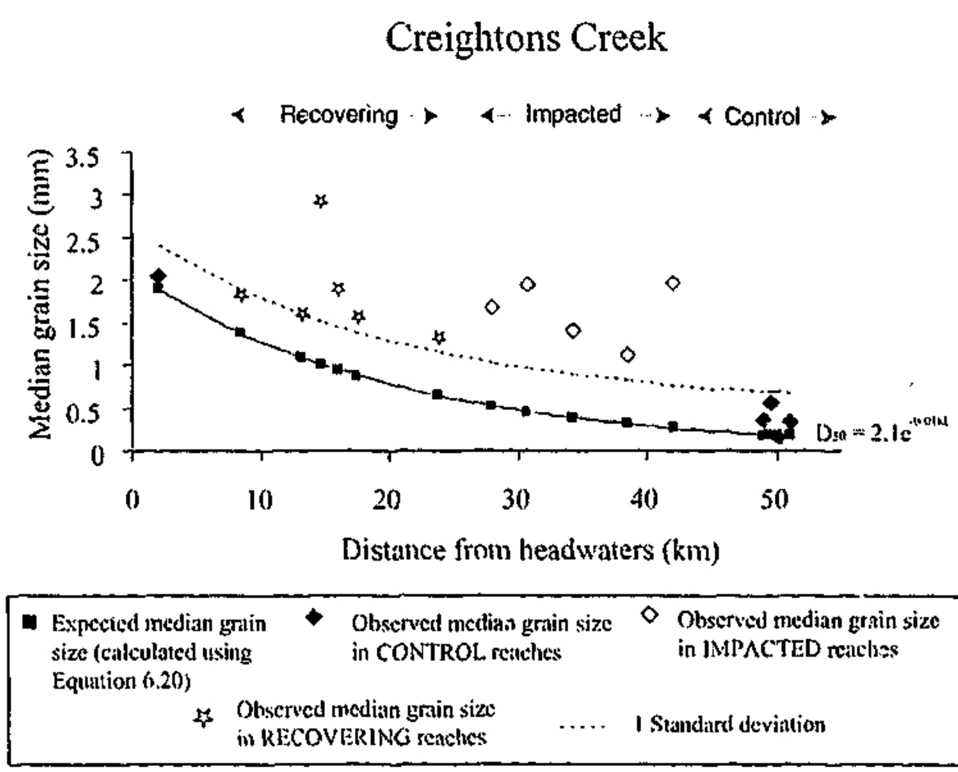


Figure 7.12: Difference between the observed and expected median grain size along Creightons Creek.

This result does not necessarily mean that the recovering reaches are actually 'recovering' from one grain size to another, as the natural granite exposed in the headwaters suggests that there would have been considerable amounts of sand sized sediment in these reaches even prior to disturbance. It is expected, however, that there may have been greater proportions of clay and silt that would have been trapped in these reaches, if/when they were the chain of ponds type systems described by the first settlers (Chapter 4).

Overall, it is possible to conclude that the natural bed sediments of Creightons Creek have been altered by the sediment slug. In all the impacted and recovering reaches, without exception, the sediment size is coarser than it would be if there were no slug in the system.

Wannon River

A total of 85 sediment samples were collected along the Wannon River. In each reach, five separate sediment samples were collected according to the methods described in Section 5.6.2. In addition to the 12 study reaches used along the stream, an extra five control sites were located upstream of the slug. This allowed a better evaluation of the data over the entire length of the Wannon River. The five extra sample sites were located between 20 and 140 km from the headwaters of the Wannon River, with sampling procedures the same as for Reaches 1-12. Sampling of the 5 extra upstream sites meant that there were a total of 8 reaches (40 samples) which could be considered as un-impacted in terms of sediment slug disturbance. An exponential curve was fit to the data collected from these 8 sites. This curve provided a relationship between grain size and distance downstream. The curve was then extrapolated to the downstream reaches to determine if there was a difference between the observed and expected values (Figure 7.13). Each reach is represented by the average grain size for that reach, which is the average D_{50} of the 5 sediment samples.

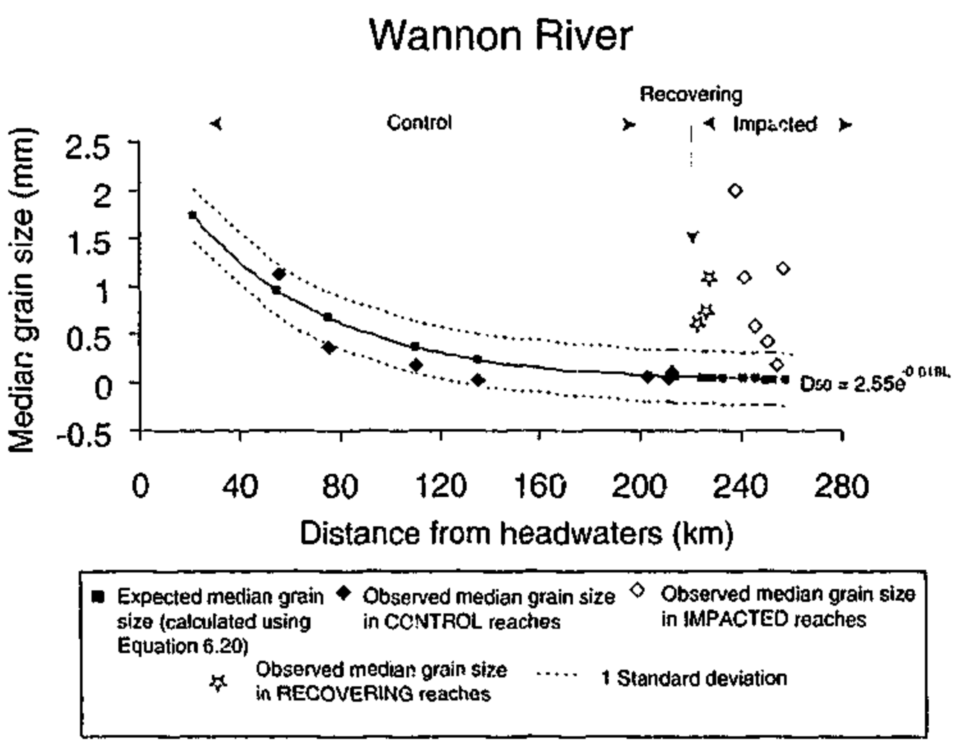


Figure 7.13: Difference between the observed and expected median grain size along the Wannon River.

All of the impacted and recovering reaches, with exception of Reach 11, had median sediment sizes greater than one SD from the expected value. This is evidence that the sediment slug has altered the natural sediment of the river. Hence, the bed sediments in the Wannon River downstream of Reach 4 (Bryans Creek) are greater than what would naturally occur had there been no disturbance.

Ringarooma River

The analysis procedure used on the Ringarooma River was slightly different from both Creightons Creek and the Wannon River. Previous analysis of the downstream changes in sediment size had been conducted by Knighton (1999) [although I was not aware of this work until I had already collected the sediment samples and had planned a similar type of analysis]. However, Knighton (1999) had used five more sample reaches in his analysis; therefore, his curve was more comprehensive. Instead of fitting an exponential curve to the control reaches and extrapolating it to the disturbed reaches downstream (as done on Creightons and the Wannon Rivers), the relationship derived by Knighton (1999) was used, which related sediment changes to distance downstream (Equation 7.12).

$$D_{50} = 70.8e^{-0.009L} \qquad \text{Equation 7.12}$$

where D_{50} is the median grain size at a site, and L is the distance of that site from the source of the river. I also made some alterations to the grain size analysis procedure, due to highly variable sediment sizes along the Ringarooma River. In the reaches where cobbles dominated the bed surface, a Wolman pebble count (as described in Section 5.6.2) was used to characterise the median sediment size for that reach. Reaches 1-6 were considered to be cobble dominated. The reaches downstream of Herrick were predominantly coarse sand and fine gravels and the D_{50} for these reaches were determined using bulk sieve analysis (as described in Section 5.6.3).

It is possible that the variation in methods (ie. bulk sampling vs Wolman Count) could reduce the accuracy of the analysis; however, the grid-by number (Wolman Count) and volume by weight techniques (bulk sampling) have been regarded as equivalent (Kellerhals and Bray, 1971; Knighton, 1999). To accommodate for the large variation in grain sizes along the Ringarooma, the deviation of the observed and expected data is assessed using 2 SD rather than 1 SD. The expected value was calculated using Knighton's equation (Equation 7.12); the observed values are represented by the sediment data that was collected along the 10 reaches used in this study. The results are shown in Figure 7.14.

This analysis shows that there are considerable variation in the D_{50} of both the control and recovering reaches, with the D_{50} ranging between 40 mm and 63 mm. The recovering reaches appear to have evacuated much of the fine sediment, and the D_{50} has returned to within 2 SD of the expected values. The downstream impacted reaches still have a D_{50} much lower than what would naturally occur. As noted by Knighton (1999), there is very small transition area between a cobble/gravel dominated and sand/gravel dominated bed. There is only 5-10 km between the sites that can be considered to have 'recovered' compared to severely disturbed reaches.

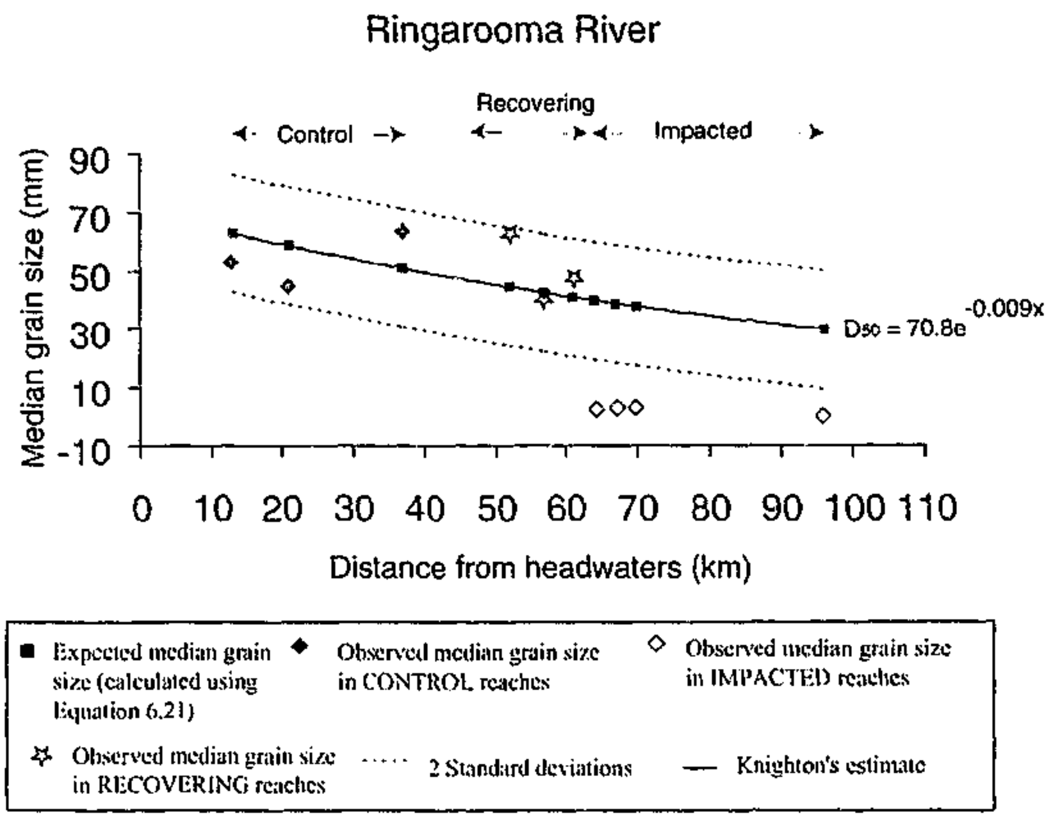


Figure 7.14: Difference between the Observed and Expected median grain size along the Ringarooma River.

This analysis has shown that the sediment slug has reduced the sediment size of the Ringarooma River to at least 2 SD less than what would naturally occur. Had the sediment slug never impacted this river, the sediment sizes at Reach 10 would be approximately 30mm instead of the 2.1 mm at present.

Implications of these results for assessing the impact of the sediment slug

This analysis has shown that the size of the natural bed sediments have been altered by the introduction of a sediment slug for each of the three study streams. On Creightons Creek and the Wannon River the sediment slug has caused an increase in the D_{50} of the bed material; on the Ringarooma, the sediment size has decreased. Further analysis (in Chapter

8) will determine if the sediment slug has also changed the variability or heterogeneity of the bed material. The results presented in this chapter provide enough evidence to show that the natural sediment size of the three streams has been altered by the sediment slug, therefore, any subsequent change in the variability of the sediment will also be a function of the sediment slug impact.

7.2.5. Changes in sediment stability

It is not really possible to assess the change to sediment stability down a catchment, as too many of the variables required to make an accurate assessment of the pre-disturbance condition have changed eg. sediment size, cross-sections, bed forms, hydrology, hydraulic roughness etc. Hence, there is little point reconstructing values that represent the pre-disturbance level of sediment stability.

Chapter 6 presented the results of the sediment stability analysis, and these results are considered sufficient detail to assess the difference in sediment stability between the different reach types. Hence, the traditional space for time approach will be employed. This assumes that the sediment stability in the control reaches represents the pre-disturbance sediment stability at all sites. A summary of these findings for each stream is outlined below:

- On Creightons Creek it was shown that the sediment slug has increased the rate of sediment entrainment by roughly 12 times between the control reaches downstream of the slug and the impacted reaches in the slug;
- On the Wannon River the sediment stability has decreased approximately ten times between the slugged and non-slugged reaches (this is an average value and does not include Reach 11);
- On the Ringarooma River the control reaches were shown to be at least 15 times more stable than the impacted (slugged) reaches.

7.2.6. Summary

The main aim of this section was to determine if any differences in the data between the control, impact and recovering sites was due to the presence of the sediment slug, or simply a function of natural variation. It was shown that in most cases the sediment slug had resulted in a considerable (and in most cases statistically significant) difference between the control and impacted sites.

The results from Section7.2 now allows the Geomorphic Variability data to be analysed for changes in variability knowing that any differences found will be a function of the sediment slug and not simply natural variation. The analysis and results presented in the above sections have essentially addressed many of the scaling issues that have not been previously evaluated in studies that employ ergodic reasoning. The Geomorphic Recovery Model can now be evaluated with greater confidence.

7.3 Scaling the impact of the sediment slug on each stream: channel size vs slug volume

Continuing with the issues of scale, this section will present a method for scaling the impact of the sediment size with respect to the size of the stream. Stream systems are quite resilient to many forms of environmental disturbance; however, it is expected that there will be an important threshold limit to the sediment that a stream can accommodate before environmental degradation occurs. It is expected that this threshold will be different for streams of different size. For example, a sediment depth of 2 m will have a very different effect on a channel that has a bankfull stage of 3 m, versus a channel with a bankfull stage of 6 m. This section attempts to quantify the impact of the sediment slug on each stream, not simply in absolute terms, but scaled with respect to the size of the channel. This will be important for evaluating the response of the other variables with respect to the 'relative' level of disturbance.

The technique proposed requires an estimation of the size of the channel prior to disturbance, as well as the volume of sediment that forms the slug. This is impractical to do for entire streams or rivers; therefore, for this study estimates were made for each reach.

The process requires making an estimate of the cross-sectional area of each reach assuming that there is no sediment in the stream; this requires estimating the width and depth of the channel without sediment. Due to the changes that the streams have undergone as a result of the slugs impact, and lack of hydraulic geometry data for Australian streams, it is not practical to re-construct the pre-disturbance channel widths and depths (as described in Section 5.5.5.4). Instead, the channel dimensions are calculated using the current width and depth of each reach, then the mean sediment depth of the slug for that reach is added to determine the pre-disturbance channel depth, PDD, according to Equation 7.13. The mean channel width is then multiplied by PDD, and the reach length according to Equation 7.14. This then provides an estimate of the pre-disturbance reach volume (m^3) (Figure 7.15).

PDD = channel depth (m) + mean sediment depth (m) Equation 7.13

Volume = channel width* PDD * reach length (m^3) Equation 7.14

To determine the scale of the disturbance, the size of slug (m^3) is then divided by the volume of the channel (m^3) to obtain a non-dimensional value. This can be expressed as the % area in each disturbed/filled reach (Equation 7.15).

% reach filled = size of slug (m^3)/reach volume (m^3) Equation 7.15

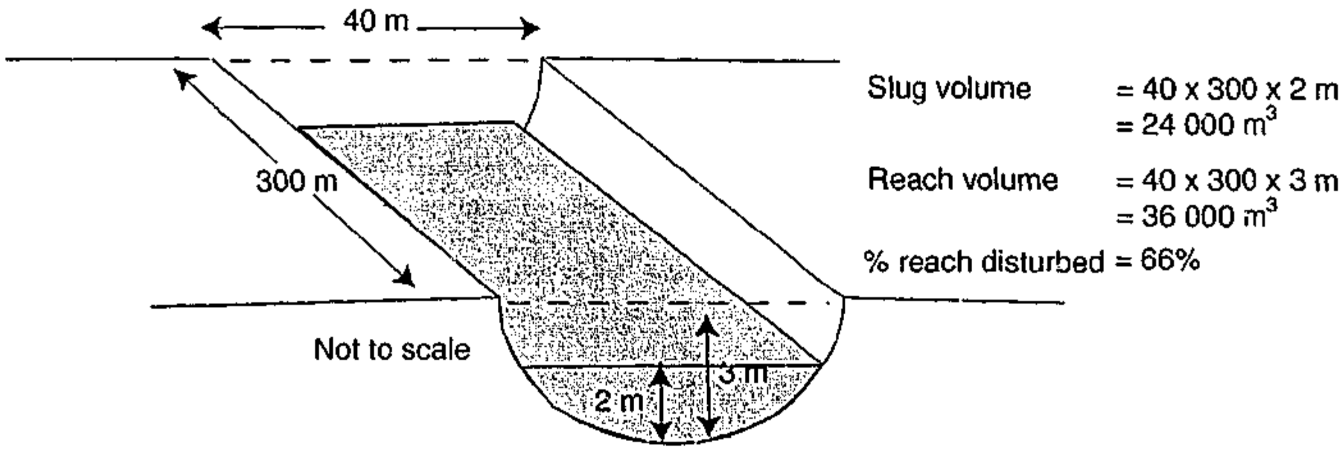


Figure 7.15: Example of how the % volume of the reach disturbed is calculated using average dimensions. The sediment depth (2 m) and channel depth (3 m) represent average values for the cross-section.

There are a number of assumptions that are used in this technique:

- That the sediment depth in each reach is uniform;
- That the probing technique is an accurate measure of sediment depths;
- That the present cross-sectional shape is similar to the pre-disturbance cross-sectional shape.

The final results will provide an estimate (as a %) of the cross-sectional volume in each reach that has been filled by the sediment slug. The results of this analysis for each of the three stream are presented below.

7.3.1. Creightons Creek

The total volume of sediment in the Creightons creek slug has been estimated to be approximately 240,000 m^3 (Davis and Finlayson, 2000); given that the catchment area is only 141 km^2, the volume of sediment in the slug is considerable in proportion to the size of the channel. Calculating the impact of the slug proportional to the channel size, is a way of non-dimensionalising the impact, so that reaches from different parts of the catchment can be compared. The results of this analysis are presented in Table 7.3 and Figure 7.16. Impacted reaches, 5-10, have had between 40-70% of the channel volume filled by a sediment slug (Figure 7.16). The recovering reaches have between 20-37% of the channel volume filled with sediment.

Table 7.3: % volume of channel that has been impacted by the sediment slug on Creightons Creek

Reach	Sediment volume (m^3)	Pre-disturbance reach volume (m^3)	% reach filled with sediment slug
1	66.6	2862	2.33
2	54.2	2389	2.27
3	51.5	2264	2.27
4	378	2124	17.8
5	1433	2604	55.0
6	1476	3080	47.9
7	2593	3695	70.2
8	1238	3055	40.5
9	1397	2646	52.8
10	1356	2568	52.8
11	604	2007	30.1
12	592	2980	19.9
13	322	877	36.7

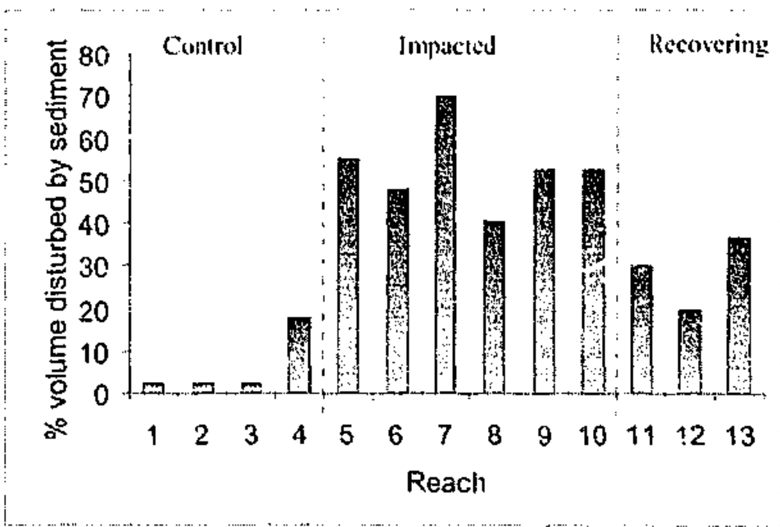


Figure 7.16: % volume of channel that has been impacted by the sediment slug on Creightons Creek

7.3.2. Wannon River

The total volume of sediment in the Wannon River slug has been estimated to be approximately 280,000 m^3 (Rutherfurd and Budahazy, 1996); the total catchment area of the Wannon River is 4490km^2, and only the lower 50 km has been impacted by sediment. Given the large size of the Wannon River and the relatively small volume of sediment, it is of interest to determine what proportion of the stream has been impacted by the slug. The results of the scaling analysis are presented in Table 7.4 and Figure 7.17.

Table 7.4: % volume of channel that has been impacted by the sediment slug on the Wannon River

Reach	Sediment volume (m^3)	Pre-disturbance reach volume (m^3)	% reach filled with sediment slug
1	127	42525	0.3
2	89.3	49427	0.2
3	92.3	37417	0.2
4	3928	31607	12.4
5	11102	53872	20.6
6	10834	53208	20.4
7	8175	35311	23.2
8	10949	51184	21.4
9	10515	64287	16.4
10	5993	77133	7.8
11	3044	89655	3.4
12	5863	82867	7.1

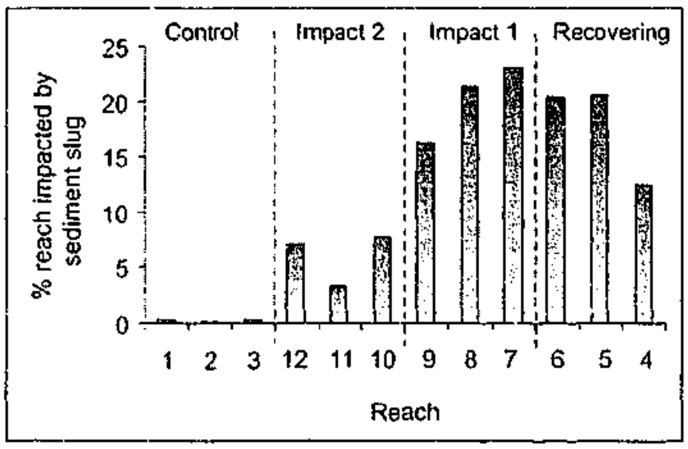


Figure 7.17: % volume of channel that has been filled by the sediment slug on the Wannon River

The results from the scaling analysis show that the area with the most sand is the impact 1 group, which has had between 16-24% of the channel volume impacted. The recovering reaches are not that different from the impact 1 group, having between 12-21% of the channel disturbed; the impact 2 group, further downstream, only has between 3-8% of the total volume of the channel filled by the slug.

The large size of the channel in the impact 2 reaches (ie. average bank heights of 6 m and channel widths of 45-60 m) means that the small amount of sediment starting to move into this section has little effect on the channel per unit volume. On the other hand, despite the sediment depths being less than 1/5 the bank height (criteria for the definition of sediment slug given in Chapter 5) in the recovering reaches, the slug is having a much greater effect (as the channel is slightly smaller).

7.3.3. Ringarooma River

The total volume of sediment in the Ringarooma River slug has been estimated to be approximately 40 million m^3 (Knighton, 1987); the total catchment area of the Ringarooma River is 912 km^2. Given the size of the Ringarooma River catchment, and the massive volumes of sediment, it is of interest to determine what proportion of the stream has been impacted by the sediment slug. The results of this analysis are presented in Table 7.5 and shown graphically in Figure 7.18. It is important to note that these values are most probably underestimates for Reach 8 -10.

Table 7.5: % volume of channel that has been filled by the sediment slug on the Ringarooma River

Reach	Sediment volume (m^3)	Pre-disturbance reach volume (m^3)	% reach disturbed by sediment slug
1	49.7	6364	*0.77*
2	139.8	12603	*1.10*
3	96.6	20982	*0.46*
4	676	33544	*2.01*
5	899	18186	*4.94*
6	12887	68127	*18.9*
7	30373	5[illegible]353	*52.1*
8	45018	89206	*50.5*
9	42770	79724	*53.7*
10	51418	81276	*63.2*

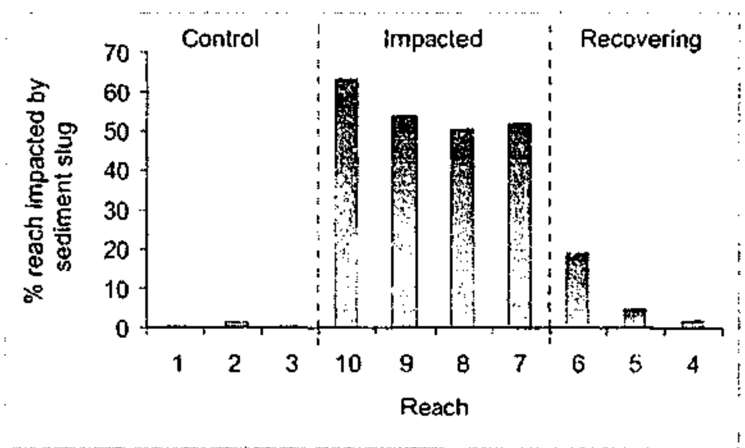


Figure 7.18: % volume of channel that has been filled by the sediment slug on the Ringarooma River

The results show that the downstream impacted reaches (7-10) are the most disturbed per unit volume of channel (Table 7.5 and Figure 7.18). In these sections between 50-64% of the channel has been filled. The recovered reaches, which have, in the past, also been severely disturbed, now only have between 2-19% of the channel filled by sediment.

7.3.4. Summary

The scaling analysis described the 'relative' impact of the sediment slug in proportion to the size of the channel. Using the scaled values it is possible to compare the impacts between streams regardless of channel size. Based on the results in this chapter, the Ringarooma River appears to be the most disturbed with between 50-64% of the original channel being filled. Creightons Creek comes a close second with between 40-70% of the channel volume filled in the impacted reaches. The Wannon River is the least impacted with less than 25% of the channel filled by the sediment slug.

7.4 Summary of procedures and findings

This chapter presented a number of techniques for evaluating the effect of scale on the Geomorphic Variability data. The first half of this chapter presented techniques for determining if the changes on the three study streams were a result of the sediment slug, or simply a function of naturally variability. The second half of the chapter presented a method for estimating the impact of the sediment slug with consideration for the size of the channel.

The main conclusions from the work presented in this chapter are as follows:

- Determining how the geomorphic structure of the stream changed in the absence of disturbance involved being able to estimate the pre-disturbance condition. This process varied for each of the main variables that make up Geomorphic Variability: thalweg, cross-sections and sediment size.
- Predicting pre-disturbance thalweg condition involved scaling a specific feature within the thalweg; pools and riffles were used for the purpose. The pre-disturbance mean pool depth for each reach was estimated by combining the work of a number of researchers and finally scaling pool depth to catchment area. It was found that the mean pool depth following disturbance by sediment slugs was significantly different from the pre-disturbance estimate for all of the impacted reaches on each stream;
- It was not possible to estimate the pre-disturbance cross-sectional variability for each stream. Instead, the CoV of the width and depth of each cross-section was used. The CoV is a dimensionless value, thus, the analysis was based on the assumption that the CoV will be the same regardless of the position along the stream. Statistical tests were then used to detect the difference between reaches. It was found that depth was more sensitive than width, and only Creightons Creek and the Ringarooma River showed significant differences between the control and impacted reaches;

- To estimate the pre-disturbance mean sediment size, an equation was applied that related mean grain size to the distance from the source (headwaters). The current grain size in the slugged reaches is at least one SD greater than the natural sediment in the case of Creightons Creek and the Wannon River, and a least 2 SD smaller in the case of the Ringarooma River.
- Using data from previous chapters, it was reiterated that the sediment slug had resulted in major changes in the sediment stability of many reaches, particularly between control and impacted sites;
- The results of the scaling analysis showed that the Ringarooma River has proportionally been the most disturbed with at least 50-64% of its channel filled with sediment (it is expected that these values would be greater with more accurate sediment depth data). Creightons Creek has had between 40-70% of its impacted reaches filled with sediment and the Wannon River has had no greater than 25% of any reach filled with sediment. These results present a scaled value of the impact of the sediment slug on each stream. This data will also allow reaches from different parts of the catchment (and potentially from different streams) to be compared;
- Overall, the analyses carried out in this chapter have shown that (in the majority of cases) the differences between the control, impacted and recovering reaches are a function of the sediment slug and not simply related to variations in natural conditions.

Based on the results in the chapter, it is possible to go on and determine if there is a change in the variability of the data, between the different disturbance groups (control, impacted, recovering). This analysis can now be done knowing that any significant results are likely to be a function of the sediment slug impact and not simply natural variation. Chapter 8 presents the various analysis techniques that can be used to quantify the variability of each data set.

Chapter 8

Data analysis techniques used to characterise the Geomorphic Variability of a stream reach

8. Chapter 8 - Data analysis techniques used to characterise the Geomorphic Variability of a stream reach

8.1 Introduction

Chapter 7 presented a range of methods for determining if the data actually deviates from the expected (un-disturbed) condition. In most cases, the mean values for each of the variables (thalweg, cross-sections, sediment size and sediment stability) were shown to have been altered by the presence of the sediment slug. However, as described in Chapters 2 and 3, it is the variability, rather than a deviation from average conditions, that is considered a more appropriate measure of geomorphic health (eg. Cooper *et al.*, 1997; Downing, 1991; Palmer and Poff, 1997; Palmer *et al.*, 1997; Thoms and Sheldon, 1996).

This chapter presents a range of techniques that can be used to quantify the variability of the data sets. In particular, it deals with three of the four main variables that describe the geomorphic variability and character of a stream:

- Thalweg variability
- Cross-sectional variability
- Sediment size variability

The sediment variability data was not analysed using the same approach as the above variables due to the format of the data. This does not reduce the importance of the sediment stability data, and it will be incorporated again in the next chapter.

This chapter has 8 sections. The next one (Section 8.2) presents a brief review of the different type of techniques that have been used to quantify spatial heterogeneity in a range of scientific fields. The more appropriate techniques for quantifying the data sets are then presented in detail in Section 8.3.

There have been few studies that have rigorously tested the techniques presented in Sections 8.2 and 8.3; many of the techniques have not been previously applied to river data. Section 8.4 describes the process of testing each of these methods for their usefulness, and cross-correlation between the various techniques. This is done by developing a number of synthetic data sets for the thalweg, cross-section and sediment size data. The methods and results of each of these calibrations is given in Sections 8.5, 8.6 and 8.7, respectively. From this analysis, a smaller set of un-correlated variables are selected to quantify the variability of the real river data. Section 8.8 then presents a summary of the various techniques, and describes how they were applied to the data. Section 8.9 describes the statistical techniques used to evaluate the differences between the different data sets following the application of the variability measures, and Section 8.10 summarises the findings of this chapter.

8.2 Quantifying the complexity of instream habitat and geomorphic features

With the continuing destruction of habitats on a global scale, many fields of science have increased their research effort into quantifying habitat. Habitat is an area that an organism (eg. animal, plant, fungi) will live and/or breed; essentially habitats are areas of 2 or 3 dimensional space which can be constructed from a variety of materials. Aquatic habitats are usually comprised of sediment and vegetation elements within a channel, which, are affected by the flow of water over this material.

<u>Purpose and justification of the data analysis process</u>

Section 8.2.1 discusses a range of different analysis techniques that have been used to quantify spatial variability. Most of the studies come from the fields of ecology, hydrology, or geomorphology. The main difference between the ecological and hydro-geomorphic studies is that ecological studies use these techniques to measure habitat, and relate it to the diversity and abundance of species within particular environments. To date, however, most of the ecological habitat studies using spatial statistics have been conducted within marine environments; very few studies have been conducted in river habitats.

The hydro-geomorphic studies used the spatial methodologies differently from the ecological studies. In the former, the techniques were generally applied to quantify the variability for the purpose of modelling the patterns of river channel change. *Hence, there is a gap in the application of such techriques: the ability to quantify in-stream geomorphic heterogeneity (for the purpose of understanding the distribution and abundance of physical habitat).*

Hobson (1972) outlined a number of basic requirements that should be met by techniques used to quantify spatial data. The techniques should be:

- conceptually descriptive, so as to provide a mental image of the data being tested;
- easily measured, with minimal equipment and applicable to large data sets;

- able to be analysed at a variety of scales.

Li and Reynolds (1994) also emphasise that there are many techniques that measure environmental heterogeneity that are not necessarily appropriate for spatial information (eg. Shannon index). Many techniques do not have spatial elements in their mathematical formulae, and are therefore not suitable for measuring spatial data. For those techniques that were suitable for quantifying spatial data, a detailed literature search was undertaken. Papers from a wide range of scientific fields were consulted; however, the next section will describe only those techniques that have relevance and application to fluvial geomorphic data.

8.2.1. Previous research used to quantify complexity

Quantifying the heterogeneity or complexity of a habitat, river-bed or coast-line, essentially involves quantifying the variability of a line (thalwegs and cross-sections) and/or the arrangement of particles in space (sediment).

Quantifying line complexity

The methods for quantifying the complexity of a line can be roughly divided into six groups: (1) fractal theory, (2) vector dispersion or dimensions, (3) angle deviations from a surface, (4) parametric statistical techniques such as standard deviation and variance, (5) time series analysis (eg. smoothing techniques and variograms), and a group (6) titled 'other', which incorporates any technique (eg 'chain and tape) that does not fit neatly into the above categories.

It is difficult to determine the origin of each of the different techniques. Many of the ideas for them were developed in geophysics and geomorphology; yet, they have been extensively and creatively applied by ecologists in more recent studies. A series of studies by marine ecologists (eg. Beck, 1998; Carleton and Sammarco, 1987; Connell and Jones, 1991; McCormick, 1994) described the various methods used to quantify coral reef assemblages, rock platforms and mangrove habitats. The techniques used included variations of vector dispersion (VD) and vector strength, deviations from a range of planer surfaces (eg horizontal, vertical), sum of height deviations (Σdh^2), chain and tape (actual line length to straight line distance) and fractal dimensions (D). There are numerous other papers (eg. Nams, 1996; Sugihara and May, 1990; Williamson and Lawton, 1991) that describe the application of fractal analysis in habitat studies. Each of these techniques provide a numerical estimate of the 'variability' of a line. Generally, the higher the number, the greater the variability.

From a different perspective, Cooper *et al.* (1997) reviewed a range of geostatistical methods, and described how they could be applied to ecological data. Such techniques included semi-variograms, autocorrelation and spectral analysis. The paper focused mainly on population and community data, rather than topographic habitat data.

As well as ecological studies, the disciplines of hydrology, hydraulics and geomorphology have applied many of these techniques. A paper by Ghosh and Scheidegger (1971) described techniques such as autocorrelation, spectral analysis, variance, standard deviation, and presented a new term - the 'degree of wiggliness', *w*. The degree of wiggliness involves measuring the dispersion of angles around the mean, and provides an indication of the curvature of the line.,

There have been many hydrological studies that have employed time series applications when attempting to model longitudinal river bed profiles. Such techniques include the semi-variogram (eg. Robert, 1988; Robert and Richards, 1988), moving averages and autocorrelation (eg. Knighton, 1983) and harmonic, spectral and autoregressive techniques (eg. Richards, 1976). A comprehensive review of a range of techniques used to quantify the longitudinal changes in bed patterns was also carried out by Madej (1999). Some of the techniques described by Madej were trialed in this study, including spectral analysis and autocorrelation techniques; however, it was found that many of the techniques were suitable only for data that had been collected over considerable time periods. For example, Madej had at leat 20 years of morphological data from the one study stream. This type of data is not available for any streams in Australia, let alone the streams used in this study. The absence of data collected through time made the techniques described by Madej (1999) difficult to interpret and therefore they were not applied.

Another recent hydro-geomorphological study by Western *et al.* (1997) used variations in a cross-sectional shape parameter (ψ) to quantify the longitudinal change down a river. This analysis was carried out at a coarser scale, but applied to much greater river lengths. There are no studies that have quantified cross-sectional variability at small scales, such as those used in this study (ie. 50 cm).

Quantifying space (sediment) complexity

It is not possible to apply the techniques of the previous section to the sediment data, as sediment is made up of a range of shapes, rather than lines. The literature that describes quantifying the heterogeneity of sediments is less comprehensive than for 2-dimensional space. Here, there seems to be at least four statistical techniques that are traditionally used to estimate the variation or dispersion of a given sediment sample. These include sorting, skewness and kurtosis, described in Briggs (1977), and a measure of sediment heterogeneity described in Schwoerbel (1961), and applied by Williams (1980). Each of these techniques are described in detail in more Section 8.3.3.

8.3 Data Analysis Techniques for quantifying a spatial series

The large range of data analysis techniques available in the literature make it difficult to chose a single analysis technique for the data collected. It would be much easier to chose just one technique and apply it; however, most of these methods have never been applied to geomorphic river data. Subsequently, there has been no rigorous testing to determine if the data analysis techniques are appropriate for quantifying the Geomorphic Variability of a channel.

It is also expected that river systems are different to many other natural features, such as coral reef assemblages or mangroves, so it is important to evaluate the application of these techniques specifically for geomorphic river data. It may also be found that there a number of similarities between the different habitat types. Rivers and creeks are different to other aquatic habitats such as coral outcrops, due to their parabolic cross-sectional form, decreasing slope from the headwaters and interaction with other features in the catchment eg. vegetation.

This section presents a range of techniques to quantify the variability of the thalweg, cross-section and sediment size respectively. Some of the techniques were chosen from the literature review above; others are new techniques developed specifically for this analysis. Each of the techniques were also selected according to the criteria for quantifying spatial data that were outlined by Hobson (1972) in Section 8.2.

8.3.1. Thalweg

This section outlines the range of techniques used to quantify the variability of the thalweg profiles. The techniques outlined below are considered appropriate for quantifying the variation in the bed on a 2-dimesional scale. Except where specifically stated, all the data analysis was carried out using the Excel 97™ spreadsheet program.

Analysis technique 1: Local Linear Smoothing (Loess Curves)

'Loess curves' is a non-parametric smoothing technique used to identify underlying trends in noisy data (with some adjustment against extreme observations or outliers). The Loess Curve method used in this analyses was based on Makridakis *et al.* (1998). Essentially a curve is fitted to the thalweg data, rather than a straight line (as in regression). Initially, local regression is calculated, then the irregular component is calculated using Equation 8.1.

$$\hat{E}_t = Y_t - \hat{T}_t \qquad \text{Equation 8.1}$$

Equation 8.1 represents the difference, $\hat{E}_t$ between each observation Y_t and the fitted curve $\hat{T}_t$. The local linear regression is then calculated again, but this time observations with large errors receive smaller weights than for the estimate of the trend cycle curve. Then, a new irregular component is determined by subtracting the new estimate of T_t, from the data. The data is then smoothed as this procedure runs through further iterations. For each run, a value of N, representing the proportion of the data to be included in each local regression, needs to be determined. For the Loess calculations, N was set at 0.3 for all rivers: an N value of between 0.1 and 0.8 is usually chosen, and 0.3 provided the most consistent results for all streams (ie. least error). The value of N was kept the same for each stream so that profiles could be compared.

To evaluate the variability of each profile, the mean squared error (MSE), of the Loess Curve (thalweg profile) was used. The higher the MSE the more variable the profile. The calculations were all carried out using the Loess function in SYSTAT™ statistical package (Version 9.0).

Analysis technique 2: Standard deviation of depths (SD)

A method described by Lisle (1995) uses the irregularity of thalweg profiles to assess habitat complexity. In this method, the spatial variation of residual depths (σd_r) was assessed over different lengths of channel. This method was adapted to be independent of water depth, and it used the standard deviation (SD) of bed elevations from the highest point of the bed. The greater the SD of bed elevation deviations, the greater the variability.

Analysis technique 3: Fractal Dimension

Several methods for measuring structural complexity were outlined by Beck (1998). The four indices calculated were D (fractal dimension), VD (vector dispersion), Σdh^2 (consecutive substratum height difference), and chain (chain and tape). This section describes the fractal dimension (D) which was initially described by Sugihara and May (1990), calculated using the fractal dividers method, or Hausdorff dimension. It involved determining how the apparent length, L(δ), changes as the measurement interval for the thalweg is increased. For a fractal curve, the log apparent length grows linearly as the interval of measurement decreases. By plotting the apparent length L(δ) against the interval of measurement, a linear relationship is formed from which a regression equation can be fitted. The fractal dimension D, can then be calculated by subtracting the slope of the linear regression, from 1.0 (D = 1- slope) where 2>D>1. In Figure 8.1, the fractal dimension value for D is 1.0014. The higher the value of D, the greater the variation in the bed profile.

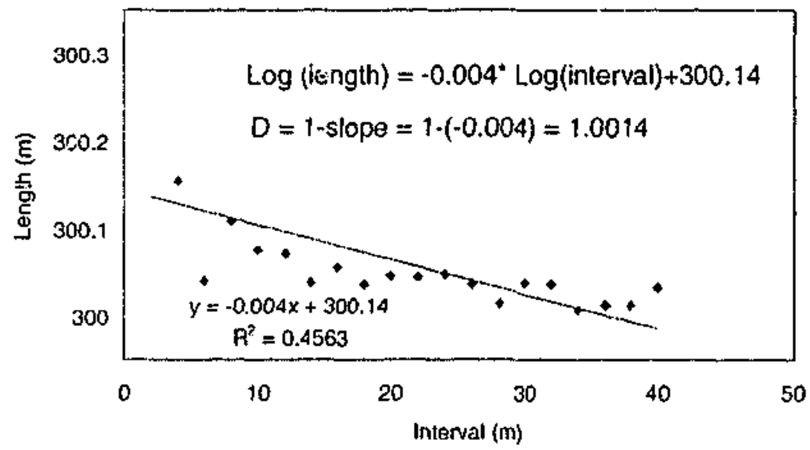


Figure 8.1: Application of fractals technique to thalweg data.

Analysis technique 4 -' Chain and tape' method

The chain and tape method is similar to that described in Beck (1998) and initially presented by Connell (1991); it is calculated as the ratio of the apparent distance to linear distance (L_A/L_s). For the thalweg data, it is calculated as the ratio of the length of the topographic bed distance (L_A) to the length of the reach (L_s) (Figure 8.2).

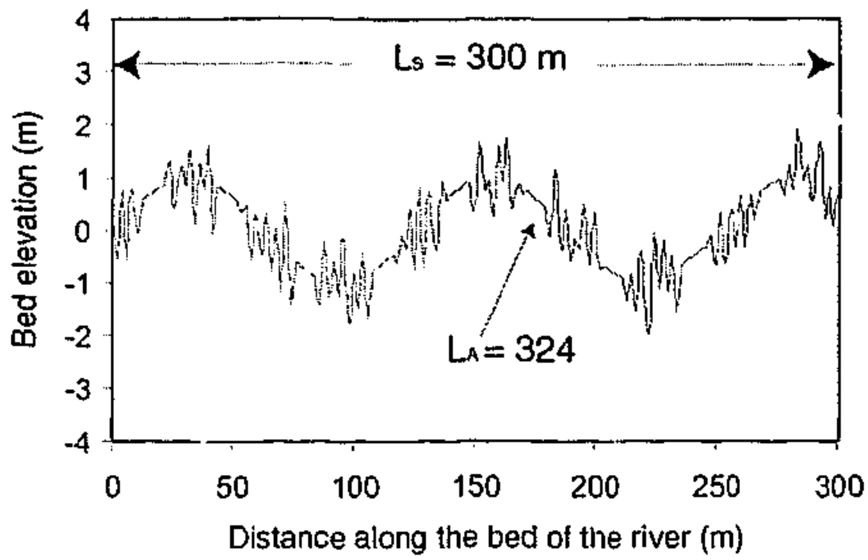


Figure 8.2: Application of the chain and tape method to thalweg data.

Analysis technique 5: Vector Dispersion (VD)

Vector Dispersion (VD) is a measure of angular variance (θ). It was calculated in Beck (1998) from a 2-dimensional modification of the formula in Carleton and Sammarco (1987) and given by Equation 8.2; Figure 8.3 depicts the concept.

$$VD = \frac{\left(n - \left[\sum_{i=1}^{n} (Cos\theta_i)\right]\right)}{n-1}$$

Equation 8.2

where n is the number of points along the transect, and θ is the angle of each thalweg point from horizontal. The greater the value of VD, the greater the variability of the thalweg profile.

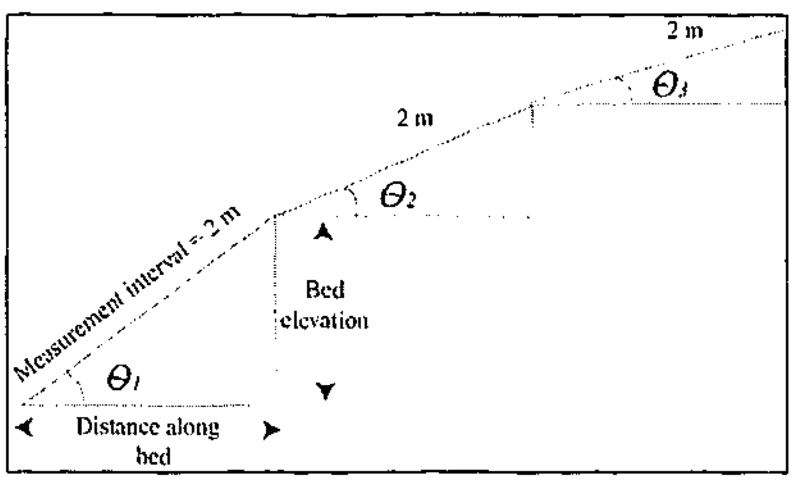


Figure 8.3: Description of vector dispersion technique applied to the thalweg data

Analysis technique 6: Sum of squared height deviations (Σdh^2)

Consecutive substratum height differences (Σdh^2) were first described by McCormick (1994), and later applied by Beck (1998). The value is simply calculated by the summation of the squared differences between consecutive points along a topographic profile. The higher the value the greater the height deviation.

Analysis technique 7: Wiggliness Factor 'w'

A quantitative parameter 'w', otherwise known as the 'degree of wiggliness' (after Ghosh and Scheidegger, 1971,) was used to express the deviation of angles along the thalweg from the mean elevation (Equation 8.3).

$$w = \sqrt{n \sum (\Delta\Phi_i)^2}$$ Equation 8.3

where n is number of angles, $\Delta\Phi$ is the change in angle between successive points, and w is considered as the non-dimensional degree of wiggliness as the value of w is dependent on the length of the line. This is considered appropriate as the reach length remained consistent in each study.

Summary

Table 8.1 summarises the data analysis techniques that are considered to best describe the variability of the thalweg data. To bring all of the data within the same order of magnitude, some scaling adjustments were made to the data. The right hand column of Table 8.1 describes these.

Table 8.1: Summary of methods used to describe thalweg variability

Thalweg	Adjustment to data value
Loess (Local Linear Smoothing)	No correction
Standard deviation of depths (SD)	Multiply by 10
Fractal dimension (D)	No correction
Chain and Tape (C)	(C-1)*10
Vector Dispersion (VD)	Multiply by 100
Sum of squared height differences (Σdh^2)	Divide by 10
Non-dimensional degree of Wiggliness ($\bar{w}$)	Divide by 10

8.3.2. Cross-sections

This section outlines the range of techniques used to quantify the spatial variation of cross-sections. For some of the techniques, adjustments have been made to non-dimensionalise the data. This allows different sized cross-sections to be compared, both within and between reaches, along the length of the stream.

Analysis technique 1 - Channel shape using hydraulic mean depth

It is expected that sediment slugs would have an affect on changing the general shape of a channel. A method was therefore required to quantify the difference in channel shape between the impact and control sites. The technique devised by Western *et al.* (1997) was considered appropriate for this purpose. The shape parameter (ψ) is given by the ratio of the bankfull hydraulic mean depth (cross-sectional area/ water surface width at bankfull) to the bankfull depth (Z_{bf}). Using this relationship, ψ =1 if the channel is approximately rectangular, and ψ = 0.5 if the channel is approximately triangular. It would thus be expected that channels that have been severely impacted by sediment will have a ψ value closer to 1.0.

Analysis technique 2 - Trapezoid method

The expected response of a cross-section impacted by a sediment slug is for it to become more 'flattened out', and take on a more 'trapezoidal' shape (eg. Figure 8.4). Hence, assessing the trapezoidal character of the cross-sections in each reach will provide an estimate of the change in shape variability as a result of sediment slug impact.

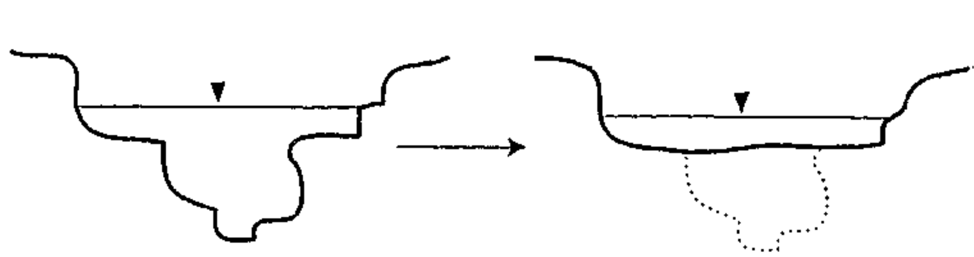
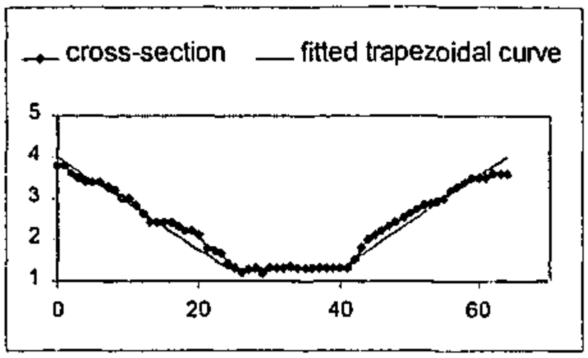


Figure 8.4: Expected change in channel shape following disturbance by sediment slug

To determine the change in shape variability, a trapezoidal function is fitted to each cross-section in each reach. The variation is then assumed to be the amount by which the true cross-section deviates from the fitted trapezoidal cross-section; this is calculated by the residual sum of squares. The standard error (SE) of the estimate is then used as a measure of the variation of the actual values from the fitted vales. A trapezoidal cross-section has limited variability in flow and morphology, and hence has a reduced diversity of habitat niches (Skinner et al., 1998). Therefore, the higher the SE value, the more variable the cross-section. For instance, the left hand cross-section in Figure 8.5 would have a lower SE than the right hand cross-section.



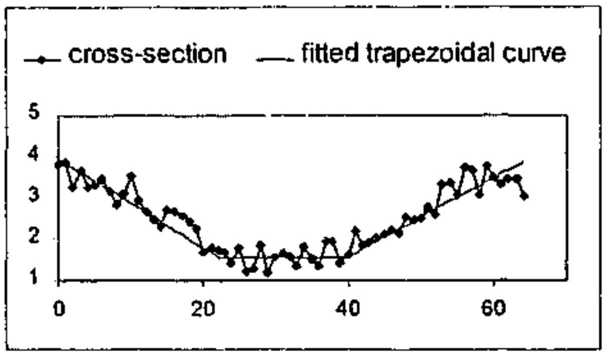


Figure 8.5: Example of how a trapezoid is fitted to a cross-section

In this study, the trapezoidal channels were fitted against the actual profiles assuming that each channel had a bed and two banks. The point at which the bed was separated from the banks was determined by:

- minimising the standard error of the trapezoid when plotted against the cross-sectional data giving the most appropriate fit of the trapezoid; and
- knowing where the wetted perimeter is in each cross-section at low flows, based on the methods described in Section 5.5.5.5.

Two different values of variability were then calculated using the trapezoidal technique:

1. the total cross-sectional variability ($Trap_W$); and
2. the variability of the bed only ($Trap_B$).

The higher the SE for each measure, the greater the variability.

Depending on the section of stream that has been sampled, there will be some cross-sections that have natural trapezoidal cross-sections eg. at riffles. The sampling strategy within each reach was random; therefore there is an even chance of having cross-sections placed in pools or riffles.

Analysis technique 3 - Adaptation of the 'Gini Co-efficient' (G)

The Gini coefficient (*G*) was used by Olsen-Rutz and Marlow (1992) to describe the distribution of channel depth measurements. This was done using changes in cross-sectional depth between consecutive temporal measurements of a given cross-section. Here *G* is evaluated using Equation 8.4, which determines the arithmetic average of the difference between all pairs of cross-sections depths (Y_i - Y_j), taken at different points in time.

$$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left|Y_i - Y_j\right|}{2n^2\,\bar{Y}}$$ Equation 8.4

In this study, the method has been adapted so it can be applied to cross-sectional changes through space. As each reach contains ten randomly spaced cross-sections, the Gini co-efficient (*G*) can be used to describe the spatial variability of cross-sections within each reach; the higher the value of the G, the greater the cross-sectional variability. Generally, a wide flat channel with little depth variability will have a low *G* value; a stream that is deep and narrow will have a greater distribution of depths, and a greater *G* value. This method provides only one value of heterogeneity per reach, which differs from the other techniques that provide one value per cross-section, or ten per reach.

Analysis technique 4 -Fractal Dimension

For analysis of the cross-sections, a slight adaptation was made to the method used on the thalweg profiles. For the thalweg data, the dividers method was used (after Sugihara and May, 1990); for the cross-sections, 'fractal mean' (after Nams, 1996). The difference between the two is that 'fractal mean' calculates D by starting at different randomly chosen points along the cross-section, and 'walks' backwards and forwards using a boot-strapping technique; otherwise all other aspects of the analysis are the same as that described in Section 8.3.1. When this method was compared with the dividers method, the results were always within the same order of magnitude (ie. wiggly lines had the highest values; the least wiggly lines had the lowest values). Therefore, it didn't matter which method is used, the main advantage in using the fractal mean is that is was computationally easier due to access to the program VFractal, also described in Nams (1996) (http://www.nsac.ns.ca/envsci/staff/vnams/Fractal.htm).

Analysis technique 5 -' Chain and tape' method

The chain and tape method is similar to that described for the thalweg, and calculated as the ratio of the apparent distance to linear distance. It is determined using *WP/w*, where *WP* is the wetted perimeter or length along the bed and *w* is the width of the channel at bankfull.

Analysis technique 6 - Vector Dispersion (VD)

The calculation of VD was exactly the same as for the thalweg profiles. It was initially considered important to non-dimensionalise the VD to account for each cross-section being different lengths. However, after close examination of the formula (Equation 8.2), the length of the wetted perimeter is used to calculate the angle ($\cos\theta$). It would therefore be inappropriate to use wetted perimeter to non-dimensionalise the data. Hence, the same VD equation is used for both the thalweg and cross-sections.

Analysis technique 7 - variation in height Σdh^2

The application of the summation of consecutive squared height differences is essentially the same method as used for the thalweg. The method was slightly modified to allow for variation in the length of each cross-section. The final result was non-dimensionalised by dividing through each cross-section by the wetted perimeter (WP). This then allowed cross-sections from different parts of a stream to be compared.

Analysis technique 8 - ' degree of wiggliness' method

This method is almost identical to that used for the thalweg. The difference being that the wiggliness factor w, is simply divided by the length of the wetted perimeter (Ghosh and Scheidegger, 1971). This is considered to be the dimensional degree of wiggliness, represented as $\bar{w}$ in Equation 8.5.

$$\bar{w} = \frac{\sqrt{n\sum(\Delta\Phi_i)^2}}{WP} \qquad \text{Equation 8.5}$$

where WP is the length of the wetted perimeter, n is number of angles, and $\Delta\Phi$ is the change in angle between successive points. Equation 8.5 essentially expresses the variability as per unit length of the line (or cross-section).

Summary

A total of eight analysis techniques were applied to the cross-sections, as summarised in Table 8.2. For ease of data analysis, adjustments were made to bring all the data within the same order of magnitude. Table 8.2 indicates this.

Table 8.2: Summary of methods used to describe cross-sectional variability

Cross-sections	Adjustments to data
Hydraulic mean depth (ψ)	No correction
Trapezoidal method	Multiplied by 10
Gini-coefficient	No correction
Fractal Mean (D_M)	(D-1)*10
Chain and Tape	(C-1)*10
Vector Dispersion	Multiplied by 10
Sum of squared height differences (Σdh^2)	Divided by 10
Non-dimensional degree of Wiggliness ($\bar{w}$)	No correction

8.3.3. Sediment Variability

The analysis process used for the sediment data was slightly different to that used for the thalweg and cross-sections. There are four methods useful for describing the variability of the particles within a sediment sample: skewness, sorting, kurtosis and heterogeneity (Briggs, 1977; Williams, 1980). With the thalweg and cross-sections it is not certain as to whether the techniques are measuring different or similar aspects of the data. With the sediment data, however, it is already established (from the literature) that the techniques measure different aspects of the sediment size distribution. The exception is analysis technique 4 (substrate heterogeneity), which has not been rigorously tested against the other techniques. Each of the measures is calculated for each site from a cumulative frequency plot of the sediment size distribution. For each of the frequency plots, the y-axis represents the % sediment retained, or % coarser.

Analysis technique 1 - Phi skewness

Skewness is a measure of the asymmetry of a sediment sample, or the non-normality of the distribution. Measuring skewness requires a comparison of the mean and median phi values, and can be calculated using Equation 8.6 (after Briggs, 1977).

$$Sk = \frac{\phi 84 - \phi 50}{\phi 84 - \phi 16} - \frac{\phi 50 - \phi 10}{\phi 90 - \phi 10}$$ Equation 8.6

The distribution can be either positively or negatively skewed. Positive skewness represents a fine tail to the sample, negative skewness represents of 'coarse' tail. Typical values of sorting for sediment samples are given in Table 8.3

Table 8.3: Typical range of skewness values (Briggs, 1977)

Description	Value
Very negatively skewed	-1 to -0.3
Negatively skewed	-0.3 to -0.1
Symmetrical	-0.1 to 0.1
Positively skewed	0.1 to 0.3
Very positively skewed	0.3 to 1.0

Analysis technique 2 - Phi Sorting

Sorting is a measure of the dispersion or scatter of sediment within a sample, and is simply an expression of the standard deviation of the size distribution (Briggs, 1977). It can be calculated using

$$Sorting = \frac{\phi 84 - \phi 16}{2}$$ Equation 8.7

A high degree of sorting is represented by a low value. Hence, a sample with a wide range of sample sizes will be poorly sorted, and have a high sorting value; whereas a sample containing a small number of ∅ sizes would have a low sorting value. A description and typical range of sorting values is given in Table 8.4.

Table 8.4: Range of sorting values (Briggs, 1977)

Description	Sorting value
Very well sorted	<0.35
Well sorted	0.35 to 0.5
Moderately well sorted	0.5 to 0.7
Moderately sorted	0.7 to 1.0
Poorly sorted	1.0 to 2.0
Very poorly sorted	2.0 to 4.0
Extremely poorly sorted	> 4.0

Analysis technique 3 - Phi Kurtosis

Kurtosis measures the 'peakedness' of the size distribution, and can be calculated using Equation 8.8 (Briggs, 1977). Kurtosis incorporates aspects of both sorting and the degree of non-normality; a poorly sorted sample will tend to have a relatively flat particle size distribution.

$$Kurtosis = \frac{\phi 90 - \phi 10}{1.9(\phi 75 - \phi 25)}$$ Equation 8.8

A sediment size distribution curve that is flatter than a normal distribution is described as platykurtic; one that is more peaked than normal is described as leptokurtic. A normal distribution is mesokurtic. A description of the range of values used to describe kurtosis is given in Table 8.5.

Table 8.5: Range of kurtosis values (Briggs, 1977)

Description	Value
Very platykurtic	<0.67
Platykurtic	0.67 to 0.9
Mesokurtic	0.9 to 1.11
Leptokurtic	1.11 to 1.5
Very leptokurtic	1.5 to 3.0
Extremely leptokurtic	> 3.00

Analysis technique 4 - Substrate heterogeneity

Schwoerbel (1961) presented a method for calculating the heterogeneity or degree of particle size diversity, using the ratio of the D_{10} to D_{60} of the sediment size in millimetres. Based on using the cumulative % of sediment retained (the equation is inverse for % passing), the heterogeneity can be calculated using

$$\text{Heterogeneity of sediment} = D_{10}/D_{60} \qquad \text{Equation 8.9}$$

Williams (1980) applied this method to assess the relationship between species abundance and substrate heterogeneity, and suggests that values will range from approximately 1.0 for low heterogeneity, to around 6.0 for high heterogeneity, although some streams may have heterogeneities greater than 10.0.

8.4 Calibration of techniques using synthetic data

Despite the increasing application of techniques to quantify spatial variability in various areas of science, there have been few papers that have critically reviewed any of the above methods. McCormick (1994) looked at the various techniques he used to correlate surface topography and tropical reef assemblages. He used a range of vector dispersion techniques, a number if adaptations of Σdh^2 and 'Chain and Tape'. He found that none of the techniques identified all possible combinations of surface heterogeneity, and advised that a combination of descriptors will provide the most information about habitat structure. Carleton and Sammarco (1987) also used similar indices, and concluded that VD was the best tool for measuring surface irregularity.

As it is apparently the first time that many of the above techniques had been used at this scale in geomorphology, it was not possible to determine which of the myriad of techniques would be the best at describing the heterogeneity of each of the data sets. It is not necessarily practical to use all of the techniques described, and it is highly probable that considerable overlap (correlation) exists between each method. This would lead to excess data analysis that would provide the same result.

The overall aim of this section is to determine the minimum number of techniques that adequately describe the variability of each of the data sets. To do this, a method is required to test each of these techniques to:

1. Determine if these techniques adequately describe the heterogeneity of the data;

2. Determine if there is any cross-correlation between the methods. If so, is it possible to reduce the number of techniques to a set that provides the greatest amount of information using the least number of methods; and
3. Eliminate the less useful techniques, and describe how the more appropriate techniques can be used.

To address these questions, a series of synthetic data sets were created with clear differences in variability. Each of the analysis techniques was then tested on each data set. Those that were not useful at quantifying the heterogeneity were removed; the remaining techniques were subject to multivariate Factor Analysis.

Factor Analysis

Factor Analysis attempts to identify underlying variables or factors that explain the pattern or correlations within a set of observed data. It makes it possible to identify a small number of factors that explain most of the variance from a larger group of variables. Hence, factor analysis will 'plot' out the data (in this case in two-dimensional space); factors that sit closely together are highly correlated, and those far apart are portraying different aspects. This technique determines which groups of techniques are similar. It is then possible to choose one representative method from each group.

Factor analysis was carried out using the 'data reduction menu' in SPSS™ Version 10.0 (1999). The principle components method was used to extract the data, and the data checked to meet all assumptions. The latter included testing for outliers, and making sure that the data was normally distributed (Howard, 1991, p 104). Each variable was also evaluated for its KMO (Kaiser-Meyer-Olkin) value, a measure of sampling adequacy, and only included if it was greater than 0.01. Each set of values was also subject to varimax rotation which more clearly identified the correlated groups.

8.5 Thalweg Variability

8.5.1. Calibration of techniques using synthetic data

To test each of the techniques described in Section 8.3.1, six synthetic thalweg profiles were created in Excel™97. Each curve contained a periodic component; the first three curves also contained a random element, created by a random number generator. All six curves are shown in Figure 8.6; their profiles are the same length (300 m), but with varying amplitude and frequency. This is meant to represent differing levels of heterogeneity, characteristic of river bed profiles. The curves are in the order of greatest expected variability (curve A) to the least variability (curve F), although (B) and (C) could be interchangeable.

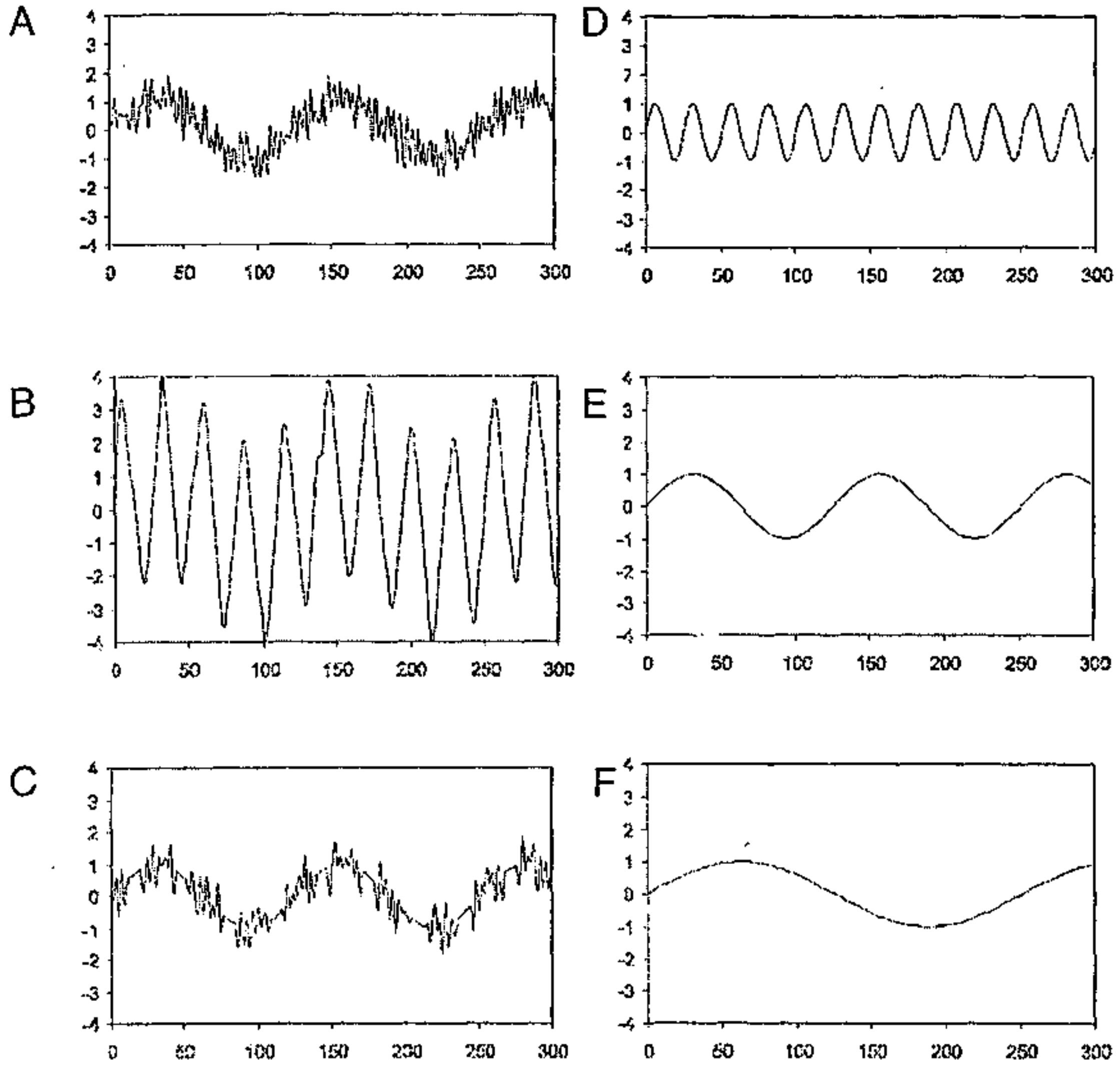


Figure 8.6: Synthetic thalweg curves

8.5.2. Results of analysis using synthetic data

The results of the data analysis using the synthetic curves are summarised in Figure 8.7. They show that all of the analysis techniques provide similar results, with curves A, B and C, having higher variability than curves D, E, and F. The main difference between the techniques is that the Loess, SD and Fractal techniques all consider curve C to have the highest level of variability, whereas the Chain and Tape, VD, sum of height deviations and wiggliness put curve A ahead of curve C, then B. Based on these results alone, it is difficult to determine which factors are most appropriate for evaluation of thalweg variability.

The results of the Factor Analysis provide a clearer picture of the relationship, highlighting the correlations between the different analysis techniques. All data were assessed for multivariate outliers using the Mahalanobis distance function; no outliers were detected (α =0.001). Only SD was not normally distributed but no transformation adequately corrected for this, however, due to the nature of this analysis, it is not considered that it will affect the results.

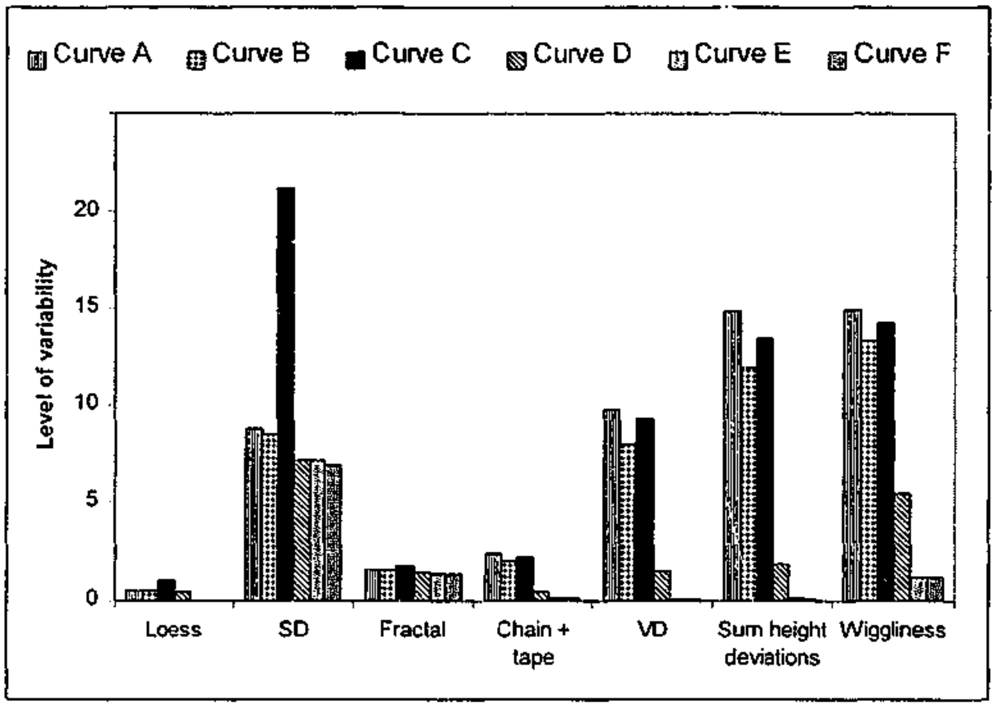


Figure 8.7: Results of data analysis of the synthetic thalweg curves.

Overall, the data analysis showed that two factors (groups) contributed to 98% of the variance in the data, with Factor 1 contributing to 87% of this variability (Table 8.6). These results show that, although most of the variables are highly correlated with each other, there are still three distinct sub-groups within Factor 1. This can be seen more clearly in the component plot shown in Figure 8.8. The three main sub-groups include: Group1 - sum of height deviations, Chain and tape, wiggliness factor and VD; Group 2 - loess and fractal; and Group 3 is SD.

The main difference between the three groups is that Group 1 (shown in italics in Table 8.6) calculates the degree of angulation of each point along the line. Group 2 (is underlined) describes the arrangement of each point based on the position of previous points along the curve, and Group 3 (in bold) looks at the deviation of points away from a straight line. Each group is important, and provides a slightly different estimate of variation. Both Groups 1 and 2 look at how 'wiggly' the line is, whereas Group 3 represents the overall height deviation of the profile, which is also important. This result suggests that the factors in each group are highly correlated with each other and only one factor from each group would be needed to adequately describe the variability of the thalweg profiles.

Table 8.6: Results of the Factor Analysis for synthetic thalweg curves (after varimax rotation)

Variable	Factor 1	Factor 2
Sum height deviations	*0.933*	0.354
Chain and tape	*0.932*	0.356
Wiggliness	*0.925*	0.369
VD	*0.921*	0.385
SD	**0.232**	0.963
Loess	0.563	0.792
Fractal	0.660	0.750
Eigenvalue	6.10	0.806
% Variance	87.1	11.5
Cumulative %	87.1	98.6

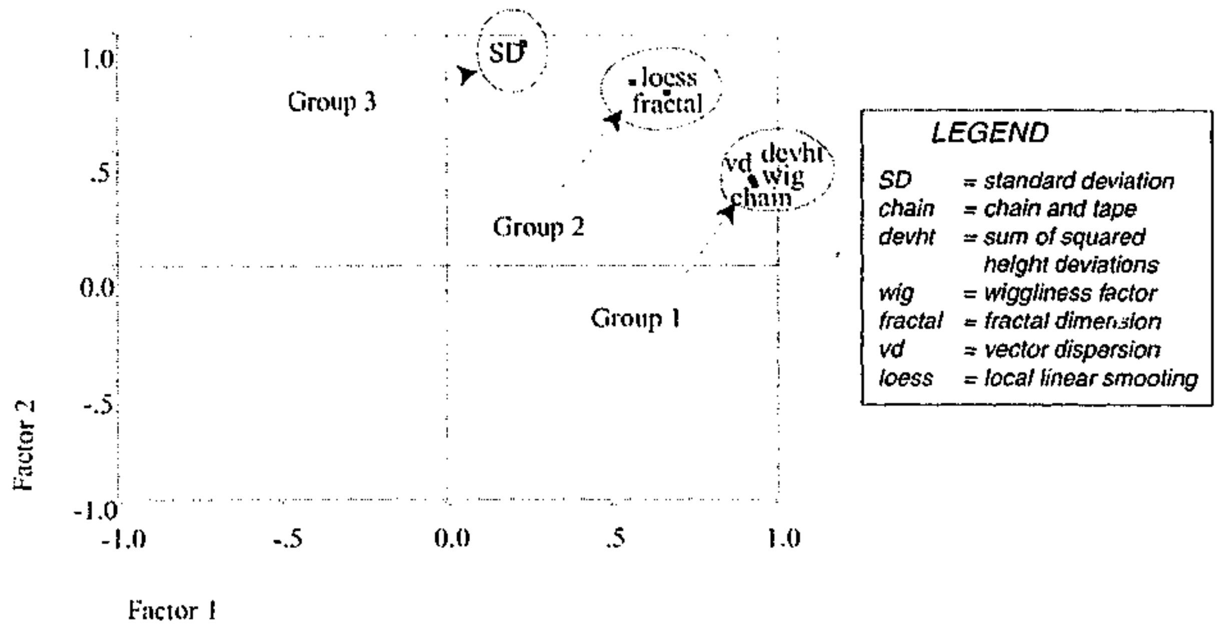


Figure 8.8: Component plot of rotated factors for thalweg analysis showing the 3 different groups.

The process of choosing the most appropriate factor (from the groups with multiple factors) cannot be done using further quantitative analysis. Essentially, it shouldn't matter which individual analysis technique is chosen, as each should yield the same results for any given data set. Thus, the main criteria used to decide the final suitable factor were (a) the analysis technique that is computationally least intensive, and (b) the technique with appropriate critical review in the literature.

Of the factors in Group 1 (sum of height deviations, chain and tape, wiggliness factor and VD), both VD and wiggliness have been considered most useful in the literature. As the wiggliness factor is slightly easier to calculate, it will be used to represent Group 1. Group 2 only has two factors (loess and fractal); seeing that fractal analysis has obtained much wider critical evaluation in the literature, it will be used to represent Group 2. Group 3 is represented by SD, and will be used to represent that group.

In summary, thalweg variability can be adequately described using:

1. the wiggliness factor (w);
2. fractal dimension (D); and
3. standard deviation of depths of the bed profile (SD).

It is important to note that any of the techniques tested in this analysis are suitable measures of thalweg variability. In other studies of geomorphic disturbance and recovery, some of the other factors may be more suitable.

8.6 Cross-sectional Variability

8.6.1. Calibration of techniques using synthetic data

To test the various cross-sectional analysis techniques (presented in Section 8.3.2), ten synthetic cross-sectional profiles were developed to represent different levels of variability; each was constructed using a parabolic curve, and a random profile (calculated from random number generator). The level of randomness and the overall shape of the curves was chosen to represent realistic river cross-section profiles. Unlike the thalweg profiles, the cross-sections usually have varying widths. To take this into consideration, the curves differed in length as well as shape variability. This provided a more rigorous test of the analysis techniques, enabling cross-sections to be compared across various scales.

There are 4 groups of paired curves which are essentially the same profile expressed over different horizontal scales (length). Curves A and B, C and D, E and F, and I and J are pairs of the same curve, with the first being twice the length scale of the second (Figure 8.9). Curves G and H are not matching pairs, but are slight deviations from curve E. It is difficult to determine the exact order of the profiles in terms of high and low heterogeneity; however, they appear to decrease in variability from curve A - J. It is expected that the shorter of the paired curves will have greater variability than the long curves, per unit length.

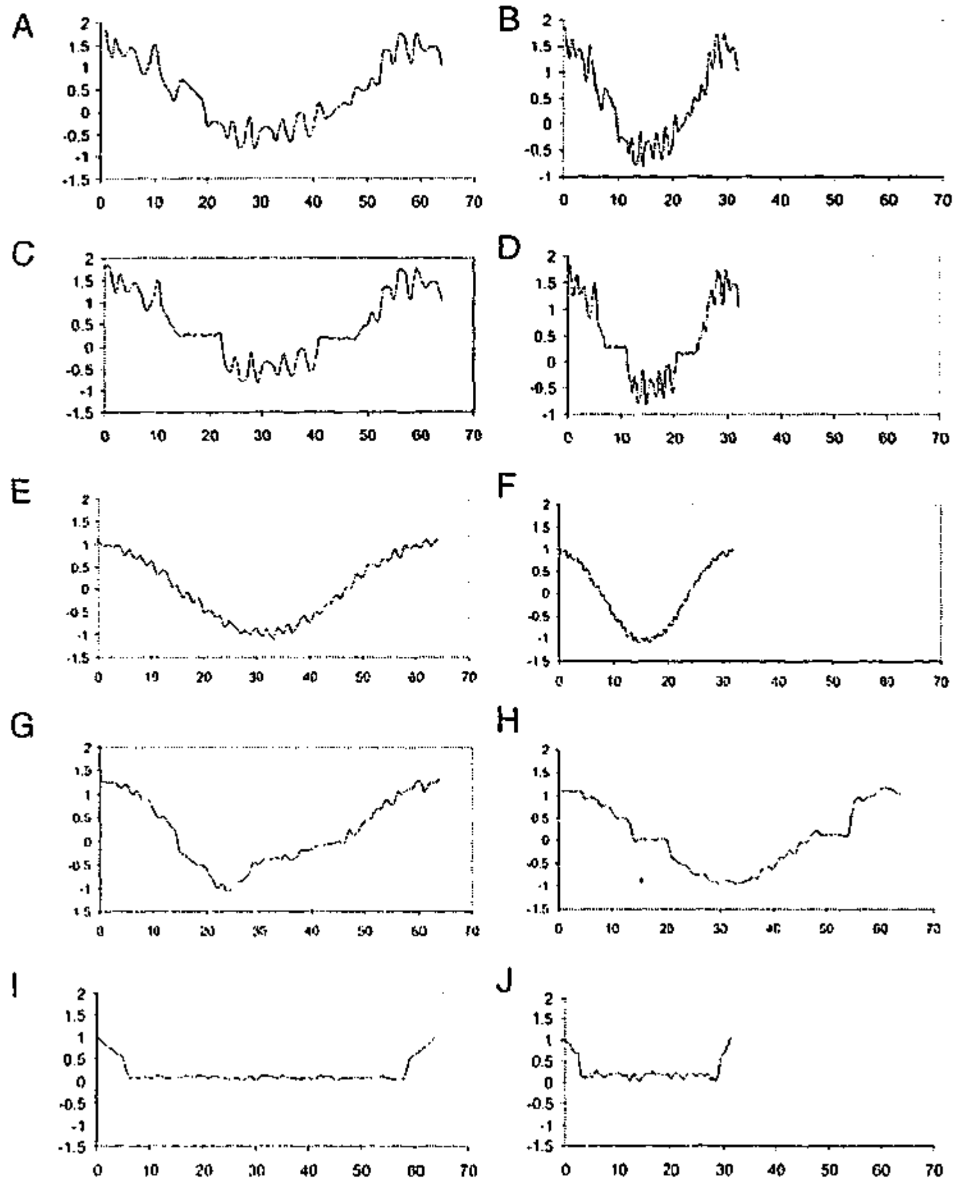


Figure 8.9: Synthetic cross-section profiles

8.6.2. Results of the analysis using synthetic data

The results of the synthetic cross-section analysis are summarised in Figure 8.10, and show differences between techniques. The fractal dimension (D), chain and tape, VD, sum of squared height deviations (Σdh^2) and wiggliness factor (w) put the curves (in Figure 8.9) in the same order of variability starting with curve B and D as the highest and curves J and I as least variable. These techniques appear to provide a logical result for the order of variability of the synthetic curves.

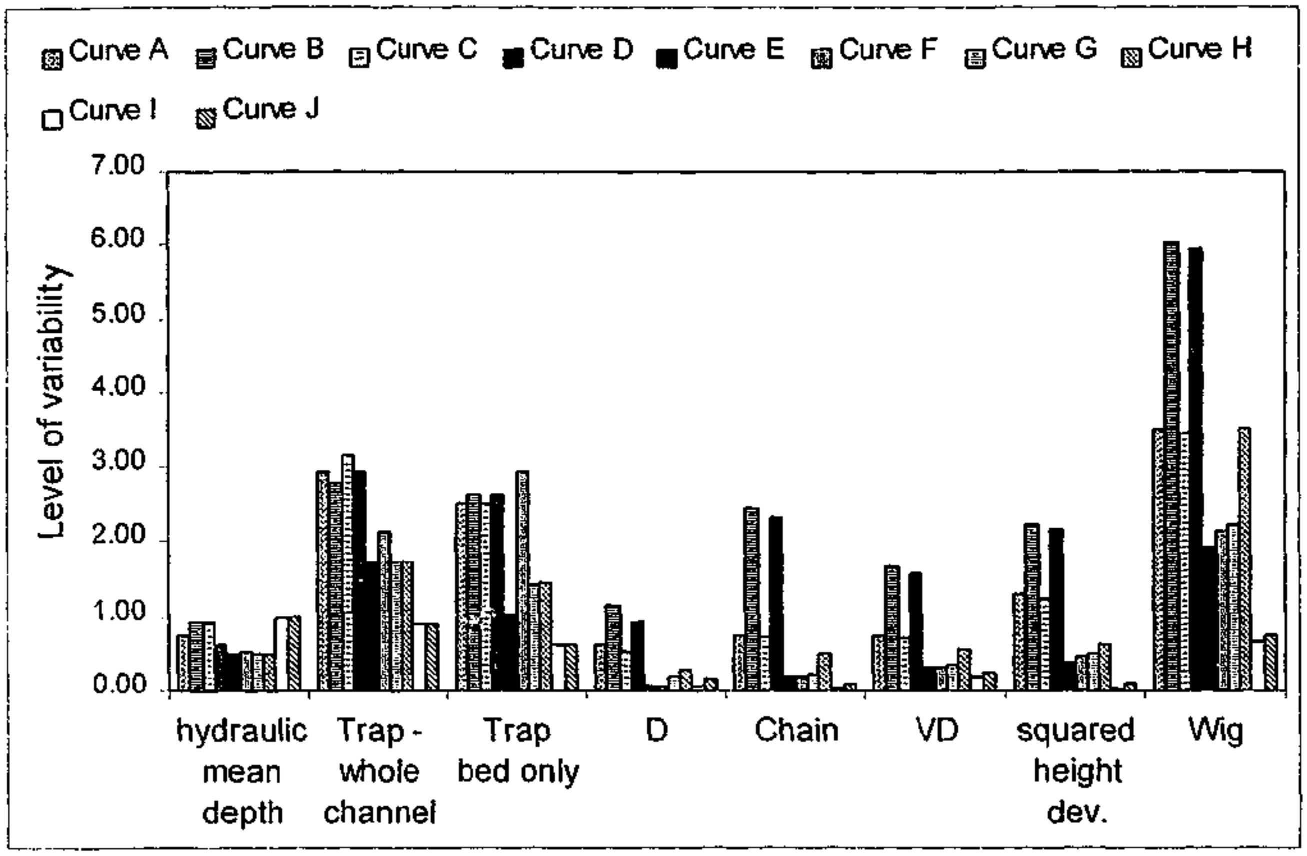


Figure 8.10: Results of synthetic cross-sectional analysis (curves shown in Figure 8.9).

The hydraulic mean depth (ψ), and both of the trapezoidal methods, differ in the order of variability they give for the curves. The hydraulic mean depth result orders the curves according to their similarity, with either a rectangle (ψ = 1.0) or triangle (ψ = 0.5). Although this is a useful indicator for determining if there has been a dramatic change in channel shape due to disturbance, it does not provide an accurate indicator of cross-sectional 'variability'. For this reason, the hydraulic mean depth technique is not considered appropriate and is not considered further.

The trapezoidal technique, which is divided into two sections (whole channel and bed only), provide different results. The first method (whole channel) provides an estimate of the overall cross-sectional variability, and places Curves C and A slightly ahead of Curves D and B which differs from the other techniques; however, Curves I and J are placed 9th and 10th as with the other curves. The 'bed only' results for the trapezoidal method have a different ordering for the results. This is because it looks only at the variability of the bed of the channel, and not the whole channel. This will probably be an appropriate technique when looking at localised micro-habitat changes. In this study, however, it is important to look at the entire in-stream environment. The whole channel is important for a number of reasons:

- There are important hydrologic and ecological interactions between the channel and floodplain, which would not be incorporated into the bed only analysis;
- It is possible to have a diverse bed structure within a very simple channel form. For example, incised streams can have diverse sediments on the bed with non-diverse vertical bank walls. Hence, using the bed only analysis would bias the results;
- Bench structures are a part of the bank; these are considered to be very important recovery features (after Erskine, 1994), and would not be detected if the 'bed-only' analysis was used.

For all of these reasons, the 'bed-only' technique was also removed from the analysis.

It is important to note that the results of the 'Gini-coefficient' were not included in this analysis. That is because this technique produced only one variability value per reach, rather than one for each cross-section (ie. 10 values), making it difficult to compare to the other results. Closer evaluation of the Gini coefficient also shows that this provides a better measure of downstream changes in depth, rather than cross-sectional variability. It would be a useful rapid indicator of reach depth variability in future studies; however, it is not considered appropriate for estimating cross-sectional variability in this study, and was removed.

After the removals outlined above, the remaining techniques considered appropriate for evaluating cross-sectional variability are:

- trapezoidal method for the whole channel ($Trap_W$)
- fractal dimension (D)
- chain and tape (Chain)
- vector dispersion (VD)
- squared height deviations (Σdh^2)
- wiggliness factor (w)

To further assess the similarity (cross-correlation) of these techniques, they were subjected to Factor Analysis as described in Section 8.4; results are presented in Table 8.7, and then graphically in the component matrix in Figure 8.11. All the data were initially tested for normality and outliers. The chain and tape data was not normally distributed, but was adequately transformed using the natural log function. The mahalanobis function also showed that there were no outliers in any of the data sets (α =0.001). The data analysis showed that two factors (groups) contributed to 97% of the variance in the data, and that

Factor 1 (shown in *italics* in Table 8.7) contributed 92% of this variability. This shows that all of the analysis techniques are very similar; only one technique, the trapezoid method, showed less correlation with Factor 1, and more with Factor 2 (underlined in table). This result suggests that VD, D, Σdh^2, wiggliness, and chain and tape (Factor 1) all provide similar estimates of cross-sectional variability; only the trapezoid method (Factor 2) provides slightly different estimates.

Table 8.7: Result of the factor analysis using synthetic cross-sectional data (after varimax rotation)

Variable	Factor 1	Factor 2
VD	*0.918*	0.391
Fractal (D)	*0.882*	0.438
Sum squared ht dev. (Σdh^2)	*0.822*	0.563
Wiggliness	*0.813*	0.555
Trapezoid	<u>0.400</u>	0.906
Chain and Tape	*0.664*	0.708
Eigenvalue	5.493	0.355
% Variance	91.56	5.91
Cumulative Variance	91.56	97.46

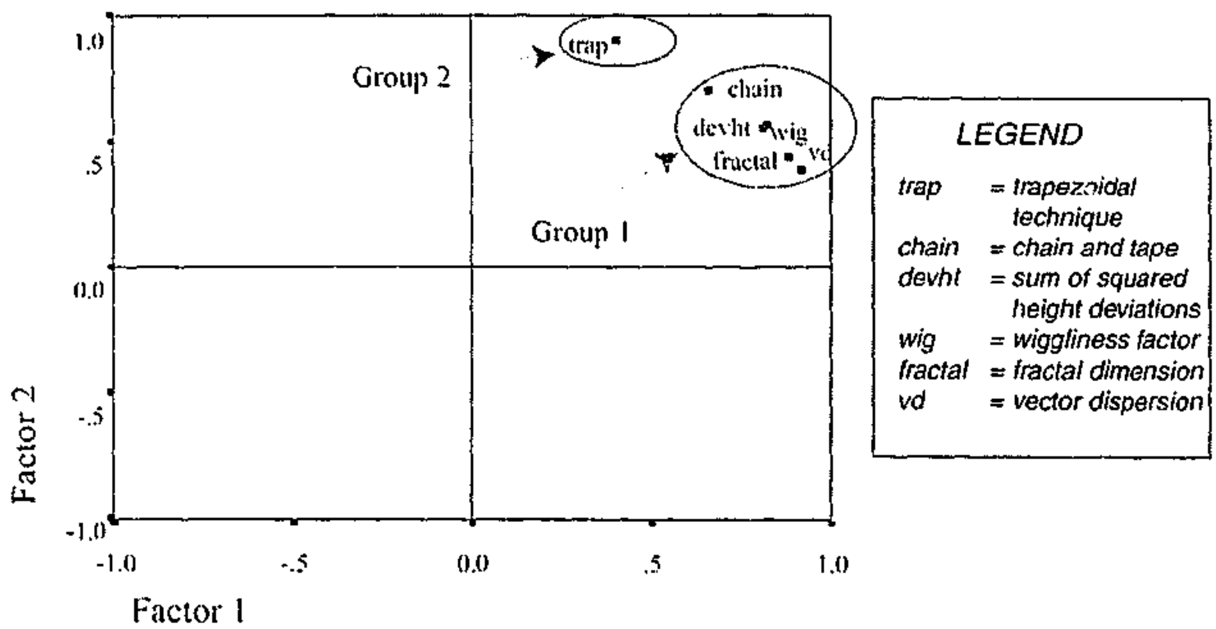


Figure 8.11: Component plot of rotated factors for cross-section analysis

It is difficult to chose which of the five variables best represents Group 1. Based on the synthetic data, application of any of the techniques would provide similar and appropriate estimates of cross-sectional variability. As VD and wiggliness both calculate the deviation of angles around each data point, only one of them would be required. Wiggliness was used in the thalweg analysis, yet VD was considered one of the better techniques for calculating heterogeneity in a study by Carleton and Sammarco (1987). On this basis, VD was adopted for this study.

Of the remaining techniques, fractal analysis is computationally the most intensive, given the number of cross-sections involved. It was also incorporated into the thalweg analysis; hence, it was not used for the cross-sectional analysis. The final two techniques are Σdh^2, and 'chain and tape'. The Σdh^2 provides an estimation of height deviations across a profile, whereas the chain tape is simply a ratio of lengths; it does not really incorporate changes in height or angle along the transect. For this reason, Σdh^2 was adopted to represent cross-sectional variability.

In summary, the initial nine variables that were chosen to quantify the cross-sectional heterogeneity were reduced to three:

1. Trapezoid method for the whole channel (Trap);
2. Vector Dispersion (VD); and
3. Sum of the squared height deviations (Σdh^2)

Each of these techniques use slightly different methods to quantify the variability of a cross-section. The trapezoid method measures the deviation of a cross-section away from a trapezoid, the VD method measures the deviation of angles along the line, and the Σdh^2 measures the change in elevation between consecutive points. Together, this group provides a well-rounded estimate of cross-sectional variability.

8.7 Sediment Size Variability

8.7.1. Calibration of techniques using synthetic data

To help select which of the sediment analysis techniques would be most appropriate, eight synthetic sediment samples were developed. The percentage composition of each of the samples is shown graphically in Figure 8.12. All the samples were 1000g and all had size distributions between 0.063 and 8 mm (or 4ϕ and -3ϕ), typical of the sediments collected from the study rivers. Sample 1 represents an even distribution of sediment sizes. Samples 2 and 3 have greater proportions of coarse sediment, with Sample 2 being the coarsest. Samples 4 and 5 have an increased proportion of fine sediment, with sample 4 being finer than 5; Samples 2 and 4, and 3 and 5, are exact opposites (ie. reversed) of each other. Samples 6, 7 and 8 were developed using a random number generator, and thus have a random range of sizes. The variation in the arrangement of sediment sizes provides a good test of the techniques described in 8.3.3.

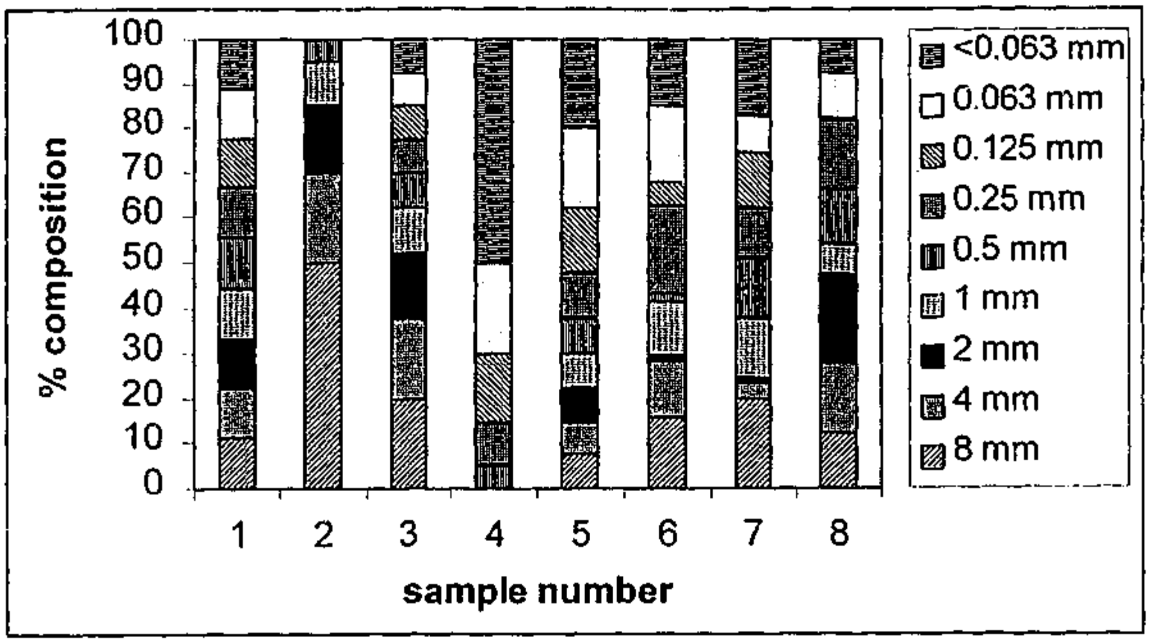


Figure 8.12: Synthetic sediment samples

Each of the samples was analysed with the four techniques described in Section 8.3.3: skewness, sorting, kurtosis and heterogeneity. Unlike the methods used to analysis the thalweg and cross-sections, those for analysing sediment samples are quite different in their function, as they measure different aspects of the sediment sample. It is, therefore, not appropriate to undertake Factor Analysis on this data, as the techniques do not have the same scale. For example, a high value does not consistently represent a sample containing many size classes, and vice versa.

The results need to be evaluated qualitatively, and assessment of the most appropriate method/s determined, with the main purpose of the analysis in mind. That is, the method/s needs to be able to differentiate between samples that are dominated by a few sample sizes, compared to samp. . that have a wide range of sediments.

8.7.2. Results of analysis using synthetic samples

The results of the analysis for each of the eight samples is given in Table 8.8. A full description of each of the sediment analysis techniques was given in 8.3.3.

Table 8.8: Results of the synthetic sediment sample analysis

Sample	Skewness	Sorting	Kurtosis	Heterogeneity
1	0.01	3.06	16.80	19.96
2	1.00	0.97	1.75	1.33
3	0.40	2.93	15.40	6.67
4	-0.91	1.02	1.96	6.05
5	-0.38	2.98	15.63	46.67
6	-0.24	3.46	21.23	28.09
7	-0.11	3.55	15.05	26.47
8	0.28	2.97	13.45	10.53

Of the four techniques, kurtosis is too abstract and does not provide a direct measurement of the variability of the sample, only the shape of the distribution. Skewness differs from both sorting and heterogeneity as the scoring index is represented using a 'bell-curve' scale. This means that samples that have the greatest variability will have a skewness of zero as the size classes are evenly distributed. Although this provides useful information about the distribution of sediments, the measurement scale would not be comparable with the other indices.

Therefore, the remaining two techniques, sorting and heterogeneity, would seem to be the most appropriate. Even though they are similar in their scaling systems, (ie. high number, high heterogeneity), they are poorly correlated ($r^2 = 0.39$) and provide slightly different estimates of the heterogeneity of the data.

In summary, the two variables that will be used to assess the variability of the sediment samples are:

1. Sorting; and
2. Heterogeneity.

8.8 Summary and application of techniques

This chapter presented 21 different techniques for quantifying the variability of three geomorphic features: the thalweg, cross-section and sediment size. Of the 21 techniques, only 8 measures were considered suitable following a rigorous evaluation of each technique using synthetic data. A summary of the chosen variables is presented below. Each of the techniques chosen will now be used to quantify the real river data that was collected from the three study sites (and previously presented in Chapter 6). The results of this analysis is presented in Chapter 9.

<u>*Thalweg*</u>

The three techniques that were considered the most appropriate for quantifying the variability of the thalweg are the:

- Wiggliness factor (w)
- Fractal Dimension (D)
- Standard deviation of bed elevation heights (SD)

The selected techniques for quantifying the variability of the thalweg were applied to the 36 thalweg profiles from the three study streams.

Cross-sections

The three techniques that were considered the most appropriate for quantifying the variability of the cross-sections are the:

- Trapezoidal method for the entire channel ($Trap_W$)
- Vector Dispersion (VD)
- Sum of squared height deviations (Σdh^2)

The three selected techniques were applied to a total of 350 cross-sections from the three rivers. Each of the techniques provided a non-dimensional estimate of the variability which allowed cross-sections from different parts of the stream to be compared.

Sediment variability

The two techniques that were considered the most appropriate for quantifying the variability of the sediment data are:

- Sorting
- Heterogeneity

As the sediment samples were all roughly the same size, and collected using the same methodology, it was not relevant to alter or scale the data. The sorting and heterogeneity measures were applied to the 180 sediment samples that were collected from the three study sites.

8.9 Statistical analysis and presentation of results

Following the application of the above techniques to each of the data sets, further statistical analysis is required to determine if there is a statistically significant difference between the groups. This section outlines the statistical techniques used to analyse the thalweg, cross-sections and sediment size variation data, respectively.

Background

The main question that is being asked of the data is: 'is there a statistically significant difference between the variability of any of the factors (eg. thalweg variability) between the groups (ie. the control, impact and recovering sections), following disturbance by sediment slugs'? To respond to this question, data sets that met the assumptions required for rigorous statistical analysis were investigated with a variety of techniques.

In terms of the statistical analysis, when there was a significant difference between the control and recovering reaches, it was concluded that the river has not recovered to its pre-disturbance condition. If, however, there was no significant difference, it is possible to conclude that the river has recovered. This analysis incorporates the concepts of ergodic theory (or space for time substitution) whereby means and variances are constant; "an infinitely long record at one point has the same statistical properties as a record taken over and infinite number of spatial assemblages at a particular point in time" (Harvey, 1967). By using the variance approach, it is possible to apply the definition of ergodic theory to analyse the results and determine which sections of stream have recovered. The outline of the methods and statistical techniques used are described for each of the variables below.

Thalweg data

To determine if there is a significant difference in the thalweg variability between the control, impact and recovering reaches, a one-way-between-groups ANOVA was conducted. Each set of data was screened to make sure it met the assumptions of normality and homoscedasticity. The Shapiro-Wilks and Levene's test were used to test each assumption, respectively (Sokal and Rohlf, 1995). When the data did not conform, data was transformed using natural logarithms. Tukey's post-hoc test was carried out to determine where the significant differences lie ($p<0.05$), both between, and within, groups (Zar, 1996) All statistical tests were carried out in SPSS™ (Version 10.0, 1999).

Cross-sections and sediment size data

The analysis of the cross-sectional and sediment size data had an extra level in the analysis; there were ten randomly placed replicates in each reach for the cross-sections, and five random replicates for the sediment samples (rather than a single value as in the case of the thalweg data). This allowed for a nested analysis of variance (also known as hierarchical analysis of variance) to be conducted. The main benefit of a nested ANOVA is that it can show if there a significant difference both *within* (eg. control) and *between* treatments (ie. control, impact and recovering). The nested ANOVA is essentially two one-way ANOVA calculations; by combining them into one step, the chance of making a Type 1 error is reduced (Sokal and Rohlf, 1995).

One of the main requirements of this type of analysis is that the subordinate level of classification (cross-sections) is randomly chosen (Sokal and Rohlf, 1995). This prerequisite is met as the cross-sections and sediment samples were measured/collected randomly within each reach (as discussed in Chapter 5). It is also an important assumption that the variances be equal; however, Zar (1996) describes how analysis of variance is usually robust enough to perform well, even if the data deviate somewhat from the requirements of normality and homoscedasticity. Nonetheless, Levene's test was used to assess for homogeneity of variances. Tukey's post-hoc test was carried out to determine where the significant differences lie both between, and within, groups. Again, the nested ANOVA calculations were carried out in SPSS™ (Version 10.00, 1999), using the GLM (general linear model) function.

Presentation of results

The results of these analyses are presented in the next chapter (Chapter 9). For each of the data sets, the results are presented in their un-transformed (pre-ANOVA) state, and in the same order; starting with the control, impacted, then recovering reaches. As with the results presented in Chapter 6, this order reflects the Geomorphic Variability model proposed in Chapter 3. The most downstream impacted reach is designated as the first impacted reach; the site that has been recovering for the longest time period is designated the last recovering reach. This order reflects the space for time approach.

8.10 Discussion

This chapter described the data analysis methods used to quantify the variability of each of the data sets. The first part of the chapter presented a brief review of the various techniques used to quantify spatial variability. The most appropriate of these techniques were then described in detail. Techniques for quantifying each of the variables (thalweg, cross-sections, sediment size) were described in turn.

The techniques were then critically assessed against synthetic data. This process identified which techniques adequately quantified the variability in the data and then Factor Analysis was used to determine the similarity (correlation) between the techniques. This process enabled a total of 21 techniques to be reduced to just 8 measures that adequately quantified the morphological data. The process of applying these techniques to the real river data was then outlined.

The final part of this chapter described the statistical techniques used to evaluate the results of the variability analysis. The results of the application of each of these techniques will now be presented in Chapter 9.

Chapter 9

Results: the impact of sediment slugs on the Geomorphic Variability of streams

9. Chapter 9 - Results: the impact of sediment slugs on the Geomorphic Variability of streams

9.1 Introduction

Chapter 8 provided an outline of the various data analysis techniques used to quantify the Geomorphic Variability of a reach. This chapter presents the results of the application of those techniques to each of the data sets. This chapter also presents a detailed discussion of the similarities and differences between the different data analysis techniques, as well as a discussion of how each of the variables respond according to the Geomorphic Recovery Model.

This chapter can be broken into six main sections. Sections 9.2, 9.3 and 9.4 present the results of the data analysis for Creightons Creek, the Wannon River and the Ringarooma River, respectively. For each stream, the data sets are dealt with in turn, starting with the thalweg, the cross-sections, then the sediment variability data. Section 9.5 summarises the results for each stream, and evaluates the response of each of the variables with respect to the Geomorphic Recovery Model. Section 9.6 summarises the different data analysis techniques and presents the single most appropriate measure of variability for each of the variables. Section 9.7 then summarises the chapter.

9.2 Results for Creightons Creek

As described in Chapters 4 Creightons Creek has the smallest catchment area of the three study sites. The main source of sediment fuelling the slug in lower reaches comes from incision in the upper parts of the catchment. A location map is presented again to show the location of the study reaches and provide a context for the results presented in this section (Figure 9.1).

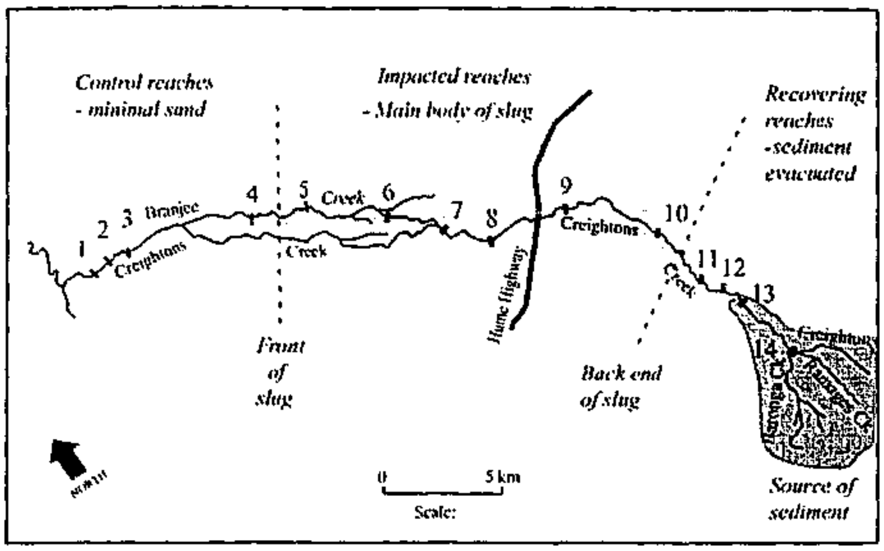


Figure 9.1: Location of reaches along Creighton's Creek

9.2.1. Thalweg results

The thalweg profiles for each reach along Creightons Creek were presented in Section 6.4.1. This data was analysed to quantify the variability of the thalwegs using three analysis techniques: wiggliness factor (*w*), fractal dimension (D), and standard deviation of depths (SD), as described in Chapter 8. Figure 9.2 shows that for all of the variability measures, thalweg variability is highest in the control reaches, then decreases in the impacted reaches, and does not appear to change (increase or decrease) in the recovering reaches (even where the sand has begun to leave the stream). Plate 9.1 shows the visual difference between the control and impacted reaches on Creightons Creek.

Each of the analysis techniques (wiggliness, SD of depths and fractal dimension) underwent a separate ANOVA test. For all of the tests, the thalwegs in the control reaches were significantly different ($p<0.05$) from both the impacted and recovering sections. There was no significant difference between values in the impacted and recovering reaches.

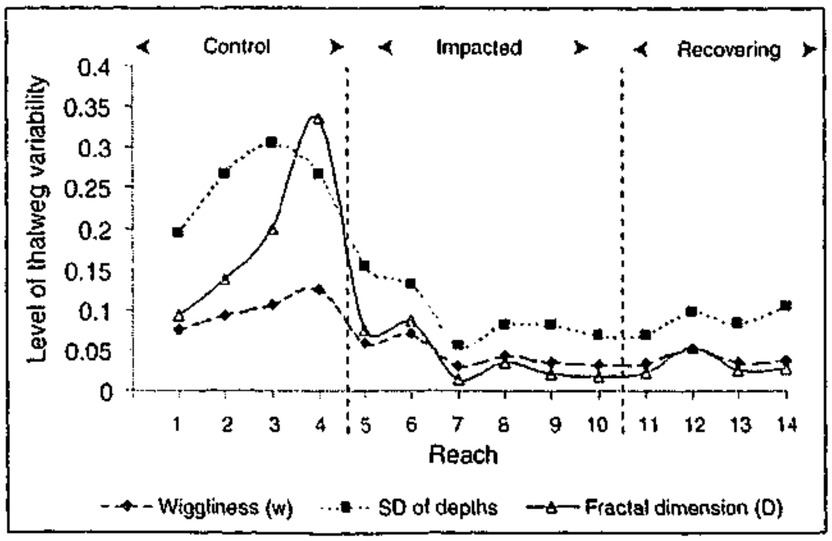


Figure 9.2: Thalweg variability measured for each reach along Creightons Creek

These results show that the introduction of the sediment into Creightons Creek has significantly reduced the thalweg variability. However, the evacuation of sediment in the recovering reaches (eg. Reach 10 in Plate 9.2) has not yet resulted in an increase in thalweg variability (as discussed in Chapter 5, the recovering reaches are those areas where the sediment depth is <1/5 of the bank height and is declining).

Plate 9.1: Difference between the control (left) and impacted (right) reaches on Creightons Creek.

Plate 9.2: The bed level is returning to near pre-disturbance levels at Reach 10 which is near the back of the slug, however, the variability has not returned.

8.1.1. Cross-section results

Each of the 130 cross-sections measured along Creightons Creek were analysed using three variability techniques: trapezoidal method, vector dispersion (VD) and sum of squared height deviations (Σdh^2). There are no cross-sectional results for reach 14, as this section of the river was severely incised. The graphical results for each of the analysis techniques are presented together for comparison (Figure 9.3, Figure 9.4 and Figure 9.5). The graphs are then followed by a separate discussion of each of the individual techniques. Each data set was analysed using a nested ANOVA as described in Section 8.9.

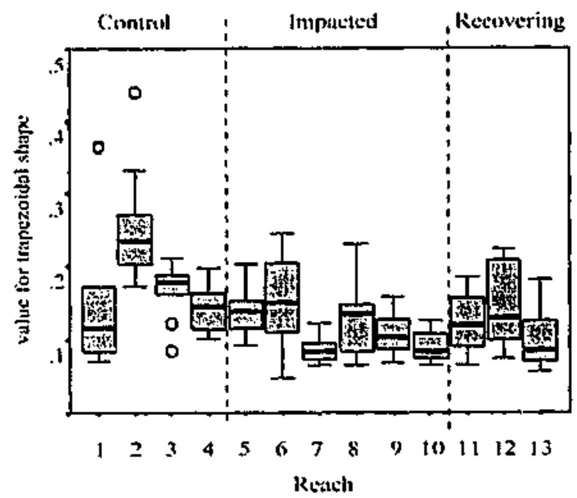


Figure 9.3: Box plot of the trapezoidal technique applied to the Creightons Creek cross-sections.

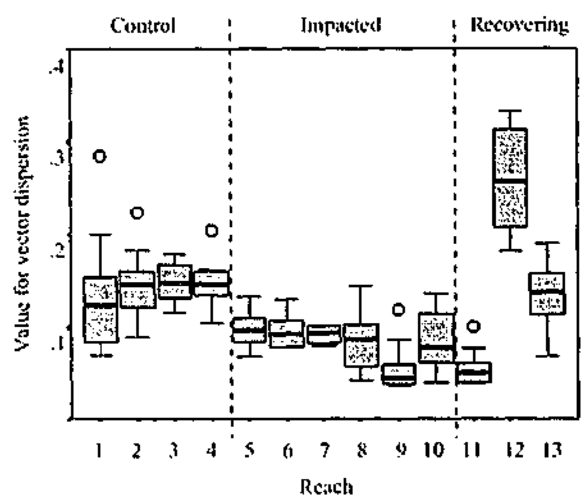


Figure 9.4: Box plot of th. vector dispersion technique applied to the Creightons Creek cross-sections.

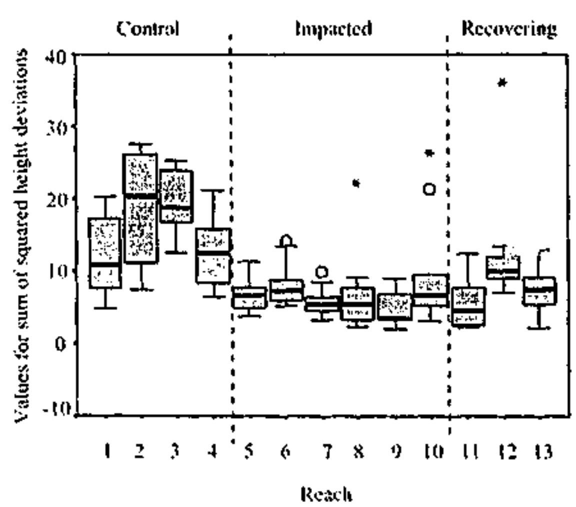


Figure 9.5: Box plot of the sum of squared height deviations technique applied to the Creightons Creek cross-sections.

Trapezoidal Method

The results of the nested ANOVA for the trapezoidal method showed that the control group has significantly ($P<0.05$) higher values than both the impacted and recovering groups; however, there is no significant difference between the impacted and recovering groups (Figure 9.3). At the reach level, a significant difference ($p<0.05$) was identified between reaches within the control group, yet there was no significant difference within the impacted or recovering sections. As seen in Figure 9.3, Reaches 2 and 3 in the control section are the main influence on the significant difference between the reaches. At the reach level, Reaches 1 and 4 do not differ significantly from any of the other reaches along the stream.

These results suggest that the stream has greater cross-sectional variability both within, and between reaches, when the stream is un-impacted by sediment. The fact that none of the reaches is significantly different in the impact and recovering sections suggests that the cross-sectional variability decreases when impacted by a sediment slug (thus all reaches take on a more trapezoidal form). Hence, the trapezoidal result suggests that the sediment slug initially reduced both the within, and between reach cross-sectional variability, and that variability has not yet returned to the recovering reaches.

Vector Dispersion

The results for the VD show a clear pattern between the three different impact levels (Figure 9.4). Reach 12 has considerably (and significantly, $p<0.05$) higher values than any other reach. This is possibly because Reach 12 represents a reach which is in the first stage of incision; it has dramatically deepened, yet, is still quite narrow. The VD measure appears to be sensitive to changes in depth as well as variability.

The results of the nested ANOVA are slightly different for the VD when compared to the trapezoidal data. For the VD data, there is a significant difference ($p<0.05$) between the control and impact sections, and the impact and recovering sections, but not the control and recovering sections. There is also a significant difference between reaches within the impact and recovering groups. The fact that there is no significant difference between the reaches in the control section, provides results inconsistent with the trapezoidal method. This suggests that the VD and trapezoidal techniques are actually measuring different aspects of the data. The trapezoidal technique essentially measures how different each cross-section is when compared to a trapezoid, whereas the VD technique measures the deviation of angles along the cross-section.

The results of the VD analysis suggest that there is less cross-sectional variability in the impacted reaches, than in the control and recovering sections. However, there are also considerable differences between reaches within the impact and recovering areas. This suggests that the impact and recovering reaches may be in a phase of adjustment, with some reaches aggrading and others incising.

Sum of squared height deviations

The results of the ANOVA for the Σdh^2 data show a significant difference ($p<0.05$) between the control and impact reaches, the impact and recovering reaches, but not the control and recovering reaches (Figure 9.5). In Figure 9.5 the values for Σdh^2 look quite different between the control and recovering reaches; however, following transformation of the data (to meet the assumptions of normality and homoscedasticity) the statistical tests actually show no significant difference between the mean values of these two groups. Hence, the level of cross-sectional variability is higher in the control and recovering reaches than in the impacted zone. Only the recovering section shows a significant difference ($p<0.05$) between the reaches. The results for the Σdh^2 are more similar to the VD results, than to the trapezoidal results, as they indicated higher values in the control and recovering reaches relative to the impacted reaches (Figure 9.5).

Summary of cross-sectional analysis

As expected, each of the analysis techniques (trapezoidal, VD and Σdh^2), showed slightly different results when subject to a nested ANOVA. The one result that is common to all of the techniques is that there is greater cross-sectional variability within the control section than in the impacted section of Creightons Creek. In two out of three cases, there was no significant difference between the control and recovering reaches. The fact that there is increasing cross-sectional variability in the recovering reaches of Creightons Creek could be a function of the stream evacuating some of the sediment forming more heterogenous bed-forms, but it is more likely to be a function of the more variable bank-forms and channel shapes evolving from channel incision.

Plate 9.3 shows an example of an incising section of upper Creightons Creek - notice how the slumping banks provide quite diverse bar and bench features. At the scale that the cross-sections were measured (0.5 m), a collapsing bank will provide greater heterogeneity than a stable bank. In addition, the process of incision creates greater depth variation with respect to width.

Hence, the results of the cross-sectional analysis for Creightons Creek shows that the impact of sediment decreases the cross-sectional variability of a channel the size of Creightons Creek. However, caution must be applied when suggesting that the cross-sectional variability has recovered in the upstream sections. It may be that the cross-sectional variability is increasing, or that this result is simply a hiatus within the long term trajectory of the channel, which will eventually continue to incise and, thus, simplify. The process of incision and its affects on the Geomorphic Variability of Creightons Creek will be discussed further in Chapter 10.

Plate 9.3: Incised stream section near Reach 11 on Creightons Creek

8.1.1. Sediment size variability

It was shown in Chapters 6 and 7 that the median sediment size along Creightons Creek had been significantly reduced due to the impact of the sediment slug. This section will show the results of the data analysis employed to determine if there is also a change in the variability of the sediments. To do this, sorting and heterogeneity values were calculated for 70 sediment samples (5 from each reach) collected along Creightons Creek.

Sorting

The sorting value may be thought of as the width of the sample distribution curve (Briggs, 1977); hence, the greater the range of sediment sizes, the greater the spread and the higher the sorting value. On Creightons Creek Reaches 1-3 have the highest sorting values, with Reach 4 the lowest (Figure 9.6). This is evidence that the front of the slug is at, or near, Reach 4. The downstream reaches have the highest sorting values despite being dominated by clay sediments. This is due to the small input of coarse sand, either from the slug upstream, or from a locally derived source (eg. floodplain). This produces a much wider range of sediment sizes, including clays, silts and sands, whereas the middle impacted reaches are only represented by sand sized sediment. The recovering reaches, 11-14, show a slight increase in the level of sediment sorting. This would be due to the presence of some coarser gravel fractions freshly eroded from the headwater reaches. There is also a greater percentage of fines that are eroded from the incised bank walls.

If Reach 4 is kept in the data analysis (as a control reach), there is no significant difference ($p<0.05$) between or within any of the impact groups. This is due to the dramatic difference between Reaches 1-3 and Reach 4. If, however, Reach 4 is removed from the analysis, there is a significant difference ($p<0.05$) between the control and impacted sections, but no difference between the control and recovering, or impacted and recovering sections. It appears that Reach 4 is at an intermediate phase of disturbance with some of the sediment slug having moved into this part of the stream.

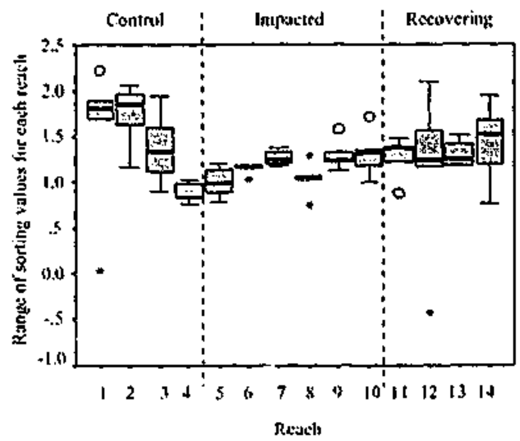


Figure 9.6: Sorting values for the sediment samples in each reach along Creightons Creek.

Heterogeneity

The results of the ANOVA show that the control group has significantly higher ($p<0.05$) heterogeneity values than both the impacted and recovering groups (with Reach 4 included). There is no difference between the impacted and recovering reaches. The only significant difference within the groups is in the control group.

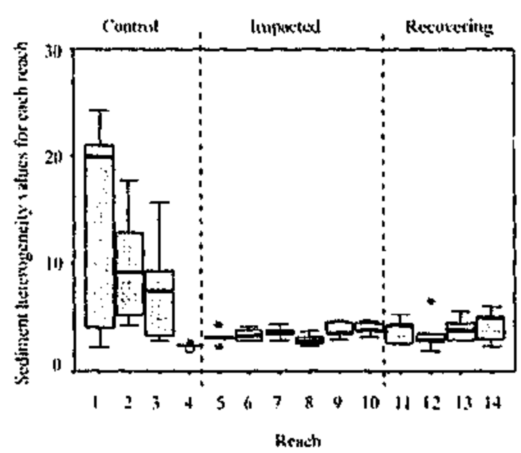


Figure 9.7: Heterogeneity values for the five sediment samples from each reach

Reaches 1-3 have the highest levels of heterogeneity, with Reach 4 being very low compared to Reaches 1-3 (Figure 9.7). Again, this is evidence that Reach 4 is near the front end of the sediment slug. Reaches 1-3 not only have higher median values of heterogeneity, they also have a greater range of values. This means that out of the five samples collected, at least one sample in each reach has a low level of heterogeneity. It is interesting to note, however, that the raw values of heterogeneity for the control reaches were as high as 20; this is much higher than any of the values recorded for gravel sediments by Williams (1980). Again, the increased heterogeneity values would be a result of a small amount of sand sized sediment being present in a clay dominated bed, which essentially increases the overall diversity compared to the upstream reaches that only have sand fractions.

Summary of sediment data analysis

The control reaches (with exception of Reach 4) have lower median grain sizes (Chapter 6), yet have higher sorting and heterogeneity values. Although the samples collected from the downstream reaches all have at least 30% clay content, there is a greater diversity of sediment sizes on the bed of the river in those areas that have not yet been impacted by the sediment slug. Based on this analysis it may seem more appropriate to categorise Reach 4 into the 'impact' group; however, the definition of slugged and non-slugged areas were defined according to sediment depths rather than the sediment size distribution, and Reach 4 fits into the 'control' group based on this system.

9.3 Results for the Wannon River

As described in Chapter 4, the Wannon River has the largest catchment area of the three study streams. The Wannon River was broken up into two impact groups for reasons described in Chapter 4 (Figure 9.8).

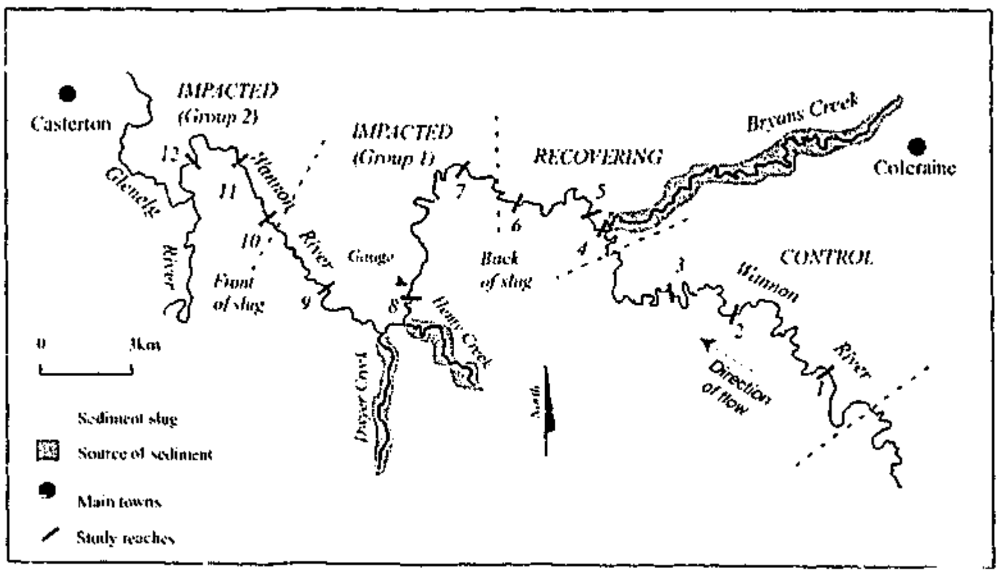


Figure 9.8: Location of study reaches along the Wannon River

9.3.1. Thalweg results

Section 6.5.1 presented the de-trended thalweg profiles for each reach along the Wannon River. This data was analysed to quantify the variability of the thalwegs using three analysis techniques: wiggliness factor (w); fractal dimensions (D) and standard deviation of depths (SD), as described in Chapter 8 (Figure 9.9).

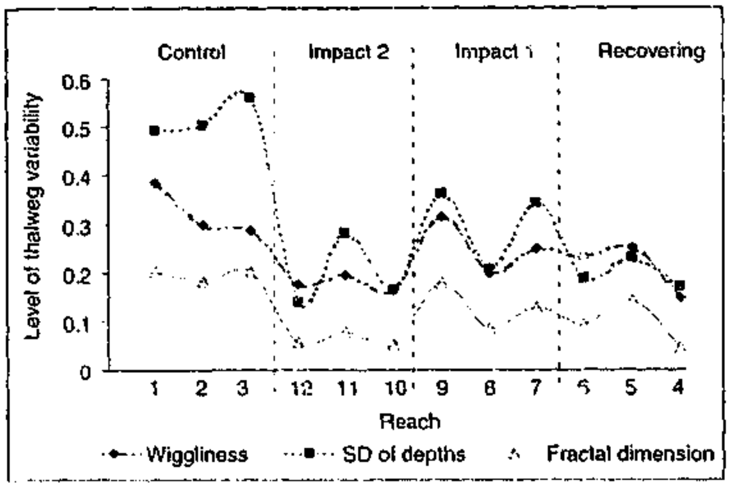


Figure 9.9: Results of the thalweg variability analysis for the Wannon River. (Note that Reaches 3 and 12 not consecutive in space, however, the data points are joined to show the trend or change in values between control and impacted reaches).

The thalweg variability results do not show any clear pattern between the different reach types (Figure 9.9). In addition, the three analysis techniques show considerable difference between the groups, with the SD of depths showing much greater difference between the reaches. This was highlighted by the results of the statistical analysis. For the wiggliness factor, the control groups have significantly higher variability ($p<0.05$) than the impact 2 group, but are not different from the recovering or impact 1 group. For the SD of depths, the control group was significantly higher than all the other groups. For the fractal dimension, the control group is more variable than the recovering and impact 2 group, but no different from the impact 1 group; however, there is a significant difference between the recovering and both impact groups. The only result that was common to all three analysis techniques is that the control group has significantly greater variability than the downstream impact 2 group ($p< 0.05$).

The wiggliness factor and fractal dimension both look at the arrangement of deviations along the line (angular variability), whereas the SD of bed elevation is a surrogate for depth variation or vertical variability. Therefore, these results shows that, at the scale of 2 m, there is a significant decrease in the depth variation due to the presence of the sediment slug, but not necessarily a decrease in the angulation of the bed surface. Even though the overall pool depth may have decreased (as shown in Chapter 7), there is still considerable small scale morphological diversity within the remaining pools to maintain an equivalent level of thalweg variability.

Note that the thalweg of the impact 1 group is more complex than the recovering reaches, which was not expected; this result appears to contradict initial theories on the effect of sediment slugs. On the Wannon River, it appears that an initial increase in sediment does not decrease the variability of the thalweg profile (based on these measures). However, when the sediment leaves the stream (ie. in the recovering reaches), the variability of the sand bedforms is replaced with a flat uniform clay bed, devoid of significant heterogeneity. The control reaches are also comprised of clay material, however, it is probable that the large pools in these reaches have taken a long time to form and are currently stable. The recovering reaches may eventually re-develop the same variability as upstream, although it may take many decades.

Hence, changes in thalweg variability along the Wannon River do not appear to be severely affected by the sediment slug input from Bryans Creek. This may be due to the fact that the channel, in its natural form, is relatively uniform. It appears that the input of sediment to the Wannon River, may increase the natural level of thalweg variability in some sections. This will be discussed further in Section 9.5.3 and Chapter 10.

9.3.2. Cross-section results

As with Creightons Creek, the cross-sectional data for the Wannon River is presented in three sections to represent the three analysis techniques (trapezoidal, VD, Σdh^2). The graphical results for each of the analysis techniques are presented together for comparison (Figure 9.10, Figure 9.11 and Figure 9.12). The graphs are then followed by a separate discussion of each of the individual techniques.

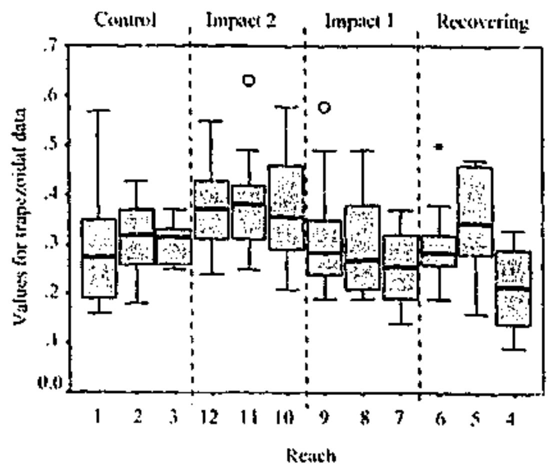


Figure 9.10: Box plot of the trapezoidal technique applied to the Wannon River cross-sections.

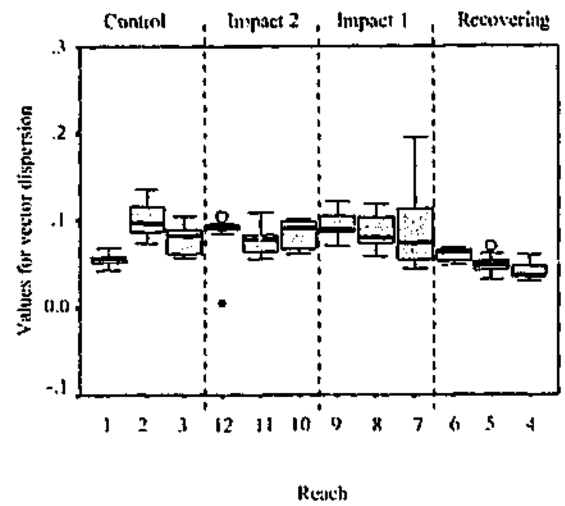


Figure 9.11: Box plot of the vector dispersion technique applied to the Wannon River cross-sections.

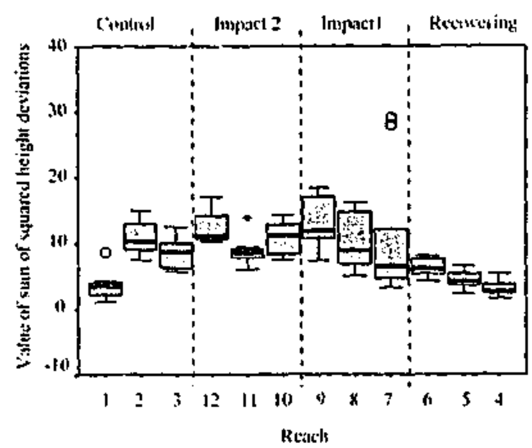


Figure 9.12: Box plot of the sum of squared height deviations technique applied to the Wannon River cross-sections.

Trapezoidal method

Other than a slight increase in the level of variability for the impact 2 group, there are no obvious trends in the data for the trapezoidal method, and there is little distinguishable difference between any of the groups (Figure 9.10). The results of the nested ANOVA show that there is a significant difference ($p<0.05$) between the downstream impact 2 group and all other groups, with the impact 2 group having greater variability. It should be noted that the impact 2 group had the lowest level of thalweg variability. There are no other significant differences between groups. In addition, there were no significant differences between the reaches within the groups. This result suggests that there is a slight increase in cross-sectional variability at the downstream end of the impact section, and that the cross-sectional variability is quite uniform both within and between sections. This suggests that the trapezoidal method has not detected any significant decrease in the cross-sectional variability as the results of the sediment slug.

Reaches 10-12 represent what happens in the early stages in sediment input. The fact that these are the most variable (in terms of cross-sectional structure) makes it difficult to show that the impact of a sediment slug (of this magnitude) has had any affect on the Wannon River. It may also be that the variability that has been detected is simply natural variability, and the sediment slug may not have had any affect on the cross-sectional variability of the Wannon River.

Vector dispersion method

The VD analysis showed that the recovering reaches had significantly lower variability ($p<0.05$) than all other groups (Figure 9.11). There was no difference between the control and impacted groups. The only section that showed statistical difference between reaches 'within' the group was the control section (Reaches 1 and 2). The results of the nested ANOVA for the VD were quite different from the results for the trapezoidal method. This result suggests that the initial impact of the sediment slug has not caused a reduction in cross-sectional variability; however, the subsequent evacuation of sediment in the recovering reaches have resulted in decreased cross-sectional variability.

Sum of squared height deviations(Σdh^2) method

The results of the Σdh^2 showed different results from both the trapezoidal and VD methods (Figure 9.12). In this analysis, the control groups had significantly lower variability ($p<0.05$) than all other groups. The cross-sectional variability was highest in both of the impacted groups when compared to the control group, suggesting that the sediment has actually increased the cross-sectional variability.

There was also a significant difference between both impact groups and the recovering group, however, there is no difference between the impact groups. Both the control and impact 2 group show significant differences ($p<0.05$) between the reaches 'within' their group. This result suggests that once the sediment starts to evacuate the stream, the cross-sectional variability declines.

Summary of cross-sectional analysis

In Chapter 6, analysis was undertaken to determine if there was any significant difference in the mean values for width and depth for each cross-section; they showed there was no significant difference between any of the groups on the Wannon River for either width, or depth. The results of the variability analysis are reasonably consistent with the changes in mean condition described in Chapter 6.

The results of the cross-sectional analysis were different for each of the techniques. Overall, however, there are no signs that the introduction of sediment into the stream has reduced the cross-sectional variability. Plate 9.4 highlights the similarity of cross-sectional shapes between the control (Reach 2 - left) and impacted reaches (Reach 9 - right). In fact, both the trapezoidal method and Σdh^2 showed that at least one (if not both) of the impacted groups was more variable than the control group, and in the VD and Σdh^2 analysis, the recovering group were less variable than both the impact groups and control group.

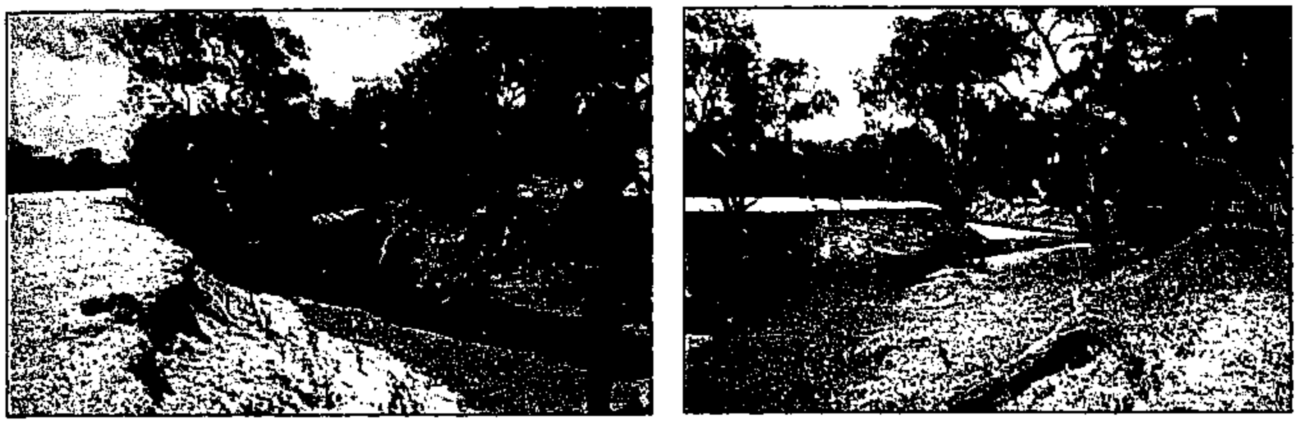


Plate 9.4: Comparison of cross-sectional shape between a control reach - Reach 2 (left) and an impacted reach - Reach 9 (right). Note the red/brown material in the left hand photo is actually a water plant (*Azolla pinnata*), and in the right hand photo the red/brown material is sand. The main difference in these photos is the water depths (approximately 2m in the left photo and less than 50 cm in the right hand photo), otherwise, structurally they are very similar.

The 'within' groups data told another story, as for both the VD and Σdh^2, the control group had statistically significant differences between reaches within the group; however, there was no difference between the reaches in the downstream impacted areas. Therefore, it is difficult to suggest that the sediment slug has increased the variability of the stream as much as it has *changed* the variability. The more reliable conclusion is that the sediment has <u>not</u> decreased the level of variability along the Wannon River.

8.1.1. Sediment size variability

Five samples were collected from each reach on the Wannon (totalling 60 samples). To determine the differences in the variability of the sediments, the sorting value and heterogeneity values were calculated for each reach.

<u>Sorting</u>

The results of the ANOVA show that the sorting values are significantly higher ($p<0.05$) in the recovering reaches compared to both impact groups (Figure 9.13). However, there is no significant difference between the control and recovering groups, the control and impacted groups, or the impact 1 and impact 2 groups. There are no significant differences between any of the reaches within any of the groups.

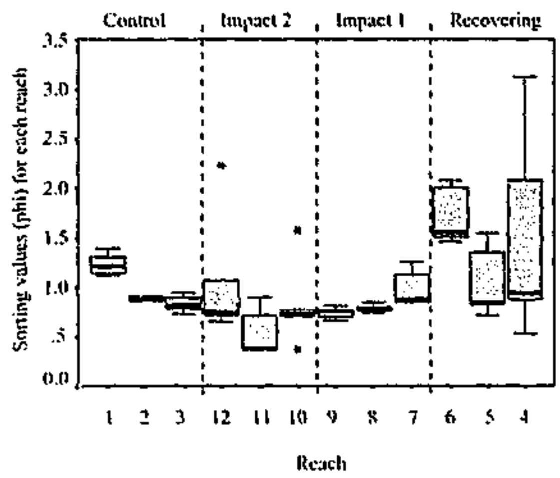


Figure 9.13: Sorting values for the Wannon River Sediment data

This result suggests that the impact of the sediment slug on the stream does not significantly reduce the sorting values (variability) of the sediments. However, as the sediment slug moves out of the stream, the interaction of sand and clay sediments acts to increase the level of sorting to a higher level than in the slugged reaches, but not significantly higher than the original un-slugged areas. This is similar to the results for Creightons Creek, where sand and clay fractions mix together increasing the level of sorting.

Heterogeneity

The range of heterogeneity values for each reach is shown in Figure 9.14; the data is slightly distorted due to the extreme outlier in Reach 4. This value was left in the figure simply to show what level the heterogeneity value can reach, although it was not included in the actual analysis. The results of the ANOVA show that the heterogeneity is significantly higher ($p<0.05$) in the control reaches compared to both impact reaches. There is also a significant difference between the impacted and the recovering reaches, yet there is no significant difference between the control and recovering reaches.

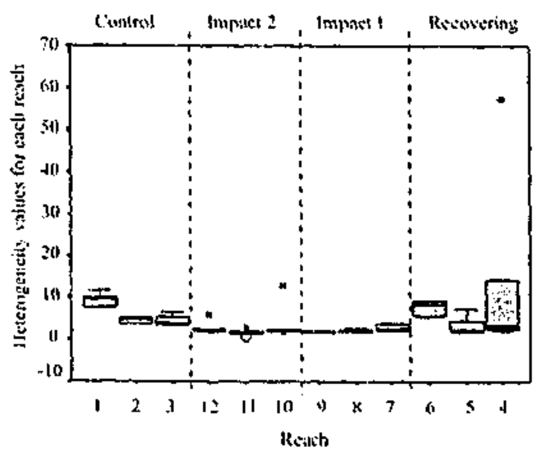


Figure 9.14: Heterogeneity values for each reach on the Wannon River

These results suggest that the sediment slug has reduced the level of heterogeneity by changing the bed sediments from clay and fine sand dominated to sand dominated. The evacuation of the main body of the slug has returned the mixture of sediments, thus increasing the heterogeneity level.

Summary of sediment data analysis

Along the Wannon River, there is a significant difference between the recovering and impacted sections, however, there is no difference between the control and recovering sections for both the sorting and heterogeneity data. The increase in these values in the recovering reaches is considered to be a function of the mixing of clay and sand sediments in the bed.

9.4 *Results for the Ringarooma River*

As discussed in Chapter 4, the Ringarooma has the second largest catchment of the three study sites and contains by far the largest sediment slug with an estimated 40 million m^3. Figure 9.15 shows the location of the ten study reaches discussed in this section.

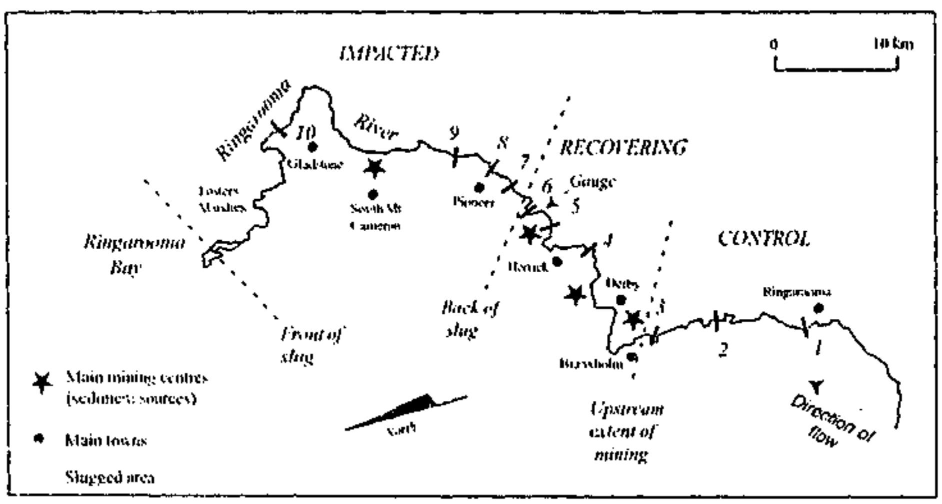


Figure 9.15: The distribution of study reaches along the Ringarooma River

9.4.1. Thalweg

Section 6.6.1. presented the de-trended thalweg profiles for each reach along the Ringarooma River. This raw data was analysed to quantify the variability of the thalwegs using three analysis techniques: wiggliness factor (w), fractal dimensions (D) and standard deviation of depths (SD), as described in Chapter 8. All of the analysis techniques show the same general result (Figure 9.16); however, there is a slight difference in the magnitude of values between sites. Overall, the results show that the sediment slug has reduced the variability of the thalweg profile; then, as the sediment moves out the bed of the river, the thalweg variability increases.

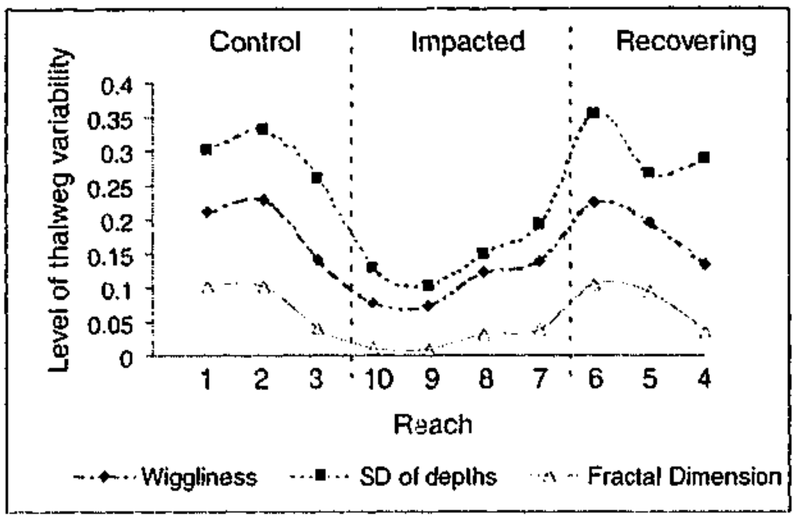


Figure 9.16: Thalweg variability results for the Ringarooma River.(Note that Reaches 3 and 10 not consecutive in space, however, the data points are joined to show the trend or change in values between control and impacted reaches).

Based on the statistical analysis, it is possible to conclude that the recovering reaches have returned to their pre-disturbance thalweg variability. This is because for all three analysis techniques, there is no significant difference ($p<0.05$ for SD of depths; $p<0.1$ for others) between the control and recovering reaches. There is, however, a significant difference between the control and impacted reaches, and the recovering and impacted reaches. In fact, the thalweg variability in Reach 6, is as high, if not higher than the control reaches. Reach 6 is undergoing rapid bed lowering which is allowing a single, deeper thalweg to re-form. This process is also re-exposing old trees and coarse sediments in the bed, increasing the variability. Overall, the evacuation of sediment from the Ringarooma River, in combination with the re-exposure of LWD and coarse bed sediments, means that the thalweg variability has returned.

9.4.2. Cross-sections

There were a total of 100 cross-sections measured along the Ringarooma River. As with the other field sites, the three techniques for quantifying cross-sectional variability were applied to the data, and the results analysed statistically. The graphical results for each of the analysis techniques are presented together for comparison (Figure 9.17, Figure 9.18 and Figure 9.19). The graphs are then followed by a separate discussion of each of the individual techniques.

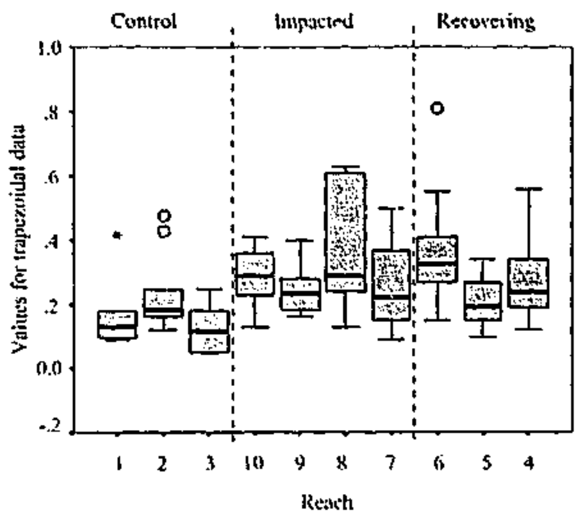


Figure 9.17: Box plot of the trapezoidal technique applied to the Ringarooma River cross-sections.

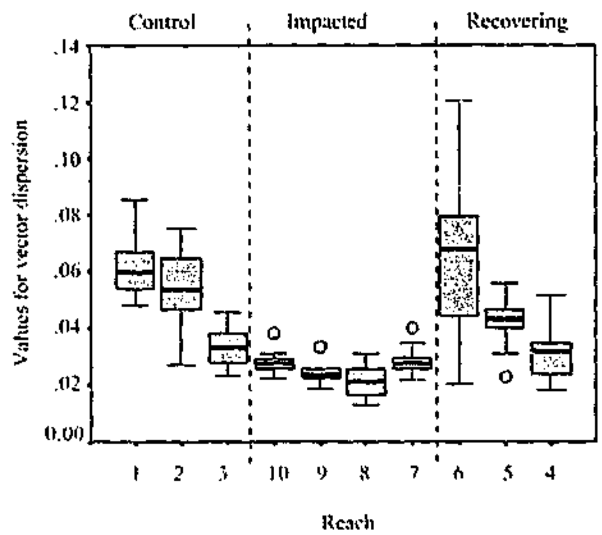


Figure 9.18: Box plot of the VD technique applied to the Ringarooma River cross-sections.

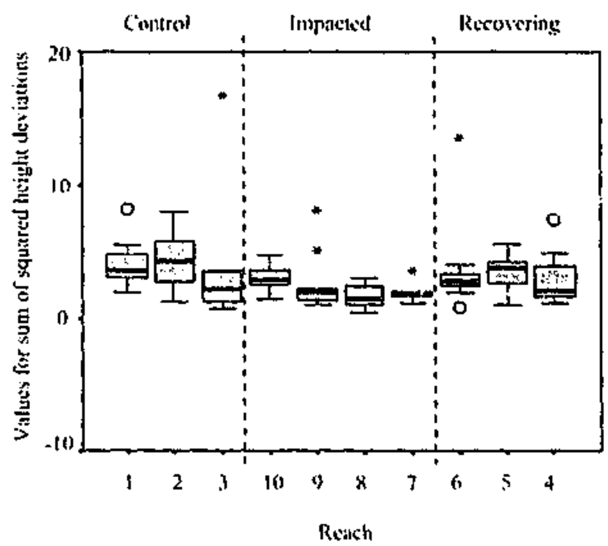


Figure 9.19: Box plot of the sum of squared height deviations technique applied to the Ringarooma River cross-sections.

Trapezoidal method

The application of the trapezoidal method presents unexpected results for the Ringarooma River data; it appears that there is greater cross-sectional variability within the impacted and recovering reaches than in the control section (Figure 9.17). The results of the nested

ANOVA show that the control section has significantly lower variability than both the impacted and recovering sections. Yet, there is no difference between the impacted and recovering sections. There is also a significant difference (P<0.05) between reaches 'within' the control group. This result was unexpected as the visual perception would be that the cross-sections along this river have been grossly simplified as a result of sediment slug impact. It is important to keep in mind that the trapezoidal method calculates variability away from a fixed trapezoidal shape (Figure 8.5). This result essentially shows that the control reaches have a cross-sectional shape more similar to a trapezoid than either the impacted or recovering reaches.

The results of the trapezoidal method make sense when the cross-sectional data is examined more closely. The slugged reaches do have quite complex cross-sections at the larger scale (as shown in Plate 9.5). The presence of multiple, rather than single, thalwegs; and the formation of multiple sand benches, backwaters and mid-channel islands, make the cross-sections less like a trapezoidal shape than the control reaches. Also, many of the impacted and recovering reaches have gone through various cycles of incision which have left multiple benches on the margins of the channel. Therefore, at the scale of 0.5 m, the trapezoidal method suggests that the slugged and recovering reaches are more variable than the control reaches.

Plate 9.5: View from Ogilvies Bridge on the Ringarooma. Despite being filled with sand there is still considerable morphological diversity in the cross-sections at the scale of 0.5 m.

<u>Vector Dispersion method</u>

The results for the VD are opposite to the trapezoidal method (Figure 9.18). For the VD data, the impacted (rather than control) reaches have lower and less variable values for the cross-sections. The nested ANOVA shows a significant difference (p<0.05) between the control and impacted groups, and the recovering and impacted groups; yet there is no difference between the control and recovering sections. There is also a significant difference between the reaches within both the control and recovering groups. This suggests that, although the cross-sections are more variable, there is also considerable natural variation within these river sections. This result is consistent with the thalweg data presented in Section 9.4.1.

The VD method is more concerned with the deviations of angles from consecutive points, whereas the trapezoidal method measures deviations away from a line. This result suggests that although there are a number of large scale geomorphic features, such as benches and bars that increase the variability using the trapezoidal method, within these larger scale features, the topography is rather uniform. Hence, the overall result for the VD at a measurement interval of 0.5 m is that the impacted reaches are significantly less variable than both control and recovering sections.

Sum of squared height deviations (Σdh^2) method

Following transformation of the data, the results of the nested ANOVA show that the control reaches are significantly more variable ($p<0.05$) than both the impact and recovering sections (Figure 9.19); however, there is no significant difference between the impacted or recovering groups. The Σdh^2 measures the deviation in elevation along each cross-section, which is similar to the VD method in that it looks at the small scale variability. However, unlike the VD result, Σdh^2 did not distinguish between the impacted and recovering groups.

Summary of cross-sectional analysis

The results for the Ringarooma River provide a different insight into the application of the three different methods for analysing cross-sectional data. Each of the techniques produced a different set of results for the Ringarooma River. The trapezoidal method suggested that the impacted reaches are more variable than the control reaches. This method calculated the deviations away from a fixed line (trapezoid) so it is better able to pick up large scale geomorphic features (eg. benches and bars). These large scale bench features were not found on Creightons Creek or the Wannon River; hence, this aspect of the trapezoidal method did not appear until tested on a wide and shallow (rather than narrow and deep) channel.

The other two techniques, VD and Σdh^2, show that the impacted reaches are less variable than the control reaches. For the VD method, the recovering reaches have a cross-sectional variability equivalent to the control reaches. Both of these techniques calculate the deviation of angles between consecutive points, which essentially provides an estimate of smaller scale variation along each cross-section.

The volume of sediment in the Ringarooma has provided a different scale at which to observe the application of the three techniques. The results have shown that the trapezoidal method is more suited to picking up larger scale variation in geomorphic structure, and that VD and Σdh^2 are more suited to picking up small scale changes. The problems and benefits with each of the techniques is discussed further in Section 9.6.

9.4.3. Sediment size variability data

The data for the Ringarooma River sediment analysis were slightly different to the previous sites due to the extreme range of sediment sizes found along the Ringarooma River. A total of 50 sediment samples were collected within the study reaches; in addition to these bulk sediment samples, Reaches 1-6 were subject to a Wolman Pebble Count (Wolman, 1954). The Wolman pebble count data was used to determine the D_{50} of the sediments (described in Chapter 5 and 6); however, bulk samples were used to determine the level of sorting and heterogeneity for each reach. Therefore, it must be kept in mind that most of the larger particles were left out of the samples for Reaches 1-6, due to methodological constraints (Kellerhals and Bray, 1971).

Sorting

On the Ringarooma there are higher sorting values in both the control and recovering reaches (Figure 9.20). The overall values range from 1.5 (poorly sorted) to 2.0 (very poorly sorted), which suggests that all the sediments, including the downstream impacted areas, have a wide range of sediment sizes.

The results of the ANOVA show that there is a significant difference ($p<0.05$) between the control and impacted reaches and the impacted and recovering reaches, however, there is no significant difference between the control and recovering reaches. There was a significant difference between Reaches (2 and 3) 'within' the control section, suggesting that there are considerable differences in the sorting values along the river (in their natural condition). This means that the impact of the sediment slug has reduced the variability (as well as the median value) of the sediment along the Ringarooma River.

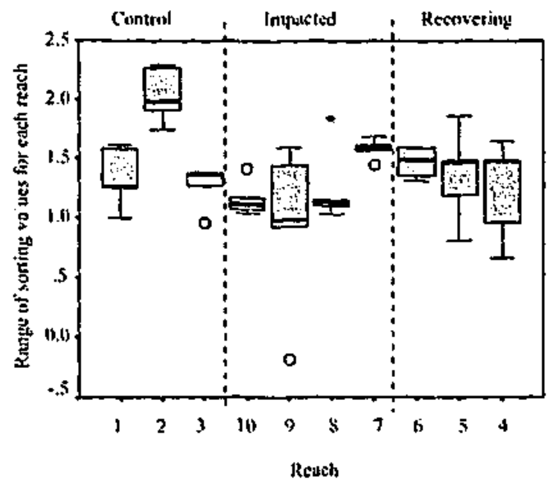


Figure 9.20: Sorting values for each reach along the Ringarooma River

Heterogeneity

The same bulk sample data was also used for the heterogeneity analysis (Figure 9.21). The results of the ANOVA show a significant difference ($p<0.1$) between the control and impacted reaches, and the impact and recovering reaches, however, there is no significant difference between the control and recovering reaches. Again, there is a significant difference between Reaches (2 and 3) 'within' the control section. This result is very similar to the results for the sorting values, suggesting that the impact of the sediment slug has reduced the heterogeneity (variability) of the sediments along the Ringarooma River. It also important to note that the transitional zone (Knighton, 1999), near Reach 6 is showing heterogeneity levels as high, if not higher than the control reaches.

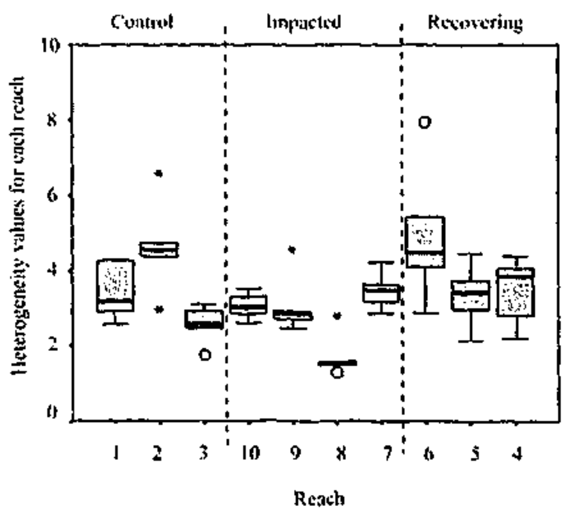


Figure 9.21: Range of heterogeneity values for the sediment samples along the Ringarooma River.

Summary of sediment data analysis

The results of this analysis show that the variability of the sediments (sorting and heterogeneity) has been reduced as a result of the sediment slug impact. Despite the extreme nature of the impact, the recovering reaches now have sediment variability levels similar to those areas that were not impacted by mining. One can conclude that, in terms of the sediment variability, the Ringarooma River appears to be on the way to a full recovery.

9.5 Summary of the response of each stream according to the Geomorphic Recovery Model

9.5.1. Background

Sections 9.2, 9.3 and 9.4 presented the results for the thalweg, cross-sectional and sediment size variability data for each of the three study sites. This section presents the results for the four variables that make up Geomorphic Variability: thalweg, cross-sections, sediment size and sediment stability. [The original sediment stability results were presented in Chapter 6]. In this section, each of the data analysis techniques for each of the individual variables are presented together on the one graph; this allows each of the variables to be evaluated according to the Geomorphic Recovery Model (Figure 9.22). The results are presented for Creightons Creek, the Wannon River and the Ringarooma River in turn.

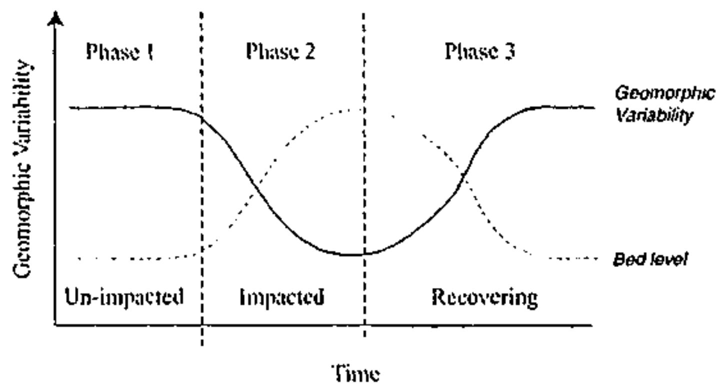


Figure 9.22: Geomorphic Recovery Model

To allow a comparison between each of the data sets and the Geomorphic Recovery Model, each of the analysis techniques are represented by a single line. For the cross-sectional data, this means that the data for each technique (eg. trapezoidal technique) is represented by an average value at each reach (ie. average of the ten cross-sections).

To enable the different analysis techniques to be represented on a single graph, each of the data sets were standardised (using Equation 9.1, from Zar, 1996, p73).

$$Z = \frac{X_i - \mu}{\sigma}$$ Equation 9.1

Standardising the data transforms the mean (μ) of each data set to equal zero (0), and variance (σ) equal to one (1). This produces the value Z, which is the normal deviate or standard score. This process allows all of the values to have the same order of magnitude. and it prevents bias in the data. The results for each stream are presented below.

9.5.2. Creightons Creek

The results of each of the different variability measures (thalweg, cross-sections, sediment size and sediment stability) show a similar pattern of variability for the length of Creightons Creek (Figure 9.23). The vector dispersion (VD) technique for quantifying cross-sectional variability is the only analysis technique that deviates from this pattern (Figure 9.23B). The reason that VD technique increases at Reach 12 is that this is an incised reach and the VD technique calculates higher variability values for streams that are deep and narrow. This limitation of the VD technique will be discussed in Section 9.6.

Overall, the results show that Creightons Creek does not follow the Geomorphic Recovery Model (Figure 9.22). For all four measures of variability, there is a decline from the control to the impacted reaches; however, none of the measures show a return of Geomorphic Variability in the recovered reaches once the bed level has reduced to less than 1/5 of the mean bank height.

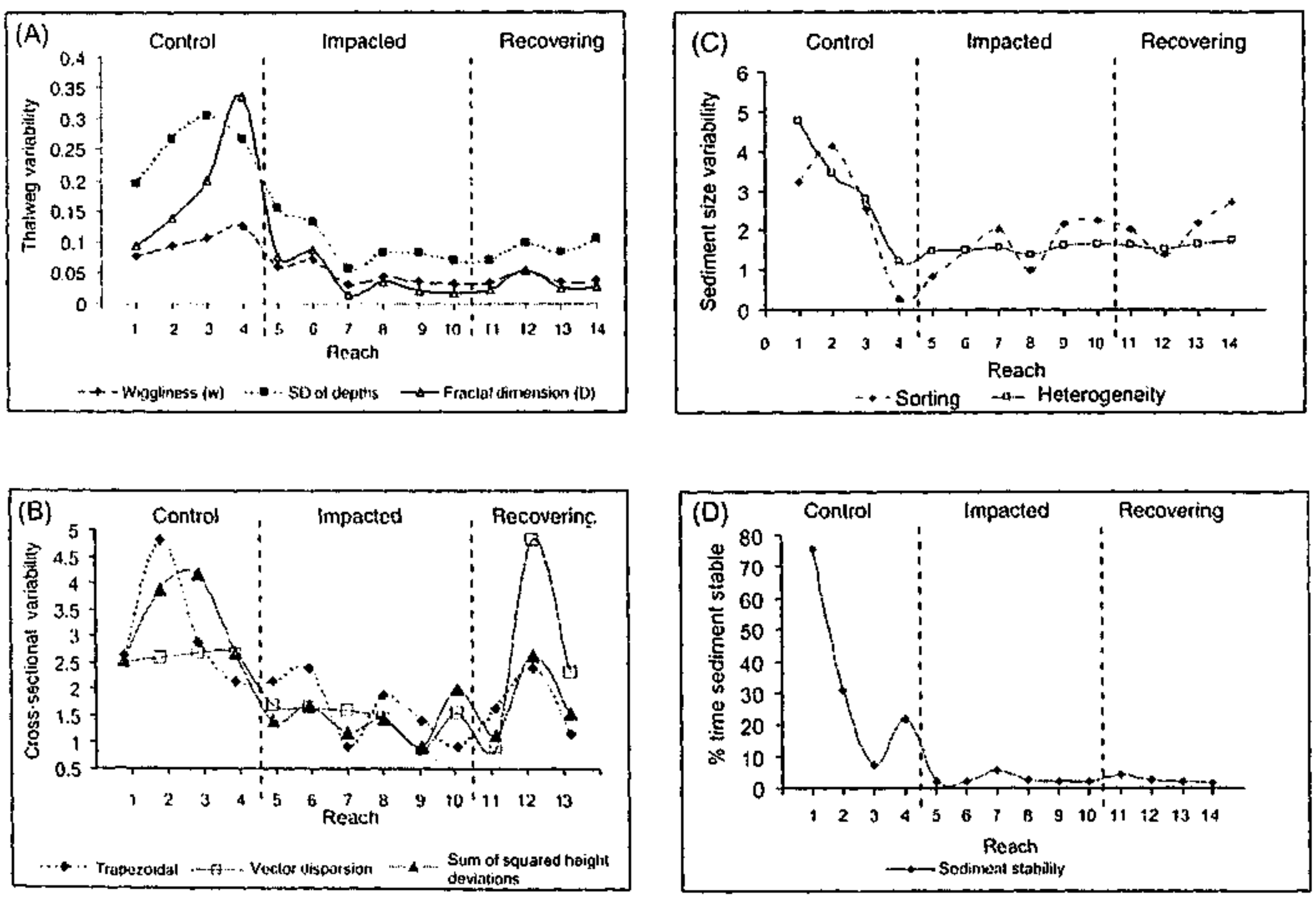


Figure 9.23: Geomorphic Variability results for Creightons Creek (A) thalweg variability: (B) cross-sectional variability; (C) Sediment size variability; and (D) sediment stability

Figure 9.23 also shows that the gradient of change along the river is not always what would be expected when compared to the Geomorphic Recovery Model. As discussed in Chapter 3, it is expected that the area of maximum disturbance will decrease the closer the reach is to the peak of the sediment slug (ie. the deepest part of the slug); however, the thalweg and cross-sectional data for Creightons Creek show that there is an increase in variability from Reach 1 to Reach 4 (ie. the control section) for most of the analysis techniques. This suggests that a small amount of sediment must initially increase the level of Geomorphic Variability (eg. Reach 4), and then once the sediment depth exceeds a certain threshold, the variability is reduced. This is because the presence of some mobile sediment (eg. sand) allows complex bar and bed features to form, and it can be easily scoured by LWD. Reach 4 represents an area where there is a balance between the stable clay sediments and the introduced mobiles sand, producing high levels of geomorphic diversity in the channel.

The cross-sections have the most unique response of each of the four variables. The thalweg, sediment size and sediment stability data all have a similar curve between the impacted and recovering sections. The cross-section data (Figure 9.23 B) fluctuates in its level of variability both between reaches and data analysis techniques. Nonetheless, if the trapezoidal value for Reach 12 was removed, all four variables would show highly similar response curves along the length of Creightons Creek.

9.5.3. Wannon River

The results for each of the variables (thalweg, cross-sections, sediment size and sediment stability) show little consistency between the different variability measures along the Wannon River (Figure 9.24). There is some similarity between the patterns for the thalweg, sediment variability and sediment stability graphs (Figure 9.24 A, C and D), with all three factors showing that there is a decrease in variability when the sediment slug is introduced to the stream. [The only exception to this is the high sediment stability recorded at Reach 11 which was explained in Chapter 6 to be a function of increased clay fractions at this site]. The sediment size variability is the only factor that has a response consistent with the Geomorphic Recovery Model, as it shows that the level of variability in the recovering reaches is similar to that in the control reaches. The most likely explanation for the low complexity in the recovering reaches for the three other variables (thalweg, cross-sections and sediment stability) is that the channel is beginning to incise in these sections.

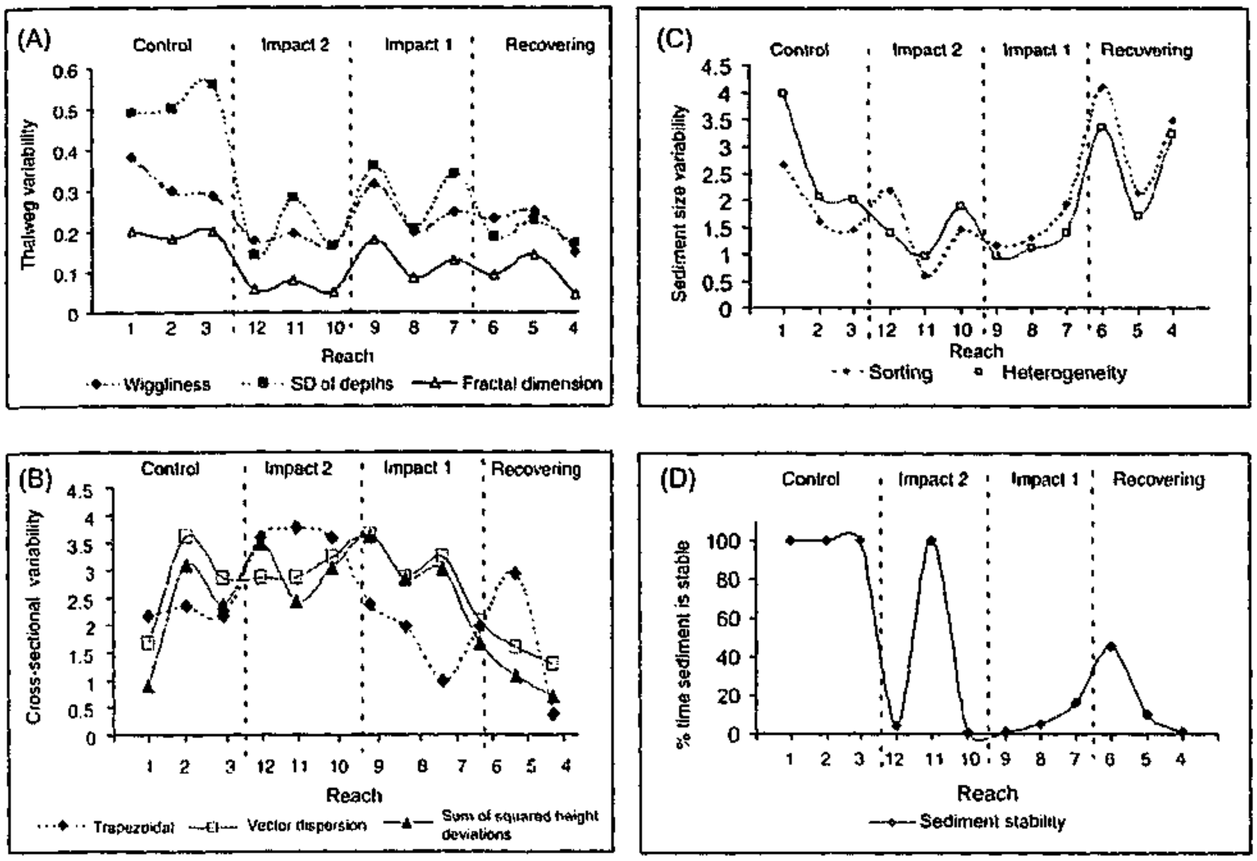


Figure 9.24: Geomorphic Variability results for the Wannon River (A) thalweg variability; (B) cross-sectional variability; (C) Sediment size variability; and (D) sediment stability. (Note that Reaches 3 and 12 not consecutive in space, however, the data points are joined to show the trend or change in values between control and impacted reaches)

The cross-sectional data (Figure 9.24 B) shows a very different response when compared to both the Geomorphic Recovery Model and the other geomorphic variables (Figure 9.24 A, C and D). The cross-sectional variability on the Wannon River appears to have responded in the opposite direction to the model, with an increase in variability in the impacted reaches. This suggests that the cross-sections have not been significantly altered by the sediment slug and the difference between the reaches are simply a function of both natural variation, and difference in the data analysis techniques. For example, the high levels of the vector dispersion value represented at Reach 2 and 9 (Figure 9.24 B) are the result of the channel being quite deep relative to its width (this is similar to the high values recorded on the incised reaches on Creightons Creek). Also, the fact that Reaches 10-12 recorded the highest values for the trapezoidal data implies that these reaches are least similar to a trapezoidal shape. This result reflects those presented in Chapter 7 where the cross-sectional data on the Wannon River did not show any statistically significant differences for the variability of widths and depths between the different impact groups.

The most suitable technique for analysing the cross-sectional variability on the Wannon River appears to be the sum of squared height deviations technique (Σdh^2). This technique actually measures lower levels of cross-sectional variability for the recovering reaches; these reaches are currently incising.

The Wannon River data also highlighted the difference in the level of stability between the clay and sand sediments, and how this can influence the variability of the sediments. For example, Reach 11 shows a high level of sediment stability (Figure 9.24 D); this is because the sediments in this reach are predominantly clay. Subsequently, Reach 11 recorded a relatively low level of sediment variability (Figure 9.24 C). The difference between the clay sediments in Reach 11 and the clay sediments in the control reaches is that the sediments in Reach 11 have formed a consolidated clay matrix, called 'river-rock' (as described in Chapter 5). This observation again highlights that it is important to have a number of measures of variability, as using a single measure of variability may lead to the incorrect evaluation of stream recovery.

The gradient of change predicted by the model (ie. a gradual decrease in variability from the control to the disturbed reaches, and a gradual increase in variability away from the disturbed reaches) was not observed in the Wannon River data. The Wannon River data appeared to have a more random, fluctuating pattern of variability. This was probably because of the pulse like movement of the sediment slug producing a number of smaller sediment waves or 'sluglettes' (Rutherfurd and Budahazy, 1996) at different points along the river. The pulse like movement of the sediment slug is highlighted by the sediment size variability and stability data in Reach 6 (Figure 9.24 C and D). Reach 6 is the closest recovering reach to the sediment slug and would be expected to have low sediment size variability (ie. predominantly sand) as well as low sediment stability. However, Reach 6 has the highest values of sediment variability and stability for any of the recovering reaches. This suggests that there are some clay fractions exposed, which may be related to a small wave of sediment moving through the reach. The implications of the pulse like movement of sediment along the Wannon River will be discussed further in Chapter 10.

9.5.4. Ringarooma River

The results of each of the different variability measures (thalweg, cross-sections, sediment size and sediment stability) are fairly consistent for the Ringarooma River (Figure 9.25).

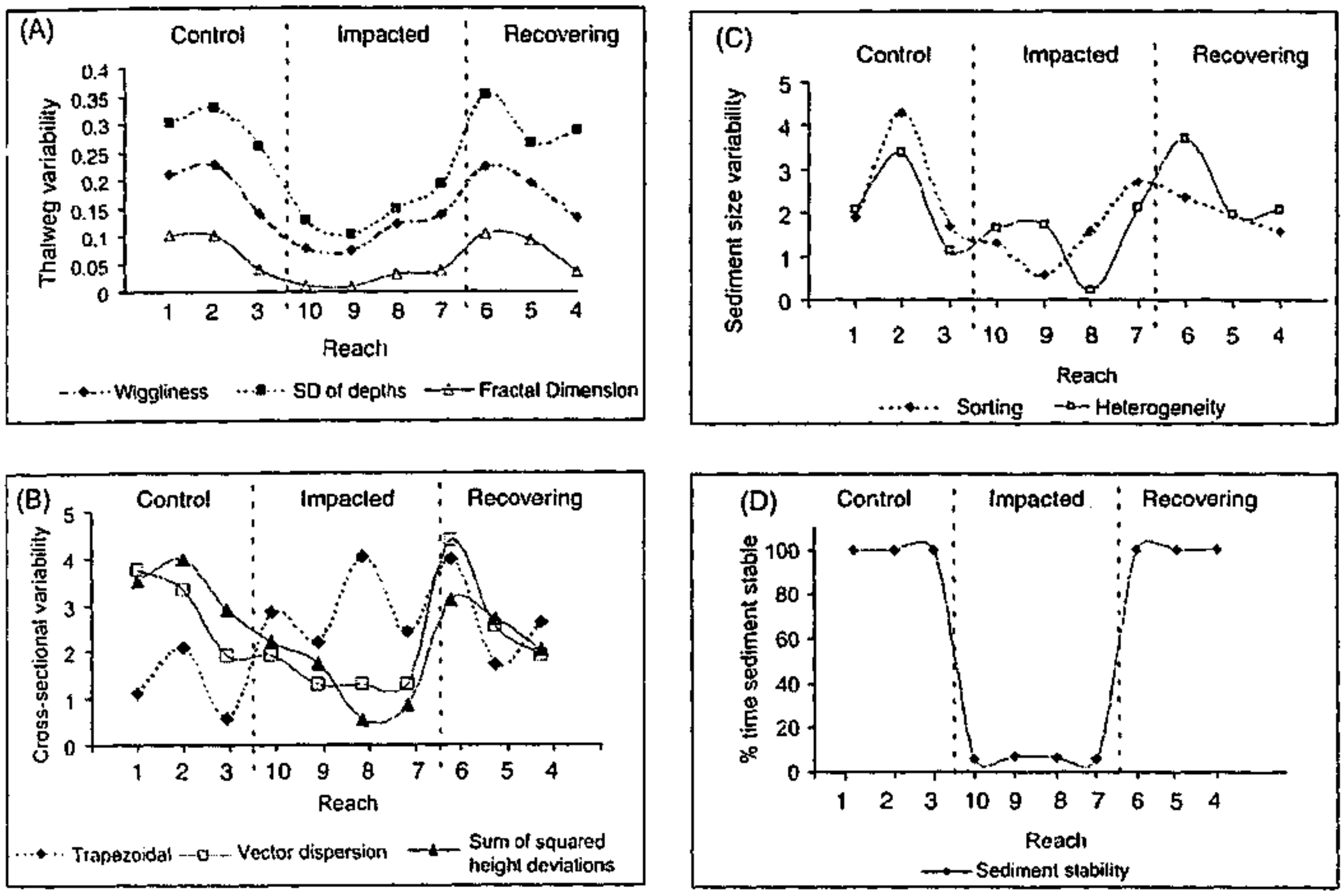


Figure 9.25:Geomorphic Variability results for the Ringarooma River (A) thalweg variability; (B) cross-sectional variability; (C) Sediment size variability; and (D) sediment stability. (Note that Reaches 3 and 10 not consecutive in space, however, the data points are joined to show the trend or change in values between control and impacted reaches).

This is the only stream that appears to follow the general pattern of the Geomorphic Recovery Model, with all of the variables showing some degree of recovery. Again the cross-sections appear to differ in their response, however, this is mainly only the trapezoidal data (as discussed in Section 9.4.2). If the trapezoidal data is removed from the analysis, all of the results show a similar pattern.

The other important aspect of the Ringarooma data is the high level of variability measured at Reach 6 (Herrick) for all four variables (Figure 9.25). This reach is the closest recovering reach to the slug (ie. area of maximum disturbance), and according to the Geomorphic Recovery Model, it would be expected that Reach 6 would have the lowest level of variability of the three recovering reaches, however, in each case, it is the exact opposite. There are a number of explanations for this:

(1) Reach 6 is located in a floodplain zone (Reach 4 and 5 are more confined within a bedrock controlled valley) which has allowed considerable lateral variability to form as the sediment slug has evacuated the stream (eg. multiple bench sequences);

(2) the re-exposure of LWD and the gravel substrate has allowed pool-riffle sequences to re-form. Assessing the reach visually, the present variability appears to be random in

configuration (Plate 9.6), and as further sediment evacuates the stream, and the reach stabilises, the variability may reduce;

(3) there is still a considerable amount of sand (slug) available to form complex bar formations which are interacting with the re-exposing LWD and coarse substrate (gravel) (Plate 9.6).


Plate 9.6: Shows how the re-exposure of LWD and coarse bed sediments is creating random diversity in Reach 6 (Herrick).

Thus, the increasing gradient of variability towards the slug in the recovering reaches is not what is predicted by the model, suggesting that the there are thresholds in the response process for streams disturbed by sediment slugs. In this case, the depth of sediment is now low enough to exhume the pre-disturbance morphology. At the same time, the waning sediment supply provides enough sediment to form complex bar and bed-form features.

The sediment heterogeneity data suggests that the impacted reaches (7, 9 and 10) are more variable than Reach 3 (a gravel bed control reach). This result shows that despite the sediment in the slug being considerably finer than the original substrate, there is still great diversity in the range of sizes within the slug (eg. sediment sizes range from ~1-50 mm). This again highlights that it is not always suitable to use a single measure of change to characterise the diversity of a stream. This result suggests that the data would be best interpreted using a combination of the variables. This would provide a more holistic overview of the geomorphic response of the stream to the sediment slug, as no single variable can provide enough information alone.

8.1 Evaluation of the factors used to quantify Geomorphic Variability

This section briefly summarises the contribution of each of the variability measures: thalweg, cross-sections, sediment size and sediment stability. Each of the analysis techniques used to describe the variability measures showed slightly different results for most of the variables (in particular the cross-sections). Nonetheless, it would be appropriate to have just one analysis technique to measure each of the variables. This would make it easier to apply these techniques in future studies of geomorphic diversity. As shown in the previous section, not all of the techniques are necessarily suitable for quantifying geomorphic diversity at the selected scale. Therefore, this section will summarise the usefulness of each factor and select just one analysis technique that best represents each geomorphic variable.

Thalweg

The techniques used to quantify the variability of the thalweg provided similar results. They suggest that, at the horizontal scale of 2 m, all of the techniques (wiggliness, SD of depths, fractal dimension) provide compatible results, and therefore similar outcomes. The only minor difference is that the SD technique calculates variability according to changes in elevation and the other techniques look more at the change in angles along the bed. The SD technique would also be a more appropriate technique for evaluating variability of pool depths, and this method was used in a recent study by Madej (2001) which looked at longitudinal profile variability. Also, the Wannon River data showed that it is possible to have a low SD of depths (ie. low pool depth), yet still have a relatively high values for the wiggliness and fractal dimension. This result appears to be typical of sand bed streams where the pool depths are low, but there are variable bed forms. Thus, because depth variability is important, SD of depths may be a more suitable measure of thalweg variability.

The thalweg also appears to be more sensitive to change than the cross-sections. This was highlighted in the Wannon River, where there was often a significant difference between the control and impact groups for the thalweg data, but no difference detected for the cross-sections. This result suggests that less sediment is needed to alter the longitudinal profile variability (ie. thalweg), compared with lateral variability (ie. cross-sectional variability).

In future studies, any one of these techniques would be suitable for quantifying thalweg variability. Nonetheless, it is the aim of this section to identify a single analysis technique that is suitable for calculating thalweg variability. This will mean that in future studies, just one technique can be used to provide a rigorous assessment of the level of thalweg variability in a reach. In this situation, the standard deviation method is the most suitable due to the reasons outlined above as well as the simplicity of the calculations required, and the similarity of this approach with the methods for predicting mean pool depths (Chapter 7).

Cross-sections

The cross-sections appeared to be less likely to change in response to sediment slug impact compared to the thalweg or sediment data. The thalweg is the first part of the bed to be impacted by a sediment slug. Cross-sections on the other hand, incorporate both the river bed and the channel boundary (banks). Therefore, unless the stream is impacted by a significantly large slug, much of the cross-sectional profile (banks) may never be directly affected by the sediment slug. If large parts of the cross-section are not impacted by the slug, then you would not necessarily expect a decrease in cross-sectional variability. Thus, it appears that the threshold of sediment required to detect cross-sectional change is greater than for the other variables. It may also be that the cross-sections will not show any significant change until the proportion of the stream that is impacted by sediment increases beyond a critical depth or volume.

Cross-sections, however, are useful for detecting change once the channel starts to incise, which is more likely to occur during the recovery phase. This was observed on both Creightons Creek and the Wannon River, where once the sediment slug evacuated the stream, the channel began to incise, altering cross-sectional form.

The results for the cross-sections provided the greatest range of results, both between streams, and between analysis techniques. The three analysis techniques used to quantify the cross-sectional variability were the trapezoidal method, vector dispersion (VD) and sum of squared height deviations (Σdh^2). Each of the techniques provided a slightly different assessment of the variability of the cross-sections, with the trapezoidal method being the most unique. This is because the trapezoidal method measured the deviation of the cross-section away from a trapezoid shape and the other techniques look at the smaller scale angle and elevation changes. On Creightons Creek and the Wannon River the vector dispersion (VD) technique gave higher variability values to reaches that were deep relative to their width; hence, it appears that the VD method is biased towards incised streams (considering them to be more variable than stable reaches). The Σdh^2 appeared to measure the change in angles along the cross-section.

Figure 9.26 presents three cross-sections from different sections on the Ringarooma River (note the varying horizontal and vertical scales). Cross-section (A) shows a very high value when analysed using the trapezoidal method as it has a very different shape to a trapezoid; however, it records low variability values for both the Σdh^2 and VD techniques. Cross-section (B) records a high value for all three techniques, but it has the highest value for the VD technique because of the steep bank walls which is indicative of cross-sections that are incising (in this cross-section the bed level has dropped dramatically, leaving behind 4 m high benches on the cross-section margins). Cross-section (C) recorded a high level for the Σdh^2 as it has considerable vertical variability given its width (it is roughly half the width of cross-sections A and B).

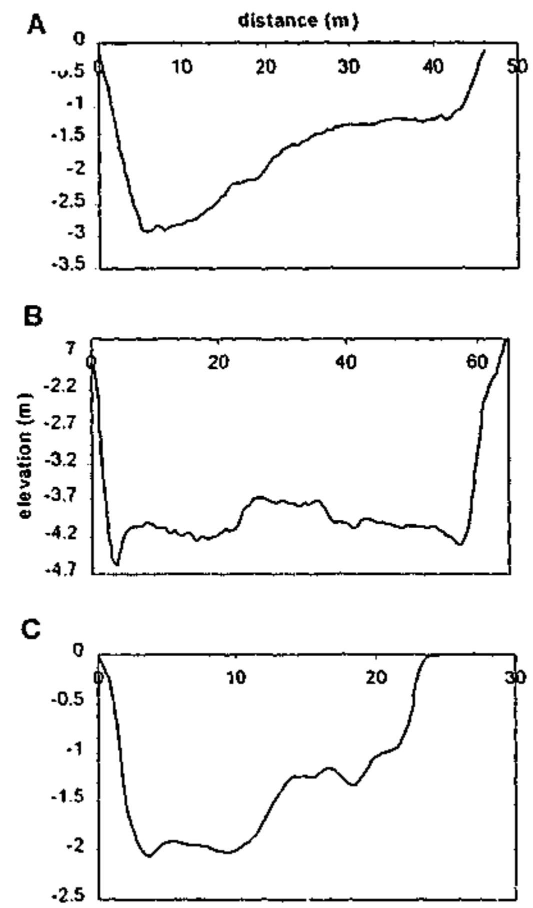


Figure 9.26: Shows the three different cross-sections from the Ringarooma River. Cross-section (A) records high variability using the trapezoidal technique; cross-section (B) shows high variability using the VD technique; and (C) shows high variability using the Σdh^2 measure.

All three measures assess cross-sectional variability differently. In choosing a single technique, it is important to select a technique that will estimate variability based on the overall configuration of the channel. The technique should not be biased by the position of the cross-section in the catchment, or the type of channel (eg. as shown on the Ringarooma River stable gravel bed streams are more likely to have a trapezoidal configuration), and the analysis technique should not interpret steep bank walls as a measure of high cross-sectional variability (eg. the VD measure in incised reaches). Therefore, if a single technique was to be used in future studies for quantifying cross-sectional variability, the sum of squared height deviations method (Σdh^2) would be the most appropriate.

Sediment size variability

The sediment variability data was also sensitive to sediment slug impact, particularly in the recovering reaches. Once the sediment begins to evacuate the stream in the recovering reaches, there is often an increase in coarse materials in the substrate. This is because the heavier particles are the last to be evacuated from the stream bed. The sediment variability data needs to be used with caution because on some streams it will initially appear that the sediment variability is increasing; in reality, the channel may be incising (eg. the Wannon River and Creightons Creek). When a stream incises, often coarser (sand or gravel) material is exhumed from the bed and banks. This is why it is important to have an estimate from the less disturbed areas (or an estimate of the expected or pre-disturbance sediment size as described in Chapter 7) to verify whether the sediment variability in the recovering reaches is actually returning to near pre-disturbance conditions or undergoing another process such as incision.

There were just two analysis techniques that were considered suitable for quantifying sediment size variability: sorting and heterogeneity. These techniques gave very similar results for each of the three study streams and in future studies either of these estimates could be used; however, sorting has been used more extensively in sediment studies and is considered the most appropriate measure of sediment size diversity.

Sediment stability

Sediment stability varies considerably with changes in mean grain size, and thus sediment slug impact. This is because there is a big difference in the shear stress values for clays and sands (0.01 and 0.1 mm); a slight change in the sediment distribution can result in a large difference in the tractive forces required to lift and transport the sediment, resulting in large differences in sediment stability. There was only one analysis technique used to measure sediment stability and this is considered a rapid, yet suitable method for estimating the % time that sediment is entrained over the flow record.

Summary

In future studies that look at small scale geomorphic and habitat changes following disturbance by sediment slugs, the most sensitive indicators of change would be the thalweg, sediment variability and sediment stability. The cross-sections are a good indicator of severe disturbance within stream systems yet they are not as sensitive to change as the other three indicators. The final four analysis techniques that are considered suitable for quantifying Geomorphic Variability are:

- Thalweg - standard deviation (SD) of depths;
- Cross-sections - sum of squared height deviations (Σdh^2);
- Sediment size variability - sorting value
- Sediment stability - % time the sediment (D_{50}) is stable

9.7 Summary

Each of the variables that make up Geomorphic Variability have presented a different perspective on the way in which streams respond to disturbance by sediment slugs. However, no single variable can be used on its own to evaluate the Geomorphic Recovery Model. It would therefore seem appropriate, and potentially more useful, if the four sub-indices were combined to represent a single estimate of Geomorphic Variability. The next chapter presents a method for combining the results from this chapter into an Index of Geomorphic Variability. This Index will provide a holistic look at the geomorphic response of each stream. This will then allow a final evaluation of the Geomorphic Recovery Model to be made for each stream.

Chapter 10

Evaluating the recovery of streams disturbed by sediment slugs using an Index of Geomorphic Variability

10. Chapter 10 - Evaluating the recovery of streams disturbed by sediment slugs using an Index of Geomorphic Variability

10.1 Introduction

Chapter 9 showed how the variability of each of the individual parameters: thalweg, cross-sections, sediment size and sediment stability changed with different levels of sediment slug impact. Chapter 9 also evaluated the response of each of the factors with respect to the Geomorphic Variability Model. Each individual factor provided important information on how stream systems changes following impact by sediment slugs; however, no single variable is appropriate for evaluating the overall recovery of Geomorphic Variability on a stream. Therefore, this chapter investigates the benefits of combining each of the individual factors into an Index of Geomorphic Variability.

Section 10.2 outlines the process of developing an Index. The Geomorphic Variability Index is then calculated for each reach and evaluated using Hierarchical Cluster Analysis (HCA) (Section 10.3). HCA will help determine if the Index is able to differentiate between the different reach types. The Index is then used to evaluate the overall response of the streams according the Geomorphic Recovery Model (Section 10.4); it is also used to assess the influence of sediment depth and LWD on the level of Geomorphic Variability measured in each reach (Section 10.5). Section 10.6 then discusses the theoretical and methodological contributions of the Index.

Section 10.7 discusses the time scales of recovery for each of the study streams and Section 10.8 gives a general summary of the response of streams to disturbance by sediment slugs, including a discussion on the applicability of both the wave model, and ergodicy, as appropriate tools for predicting recovery. A range of alternative recovery models are also presented. Finally, Section 10.9 presents the unique findings of this study and Section 10.10 summarises the chapter.

10.2 Developing an Index of Geomorphic Variability

10.2.1. Background

The purpose of an index is to simplify. By simplifying, an index strives toward parsimony - presentation of the least amount of information possible that will convey the appropriate meaning (Ott, 1978). An index seeks to reduce the measurement of two or more variables to a single number. This is usually done by mathematical manipulation. There is considerable criticism regarding the use of Index's, mainly because of the loss of individual detail at the expense of a general perspective. However, Cooper *et al.* (1994) suggested that condensing information into an Index makes the data more user friendly. This potentially increases the applicability of the data analysis techniques, which could be applied in other geomorphic studies, and thus preventing the detailed analysis conducted in this thesis. Chapter 9 (Section 9.5) also highlighted the similarity of the response if the individual variables. Therefore, it is unlikely that an Index of Geomorphic Variability will result in a significant loss of information.

A number of people have developed indices to monitor stream and environmental health (eg. Cairns, 1990; Cooper *et al.*, 1994; Death and Winterbourn, 1994; Hughes *et al.*, 1990; Ladson *et al.*, 1997; Ladson, 2000; Ladson *et al.*, 1999; Li and Reynolds, 1994; Petersen, 1992; Skinner *et al.*, 1998; Smith, 1990; Vogt, 1990); most of these deal with water quality monitoring or general riparian health. Cairns (1990) developed an Index of Ecosystem Recovery that can be applied directly to stream systems. This Index dealt with factors such as chemical and physical environmental quality following pollutional stress, as well as qualitative management based indicators. No index has been developed that deals specifically with the geomorphic structure of the stream.

<u>Theoretical and methodological contributions of an Index</u>

There are a number reasons for developing an Index of Geomorphic Variability:

(1) no single individual variable has the capacity to explain the overall recovery of a stream;

(2) each of the individual elements can be measured separately, however, in reality, the variables are linked together and influence each other through a series of complex response mechanisms (eg. Phillips, 1991);

(3) an index would incorporate four variables that reflect the response of the stream at a variety of spatial scales (eg. 10^{-1} - 10^{2} m).

By developing an Index, there will be a loss of data, resulting in a simplification of the response of the streams to disturbance. However, simplification of the data also has its advantages. In this study, each of the variables in the Index will be standardised so they can be compared not only between reaches, but also between streams. This provides a theoretical contribution in terms of being able to evaluate the response of streams against each other, instead of the single catchment case study approach that is commonly used in geomorphic research. It also provides a methodological contribution as it presents only those variables that have been rigorously evaluated and found to best quantify the variability of the four main factors that make up Geomorphic Variability.

10.2.2. Methodology

There are two main ways to develop an Index using scientific data:

1. Using multivariate statistics such as Principal Components Analysis (PCA); or
2. Using an additive or multiplicative indexing approach, as described by Ott (1978)

Each of these approaches is evaluated below.

<u>Principle Components Analysis Approach</u>

A number of studies (eg. Death and Winterbourn, 1994; Chappell, 1976; Reynoldson *et al.*, 1997) have applied multivariate techniques, namely PCA or MDA (multiple discriminant analysis), to incorporate a large number of variables into an index of overall change. PCA belongs to a family of techniques that deal with data reduction (ordination), and is a tool that helps describe the relationship and variation between data sets. When using this technique a single-valued index, containing the most variance, is constructed by deriving a set of principle components from the data matrix. This is done through a linear transformation of the variables.

In previous papers that have used PCA to develop an index (eg. Death and Winterbourn, 1994), typically 40-65% of the total variance within the variables could be explained by the main (first) axis. This axis is considered to hold the most information about the data set, and is seen as a more useful predictor of change (or the state of the system) than any of the individual variables; thus, it can be condensed into an index.

There are some problems, however, with using a technique such as PCA. It is most efficient with a large number of factors; in this study, only 4 factors were chosen. In this case, there is not enough discriminatory power for the output to be useful. There is also no rational criteria for deciding when a sufficient proportion of the variance has been accounted for by the principle components (Chappell, 1976).

<u>Additive or Multiplicative Approach</u>

According to Ott (1978), it is possible to construct a general mathematical framework to accommodate most environmental indices; this structure can then be used as a conceptual tool for understanding and comparing environmental indices. This approach appears to be more appropriate than PCA for developing an Index of Geomorphic Variability, as described below.

Ott (1978) outlined the basic mathematical structure for developing an Environmental Index. This method has been slightly adapted and is presented as a three step structure:

Step 1: Quantify the environmental variables of interest;

Step 2: Group the individual parameters to form sub-indices OR select a single representative variable for each parameter;

Step 3: Aggregate the sub-indices into an overall index.

For this study, step 1 was carried out in Chapter 8 and the results were presented in Chapter 9. The next step (step 2) was to chose which analysis techniques best represented each of the geomorphic variables. The four techniques chosen were discussed in Section 9.6 and are shown in Figure 10.1.

To form the index itself a number of different techniques can be used; however, the most common are either addition or multiplication. Other potential techniques include root-sum power, root-mean square and maximum operator (Ott, 1978). Addition is more commonly used for data that have increasing scales and multiplication for data with decreasing scales. The data in this thesis is more suited to the additive technique as the higher the value, the greater the Geomorphic Variability.

A schematic description of the process of combining each of the sub-indices into an Index of Geomorphic Variability is presented in Figure 10.1. In this diagram, T_v, C_V, S_v and SS_v represent the thalweg variability, cross-sectional variability, sediment size variability and sediment stability variation, respectively. Before the selected sub indices are added together to form the Geomorphic Variability Index (Equation 10.1), the data are standardised using Equation 9.1. This allowed each of the factors to be equally represented in the Index.

$$\text{Geomorphic Variability Index} = \Sigma\,(T_v + C_v + S_v + SS) \qquad \text{Equation 10.1}$$

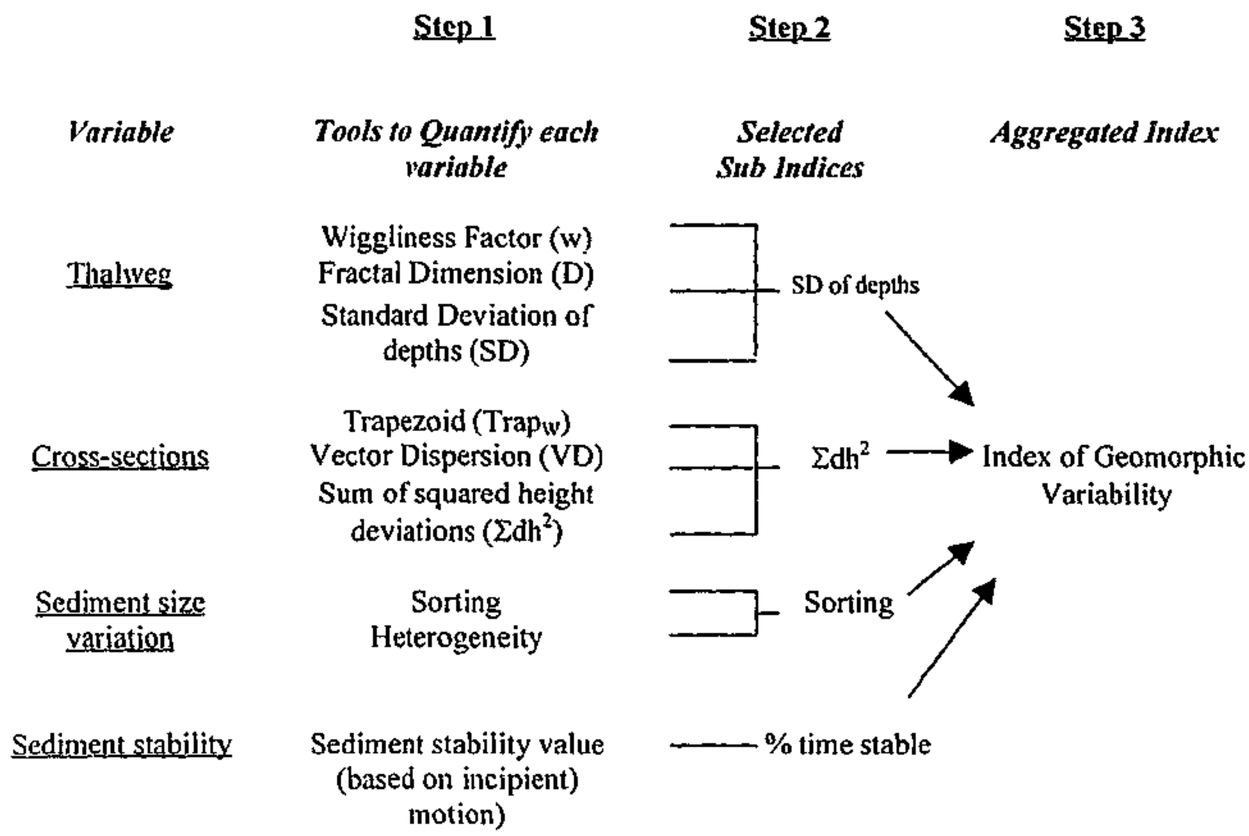


Figure 10.1: Tree diagram of the process of Index development

It is common to assign different weights to each of the sub-indices within an Index; this is usually carried out when one or more sub-indices are considered to be more important than the other variables. It also used when maximum and minimum values cannot be exceeded. For example, many water quality parameters have maximum saturation values that need to be constrained by weighting the values. For this study, a limit to the level of Geomorphic Variability that can be attained in any one reach has not yet been determined. In addition, all of the variables are considered to play an equal and significant part in defining Geomorphic Variability. Hence, each variable is given the same weighting.

10.3 Using the Geomorphic Variability Index to differentiate between impact levels

The main criteria for differentiating between the different reach types (control, impact and recovering) along each stream was sediment depth (as discussed in Chapter 5). This section evaluates whether the Geomorphic Variability Index (GVI) is able to differentiate between the different impact groups. To do this, the Geomorphic Variability Index is calculated for each reach on each stream; it was then analysed using Hierarchical Cluster Analysis. The specific statistical methods used are outlined below.

Statistical techniques

Following review of a number of statistical texts and associated papers (eg. Legendre and Legendre, 1983; Manly, 1994) it seems that Cluster Analysis is the most appropriate technique for differentiating between data of the kind collected in this study. Hierarchical Cluster Analysis (HCA) is a procedure that helps identify relatively homogenous groups of data. It uses an algorithm that starts with each data case in a separate cluster and combines clusters until only one is left.

There was no need to use a standardising procedure within the HCA as this had already been carried out on the data prior to the analysis (Chapter 9). The actual hierarchical tree that is produced from HCA was developed using the 'Ward's cluster method' function; the squared Euclidean distance was used to measure the distance between the clusters. Ward's method is different from many of the other cluster methods (eg. nearest neighbour and centroid clustering) as it uses an analysis of variance approach to evaluate the distance between the clusters, which is considered to be an efficient method. The Squared Euclidean distance method is generally a coarser technique, whereby progressively greater weight is given to objects that are further apart. It may form groups that would not normally appear using other techniques such as straight Euclidean Distance or Pearson's Correlation techniques. Nonetheless, it is considered appropriate for this analysis due to relatively small number of groups. All analysis was carried out using SPSS™ (version10.0, 1999).

To interpret the hierarchical tree, the horizontal axis denotes the linkage distance (in Euclidean distance) between the various groups of data. The cut-off distance at which the different groups can be separated on a dendrogram is determined 'arbitrarily' (Ludwig and Reynolds, 1988). Generally, the process is considered to rely on the skill of the analyst, based on 'what makes sense' (pers comm, Dr John Ludwig, CSIRO). The results for each stream are presented below.

Creightons Creek

The point at which the groups can be separated is shown using the dashed vertical line on the dendrogram (Figure 10.2). Placement of this line produces two groups. Group A contains all of the impacted and recovering reaches as well as Reach 4, a control reach. Group B contains Reaches 1-3. It is also worth noting the small sub-group within Group A which contains Reaches 4 and 12. Reach 4 is the reach at the front end of the slug, and Reach 12 is an incising reach towards the back end of the slug. The fact that these reaches were initially grouped together suggests that there is a similarity between the initial stages of impact, and the early recovering stages. It is also important to note that Reach 4 has up to 17 % of its reach filled with sediment and Reach 12 is the only recovering reach with less than 20% of its reach volume filled with sediment (19%) (Chapter 7). It therefore appears that the Index can group reaches that have similar (scaled) volumes of sediment, and this relates directly to the amount of variability in the channel. The similarity between these reaches is probably also linked to the fact that Reach 12 is a severely incising reach, which has produced variable sediment sizes in the bed, as well as a deeper channel similar to the control reaches downstream.

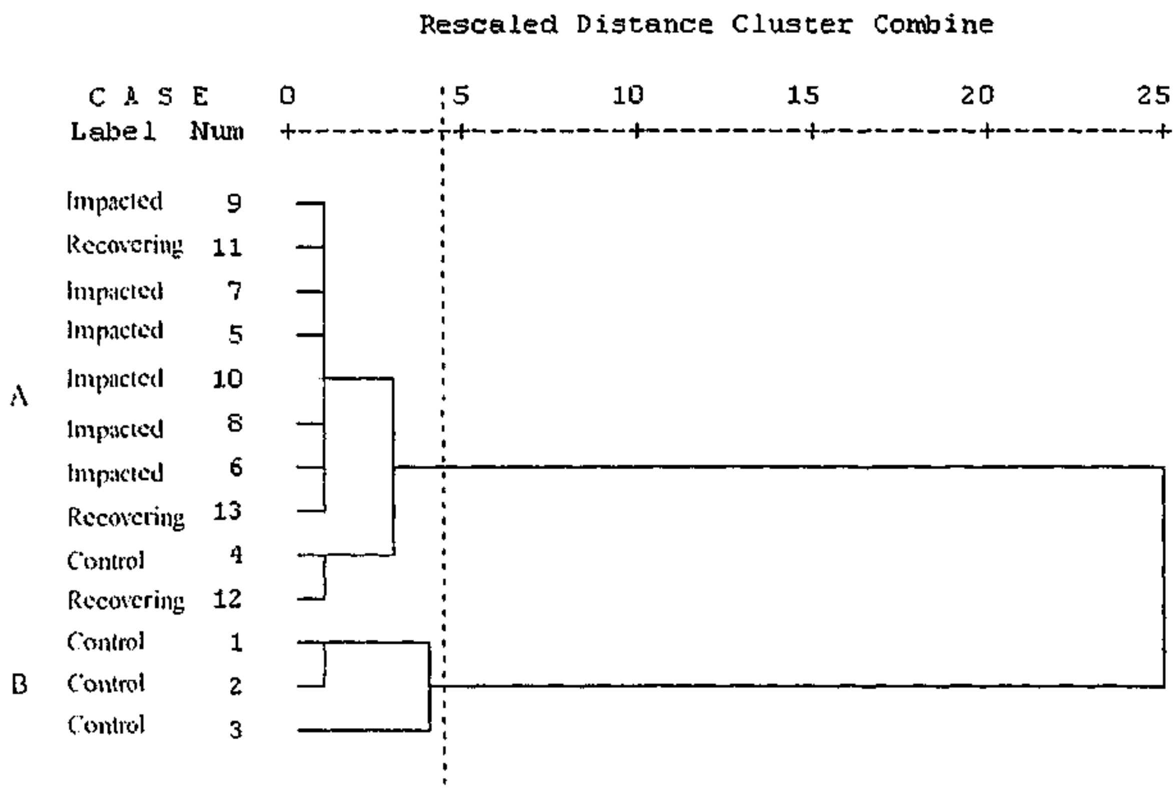


Figure 10.2: Hierarchical Cluster Analysis dendrogram for Creightons Creek

If the small sub-group containing Reaches 4 and 12 are removed from Group A, then all of the reaches in Group A have greater than 20% of their reach volume filled with sediment. Therefore, this analysis suggests that the Geomorphic Variability Index can differentiate between reaches of similar depths without having to measure the depths specifically. This does not mean that sediment depths should not be measured, instead, it reinforces that reaches with similar depths, also have similar levels of Geomorphic Variability.

<u>*Wannon River*</u>

The results on the Wannon River can be separated using a single vertical line; this splits the results into three distinct groups (Figure 10.3). Group A (Reaches 8, 10, 4, 5) and Group B (9, 11, 7, 12, 6) are both made up of a combination of the impacted and recovering reaches. This suggests that there is no difference in the level of Geomorphic Variability measured in these reaches. Reach 6 starts off as a separate group in the first clustering stage (Figure 10.3). Reach 6 is the closest recovering reach to the sediment slug and has the highest value of Geomorphic Variability for any of the impacted or recovering reaches. This again reflects that a small amount of sediment in bed of the river can result in a geomorphically diverse substrate. Group C contains the three control reaches, showing that they have similar levels of Geomorphic Variability.

The clustering of the impacted and recovering reaches highlights these reaches cannot be separated using the Geomorphic Variability Index. This may be because the % of these reaches that has been filled by sediment does not exceed 25%. Had some of the reaches been more severely impacted (eg. 50%) there may have been a more clear distinction between the reaches. Thus, this result again highlights that the level of Geomorphic Variability is closely linked to the depth or volume of sediment in the reaches.

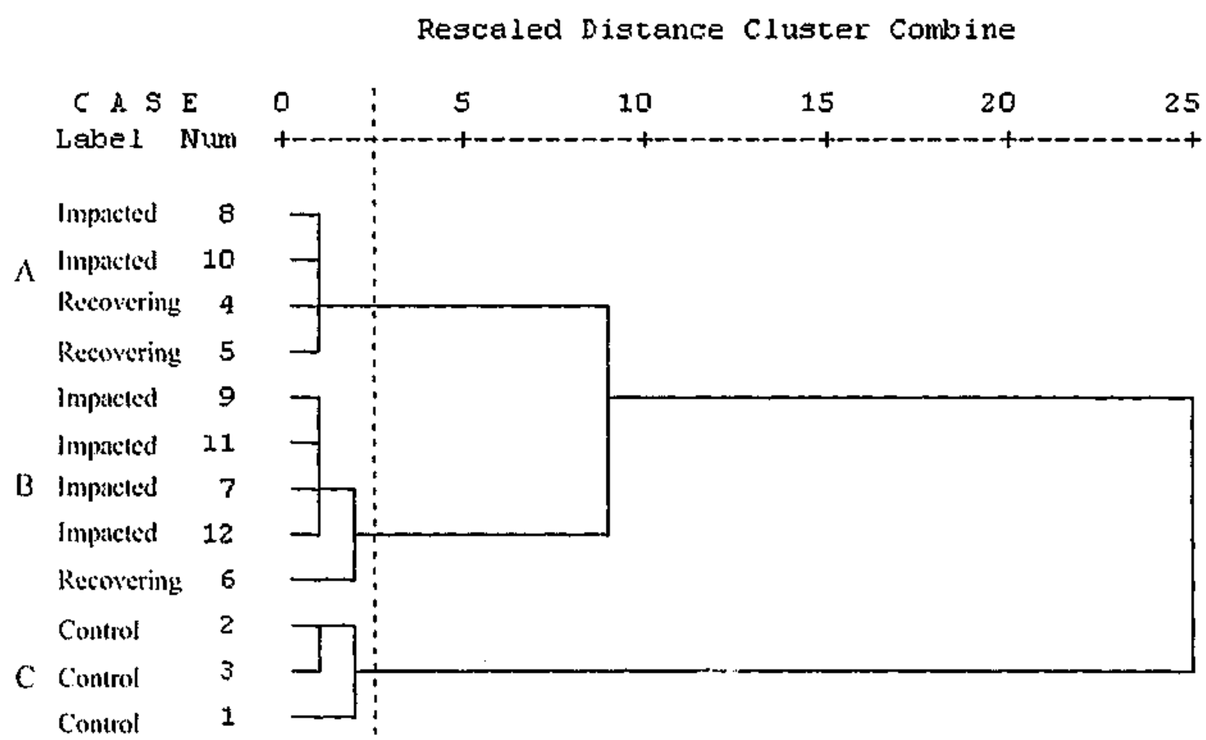


Figure 10.3: Hierarchical Cluster Analysis dendrogram for the Wannon River

Ringarooma River

The HCA results for the Ringarooma River show that there are initially three distinct cluster groups (Figure 10.4). Groups A and B are a mixture of the control and recovering reaches, and Group C contains the four impacted groups. This is the only result in which the control and recovering groups have been clustered together. This suggests that the level of variability is now similar between the control and recovering groups. Group A contains Reaches 1, 4 and 5 and Group B, Reaches 2, 3 and 6. There is no apparent reason why these groups are different. One possible explanation is that all of the reaches in Group A are relatively confined within a bedrock controlled areas; whereas Group B reaches are all located in less confined floodplain zones. This has allowed for a greater degree of lateral movement and thus higher lateral variability. Group C contains all of the impacted reaches, which all have greater than 20% of their reach volume filled by sediment.

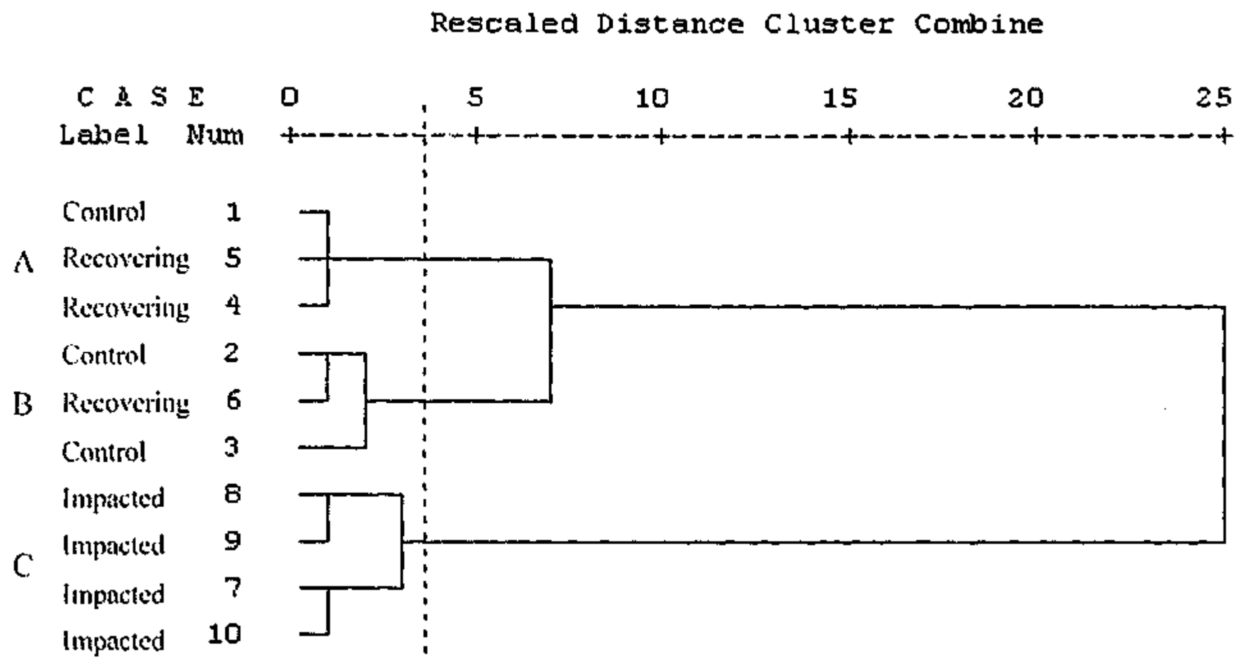


Figure 10.4: Hierarchical Cluster Analysis dendrogram for the Ringarooma River

<u>Summary</u>

The use of HCA has shown that it is possible to differentiate between reaches with different volumes of sediment using the Geomorphic Variability Index. For all three streams, the Geomorphic Variability Index was able to differentiate between the control and impacted reaches. The Index also grouped together reaches with similar variability and sediment volumes. These results suggest that Creightons Creek and the Wannon River have not yet recovered as the recovering reaches are still very similar to the impacted reaches; however, on the Ringarooma River, the recovering reaches were grouped with the control reaches suggesting a full recovery.

Initially, the different reach types were differentiated according to sediment depth (when the sediment depth was greater than 1/5 the mean bank height, the reach was considered to be impacted). The use of the HCA has shown that there is a close link between the amount of sediment in the reach and the level of Geomorphic Variability; however, it appears that there is a change in the level of Geomorphic Variability when the sediment depths increase beyond 20% of the reach volume. Hence, in future studies, the type of reach should be classified according to the sediment volume (rather than depth), with the impacted reaches being those with greater than 20% of their reach filled with sediment.

10.4 Evaluation of the Geomorphic Recovery Model using the Geomorphic Variability Index

The previous section showed that the Geomorphic Variability Index was able to differentiate between groups with different sediment volumes. Thus, it appears that the Index will be suitable for evaluating the response of each stream with respect to the Geomorphic Recovery Model. The results are presented for Creightons Creek, the Wannon River and the Ringarooma River below.

10.4.1. Creightons Creek

The response of the individual variables that make up Geomorphic Variability were presented in Section 9.5.2. For Creightons Creek, all the data sets showed a decrease in the level of variability in the impacted reaches. This section has combined the variables, so that the response of Creightons Creek can be evaluated according to the overall change in Geomorphic Variability (Figure 10.5).

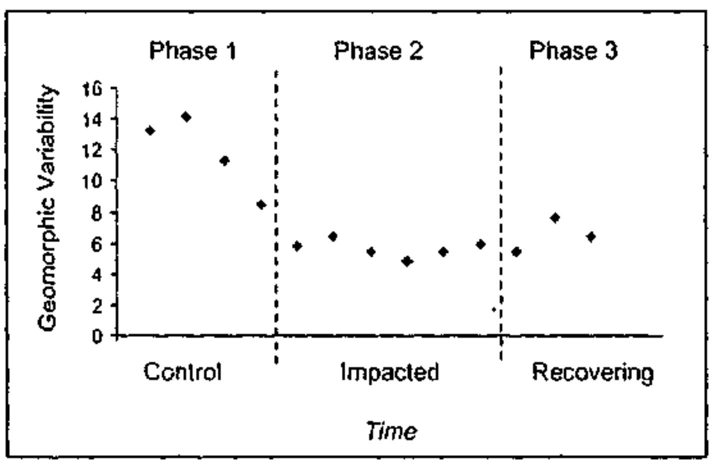


Figure 10.5: The recovery of Geomorphic Variability on Creightons Creek using the Geomorphic Variability Index

Comparison of the results for each of the individual measures of variability (Figure 9.23) with Figure 10.5 show a great similarity in the general recovery trend. This suggests that the Index is a suitable measure of the overall recovery of Creightons Creek.

The response of Creightons Creek does not conform to the recovery model being tested in this thesis. Despite the bed level returning to near pre-disturbance levels, there has not been a subsequent recovery in the level of Geomorphic Variability (Figure 10.5). The main reasons that Creightons Creek does not follow the recovery model is because of the association of the sediment slug and channel incision.

The incision process is both a source of the sediment (endogenous) as well as occurring within the areas that are classified as 'recovering'; the incision effectively interrupts or destroys the process of recovery. The channel has not re-developed any pools, nor have the bed sediments been able to stabilise whilst the incision process is occurring. Other studies such as Lisle (1981) have suggested that preferential degradation of the thalweg effectively initiates the process and bank recovery by reducing the frequency of reworking of bars of aggraded material. However, in the case of Creightons Creek, the thalweg degradation is not stabilising at a level appropriate for bank recovery. In fact, the rate of degradation and incision is destabilising the banks, which increases erosion.

Although the absolute sediment depths have returned to ~0.5 m in the recovering reaches along Creightons creek, the sediment still occupies up to 37% of the reach volume or cross-sectional area (eg. in Reach 13). The sediment in these reaches is likely to be coming from local sources such as bank erosion within the actual reaches (rather than from the eroding areas upstream). Therefore to reduce the sediment depths, the incision process needs to be controlled. Once the incision and subsequent sediment delivery slows, the channel may be able to stabilise and increase the level of Geomorphic Variability, which will assist with channel recovery.

10.4.2. Wannon River

The response of the individual variables that make up Geomorphic Variability were presented in Section 9.5.3. This section has combined the variables, so that the response of the Wannon River can be evaluated according to the overall change in Geomorphic Variability (Figure 10.5).

Previous analysis of data from the Wannon River (Chapters 6 and 8) suggested that some of the geomorphic variables were not affected by the sediment slug. In particular, there was no significant difference in the cross-sectional variability between any of the reach types (control, impacted and recovering); in some cases it appeared that the sediment slug had actually increased the level of variability. This could be the result of a number of factors:

a) the structure of the Wannon River, in its natural state, is not very variable. It consists of smooth (almost horse-shoe shaped) cross-sections and long pool sequences, separated by flat reed beds. Thus, the addition of sandy sediment has resulted in the formation of bedforms (eg. lateral and mid-channel bars, benches and backwater zones), increasing the geomorphic shape variability in some reaches; and/or

b) the amount of sediment that has formed the sediment slug is relatively small compared to the size of the channel. Hence, the volume of sediment is not enough to alter the structure of the channel significantly. Instead, the sediment has been accommodated in the natural sediment load. In the case of Creightons Creek, which is a much smaller channel, the size of the slug appears to have had a significant impact. On the Wannon River, the sediment slug would need to be much larger to reduce the channel's Geomorphic Variability.

Despite the fact that some of the data analysis techniques did not show any decline in variability when impacted by the sediment slug, the combined response of the stream tells a different story. Figure 10.6 suggests that the Wannon River has undergone a considerable decline in the level of Geomorphic Variability in response to the sediment slug (Phase 1 to Phase 2). The level of Geomorphic Variability then fluctuates considerably in the impacted reaches. In the recovering phase, the results showed a slight increase; then the stream seems to moving into a secondary decline in Geomorphic Variability. This decline was also observed in the field. This means that a small amount of sediment in the recovering reaches may initially increase the level of Geomorphic Variability, however, once all of the sediment is evacuated, the remaining surface is a flat clay bed, void of any heterogeneity. It is probable that the recovery process along the Wannon River will continue to fluctuate between different levels of Geomorphic Variability, before finally stabilising; this process could go on for many decades. Figure 10.6.

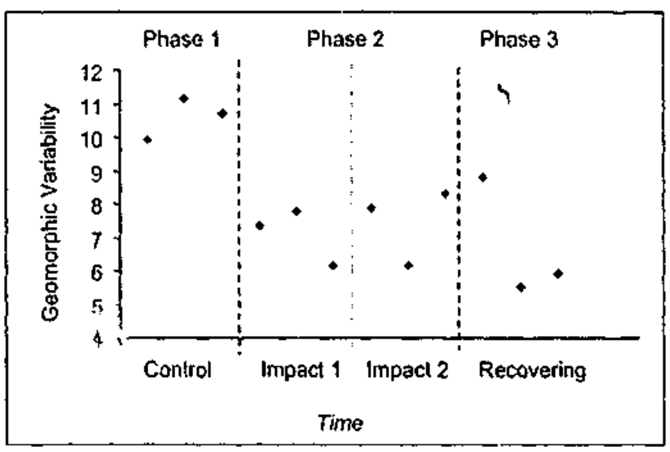


Figure 10.6: The recovery of Geomorphic Variability on the Wannon River using the Geomorphic Variability Index

The fluctuating recovery process could be attributed to a number of processes:

1. The sediment slug on the Wannon River is moving along the bed of the river in a pulse or sluglette type fashion (Rutherfurd and Budahazy, 1996) which means that some areas are less impacted than other reaches within the same slug zone;
2. It may be that some reaches accommodate the sediment better than others, and are undergoing a 'passive' response to the sediment which suggests that the sediment is simply incorporated into the natural bed-load of the stream (as described by Lewin and Macklin, 1986); other sections will be more severely impacted and undergo 'active' transformation. This will involve filling in pools, increasing the instability of the bed surface and decreasing the variability of the sediment sizes within the bed;
3. Large flood events may also remobilise much of the stored sediment within Bryans Creek (the main sediment source). This could further degrade many of the downstream reaches, producing a patchy or fluctuating recovery process. Thus, it may be that the response of the Wannon River will be more like the asymmetrical wave model proposed by James (1991), described in Section 3.5. This will be discussed further in Section 10.8.2.

Overall, the Geomorphic Variability Index has shown that the Wannon River has been degraded by the sediment slug, and the river has not recovered in areas where the sediment has evacuated the stream.

10.4.3. Ringarooma River

The response of the individual variables that make up Geomorphic Variability were presented in Section 9.5.4 for the Ringarooma data. All four data sets showed a similar trend of disturbance and recovery, subsequently when the variables were combined into an Index of Geomorphic Recovery, they also showed a similar response (Figure 10.7). The response of the Ringarooma was quite different from the other two study sites, as it appears that this river has made a full recovery according to the model presented in Chapter 3.

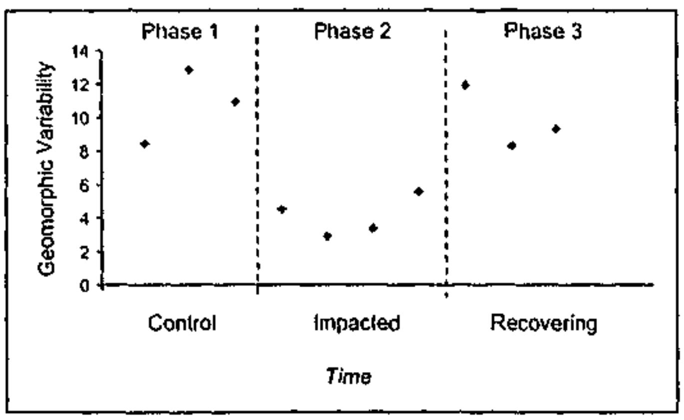


Figure 10.7: The recovery of Geomorphic Variability on the Ringarooma River using the Geomorphic Variability Index

The slight decrease in Geomorphic Variability at the end of Phase 3 is considered to be a function of natural variation as well as the higher than expected variability values measured at Reach 6. The reasons for Reach 6 having high levels of Geomorphic Variability was discussed in Section 9.5.4.

In summary, there are a number of possible reasons why the Ringarooma River appears to have made a full recovery:

1. There is a coarse gravel bed armour beneath the sediment slug; when exposed, this acts to increase the Geomorphic Variability and stability of the bed. Once the fine sands are winnowed away, the coarse gravel bed sediments also assist in the reformation of pool and riffle sequences which provide both longitudinal and cross-sectional variability to the reaches;
2. Much of the Ringarooma River is set in a confined bedrock valley, thus there are high stream powers available to transport the excess bedload (slug). Both Creightons Creek and the Wannon River are floodplain systems with considerably less stream power, and therefore less potential to move the sediment and recover. This result is supported by the research carried of Florsheim (1987) which suggest that the spatial distribution of sediment deposition during a low magnitude flow (eg. $Q_{2.5}$) is greatly influenced by bedrock controlled channel geometry; there is an inverse relationship between unit stream power and volume of sediment stored in a particular reach. As a result, sediment is deposited both upstream and downstream of bedrock constrictions, while very little sediment is deposited within constrictions;
3. The native bed material on the Ringarooma River is gravel and this means that the river is used to transporting large sediment sizes. The fact the sediment slug is predominantly sand means that the Ringarooma can quite competently transport this smaller sized material. On the Wannon River and Creightons Creek, however, the streams have had to change from transporting predominantly clay/silt fractions, to transporting sand. As described by Patheniades and Paaswell (1970) there are large differences in the sediment transport mechanics between cohesive and cohesionless sediments. This may help explain why the Ringarooma River has been so successful at transporting its large load, as well as why it has been able to stabilise (rather than incise) once the sediment has evacuated.
4. The Ringarooma River also has abundant available LWD, both within the channel and in the riparian zone, unlike the other study sites that were extensively cleared. Despite the fact that this study did not show a significant relationship between LWD and

Geomorphic Variability (see Section 10.5.2) the LWD on the Ringarooma appears to be stabilising bench and lateral bar features, and the re-exposed LWD is proving to an important initiator of variability, particularly in reaches where the sediment depths are returning to near pre-disturbance levels.

5. The dominant source of sediment on the Ringarooma is exogenous; this means that the pre-disturbance instream condition was probably near pristine. Unlike sites such as Creightons Creek, that underwent channel incision prior (and during) the disturbance, the Ringarooma River did not incise (beyond its former bed level). The surface that is being 'un-veiled' or un-covered as the sediment moves out of the stream has essentially been preserved. This has allowed the channel to reform appropriate Geomorphic Variability. It does appear that, for many of the reaches, the load was transported as a 'passive' load. Although many of the channel boundaries were 'transformed' leaving behind benches and terraces in some places, other parts of the channel, particularly those reaches with higher stream powers (gorge sections), appeared to simply act as sediment transport zones (eg. areas upstream of Reach 6); very little change occurred within the stream. This has helped with the rapid recovery of many of the reaches.

Summary

Based on the response of the three study streams, it would be expected that for other streams impacted by sediment slugs, those with characteristics similar to the Ringarooma River will be more likely to recover than streams that are similar to Creightons Creek or the Wannon River.

10.5 The influence of sediment depth and LWD on the level of Geomorphic Variability

This section looks at the values of the Geomorphic Variability Index (GVI) for each stream with respect to the independent factors, namely sediment depth and LWD. As described in earlier chapters, the level of variability in a stream is expected to be affected by both the amount of sediment present, as well as the quantity of LWD in the stream reach.

10.5.1. Geomorphic Variability against sediment depth

This thesis has presented two different methods for interpreting the amount of sediment within a stream. The first way was to use the *absolute* sediment depth values (eg. 2.4 m). The second is the amount of sediment *relative* to the size of the channel (eg. 25%).

Absolute sediment depths

For each stream, the relationship between the Index of Geomorphic Variability and the sediment depth at each reach is best represented using a Power Function (Figure 10.8, Figure 10.9 and Figure 10.10). The strength of the relationship between absolute sediment depth and the level of Geomorphic Variability is high, particularly for Creightons Creek (r^2 values of 0.82). The Wannon and Ringarooma data also show reasonably strong power function relationships (r^2 values of 0.57 and 0.63, respectively); it would be expected that this correlation would be higher on the Ringarooma River had the true sediment depths of the downstream impacted reaches had been determined.

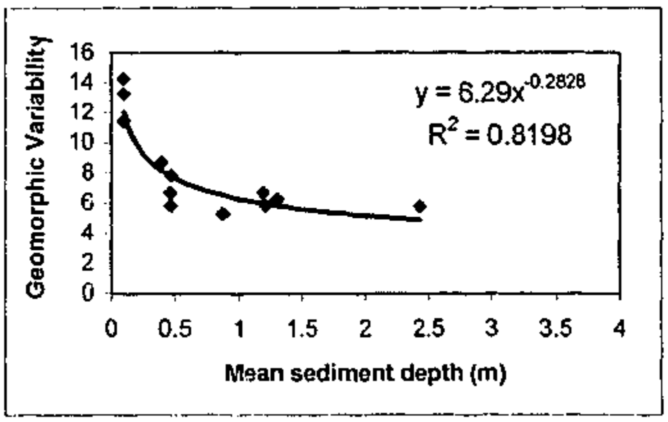


Figure 10.8: Geomorphic Variability against sediment depth for Creightons Creek

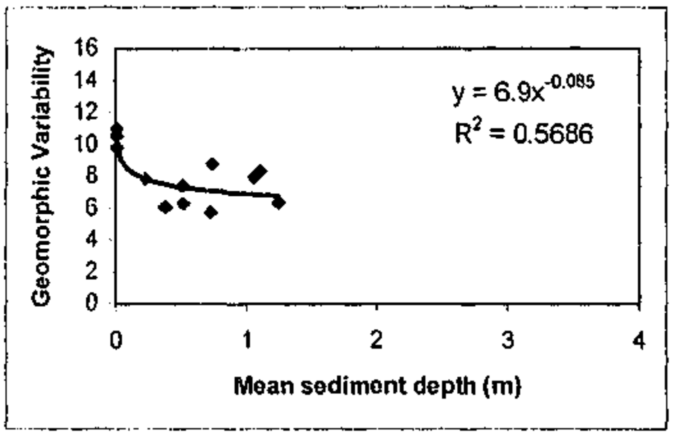


Figure 10.9: Geomorphic Variability against sediment depth for the Wannon River

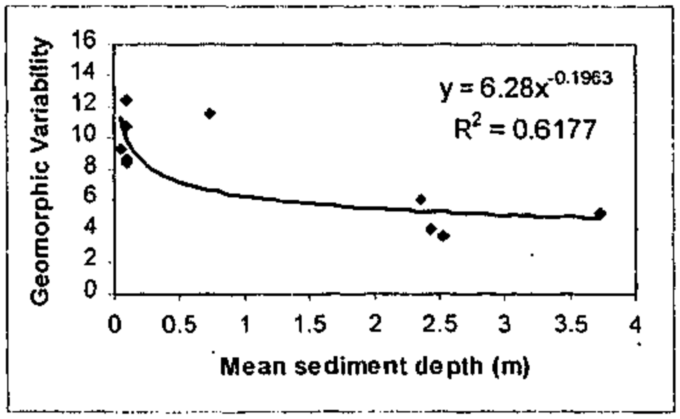


Figure 10.10: Geomorphic Variability against sediment depth for the Ringarooma River

Each of the figures have been plot with the same scales; this shows the relative values of Geomorphic Variability obtained for the sediment depths measured (Figure 10.8, Figure 10.9 and Figure 10.10). Each of the power function curves have similar shapes for the three streams with the exponent values varying between ~ -0.09 and -0.28, with an average of -0.18. This suggests that there is a similarity in the rate of decline of Geomorphic Variability with sediment depth for these three streams. The other similarity between the graphs is that the constant in the power function relationship is ~ 6.0 for each stream. The constant means that the Geomorphic Variability Index is always around 6 when the sand is 1 metre deep. This suggests that there may be a threshold response of each stream once the sediment is greater than 1 meter (regardless of the size of the stream). Further research would be required (on other slugged streams) to determine if a power function relationship in the order of Equation 10.2 would be suitable for predicting levels of Geomorphic Variability for given sediment depth data.

$$y = 6\,x^{-0.18} \qquad \text{Equation 10.2}$$

(where y = Geomorphic Variability and x = sediment depth)

Based on this research, future studies looking at the impact of sediment slugs could assume that Geomorphic Variability, and thus physical habitat, decreases with increasing sediment depth.

Relative sediment depths - % reach impacted by sediment

The results of the scaling analysis (Chapter 7) calculated the impact of the sediment as a proportion of the size of the channel in each reach, making it possible to put the data from the three streams on a single graph (Figure 10.11). The Pearson's correlation coefficient suggests that there is a significant relationship ($r = .73$, $p < 0.05$) between the % of the reach disturbed by sediment and the Geomorphic Variability within each reach. This result is comparable to the study by Alexander and Hanson (1986) that showed that there was a significant negative correlation between the amount of sand bedload and brook trout numbers. The American study was able to make a direct comparison between the amount of sediment and fish numbers, whereas this study has shown a similar relationship between the amount of sediment and Geomorphic Variability or habitat.

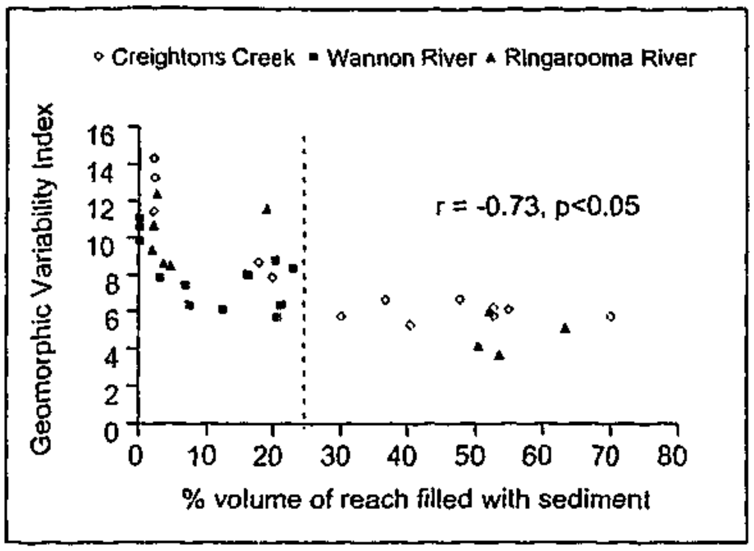


Figure 10.11: Geomorphic Variability against the % of the reach that has been filled by the sediment slug for all three study sites. The dashed vertical line shows the threshold of sediment slug impact.

Figure 10.11 also highlights that there is a drop in level of Geomorphic Variability once the sediment volume goes above 20-25%. Above this percentage, the Geomorphic Variability stays relatively constant. Note that when the sediment depth is less 20-25% of the reach volume, there is little difference in the level of Geomorphic Variability present (Index values range from ~ 6 - 14); however, once the level of sediment increase beyond ~20% the level of Geomorphic Variability plateaus at an Index value of ~6 or lower. This analysis supports many of the results that inferred that there was a threshold level of sediment required before the Geomorphic Variability declined. It also supports the results of the absolute sediment depths where there the constant value was similar for all streams at a depth of 1 metre. It may be that the sediment depth of 1 m roughly corresponds to a sediment volume of 20-25% for many of the reaches in this study.

The fact that 20% appears to be a threshold value for streams impacted by sediment slugs can be partially explained by looking at other scaled relationships relating to sediment slug impact. Chapter 7 described how pool and riffle sequences are important large scale bed-forms in many stream systems. They are often also one of the first features to be altered by sediment slugs, and are therefore useful for explaining the 20% threshold.

In Section 7.2.2 a method for predicting the expected mean pool depth for each reach was presented. Using this data and the mean bank heights for each reach (from Chapter 6), it is possible to determine the depth of the pools relative to the height of the banks (Table 10.1). To calculate what proportion a pool represents in a given reach, it is assumed that the pool is present along the length of the reach, then the depth of the pool is divided by the mean bank height (Figure 10.12A and Table 10.1). When the sediment depth increases beyond the depth of the pool, the pool feature is drowned out (Figure 10.12B).

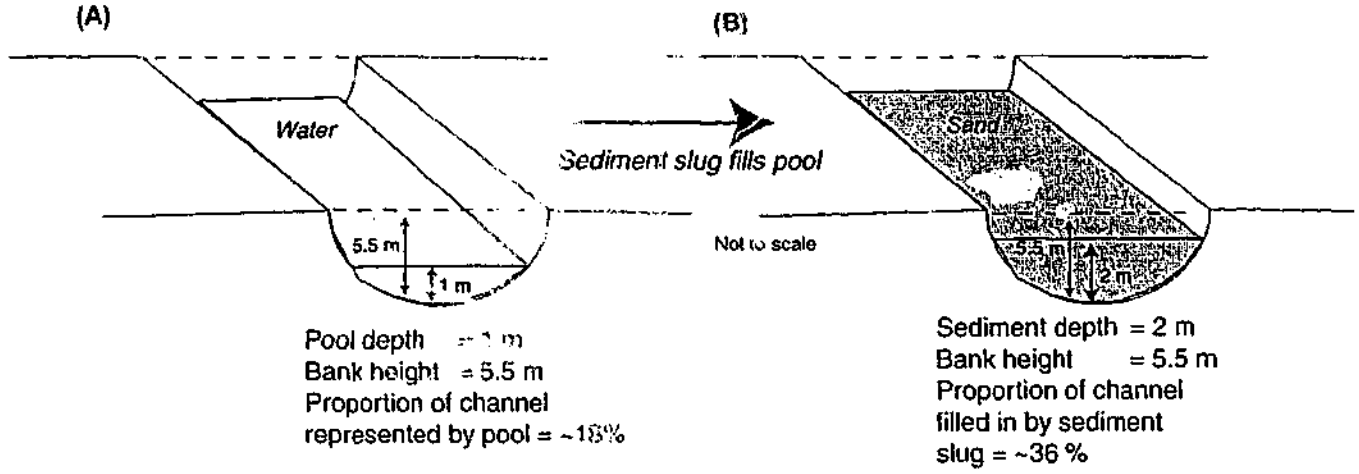


Figure 10.12: Shows how if the % of sediment filling the channel increases beyond ~20% it will essentially drown out most pool structures in the stream.

The results in Table 10.1 show that for each of three study streams the % of pool depth (on average) is less than 20% of the bank height (18%, 13% and 15%, respectively). This suggests that if sediment depths increase beyond 20% of the reach volume, then features such as pools and riffles and all associated geomorphic complexity will be drowned out and simplified (Figure 10.12). In reaches where the sediment depths are much less than the pool depths, it seems that the stream can accommodate the sediment into its natural bed-load. This is only a simple analysis, however, this example provides evidence that 20% is a useful value when assessing the impact of sediment slugs on the Geomorphic Variability of streams.

<u>Summary</u>

It appears that there is a threshold value of sediment depth at which a stream decreases its level of Geomorphic Variability; this study identified that the threshold is exceeded once more than 20-25% of the reach volume is filled with sediment. This relationship was supported by evaluating the physical relationship between pool depth and sediment depth. This is an important result with respect to the management of streams disturbed by sediment slugs, as it is now possible to quantify the amount of sediment that will initially decrease Geomorphic Variability (>20%), or conversely, the depth of sediment that a stream must attain before significant recovery can occur (ie <20%).

Table 10.1: % of pool depth against bank height for the three streams. Pool depth data re-presented from Chapter 7 and the bank height data re-presented from Chapter 6.

	Creightons Creek			Wannon River			Ringarooma River		
Reach	Mean (expected) pool depth (m)	Mean bank height	Proportion of pool vs bank height (%)	Mean (expected) pool depth (m)	Mean bank height	Proportion of pool vs bank height (%)	Mean (expected) pool depth (m)	Mean bank height	Proportion of pool vs bank height (%)
1	0.252	2.10	*12.0*	0.516	2.17	*0.4*	0.309	1.28	*24.1*
2	0.252	2.15	*11.7*	0.519	5.53	*0.2*	0.311	1.80	*17.2*
3	0.251	2.15	*11.7*	0.519	4.05	*0.2*	0.313	2.17	*14.4*
4	0.243	1.85	*13.2*	0.545	2.69	*11.8*	0.314	2.43	*12.9*
5	0.240	1.06	*22.6*	0.546	3.74	*17.0*	0.315	1.92	*16.4*
6	0.235	1.30	*18.0*	0.550	3.83	*16.9*	0.315	3.17	*9.9*
7	0.230	1.03	*22.2*	0.551	3.68	*26.2*	0.316	2.17	*14.5*
8	0.227	1.23	*18.4*	0.552	4.59	*24.3*	0.316	2.40	*13.2*
9	0.224	1.04	*21.5*	0.567	5.41	*17.7*	0.316	2.19	*14.5*
10	0.218	1.14	*19.1*	0.567	6.10	*7.7*	0.317	2.17	*14.7*
11	0.213	1.08	*19.7*	0.568	6.52	*3.2*			
12	0.209	1.95	*10.7*	0.570	6.62	*7.0*			
13	0.200	0.79	*25.3*						
14	0.188	0.86	*21.9*						
Average %			**18%**			**13%**			**15%**

10.5.2. Recovery response with respect to LWD distribution

As outlined in Chapters 5 and 6, LWD was expected to have a considerable impact on the diversity of both the stream morphology and ecology of a reach; however, the three streams in this study did not show a significant correlation between the amount of LWD in a reach, and the level of Geomorphic Variability (Figure 10.13). Despite a non-significant relationship, there appears to be a subtle and positive relationship between the amount of LWD and the level of Geomorphic Variability.

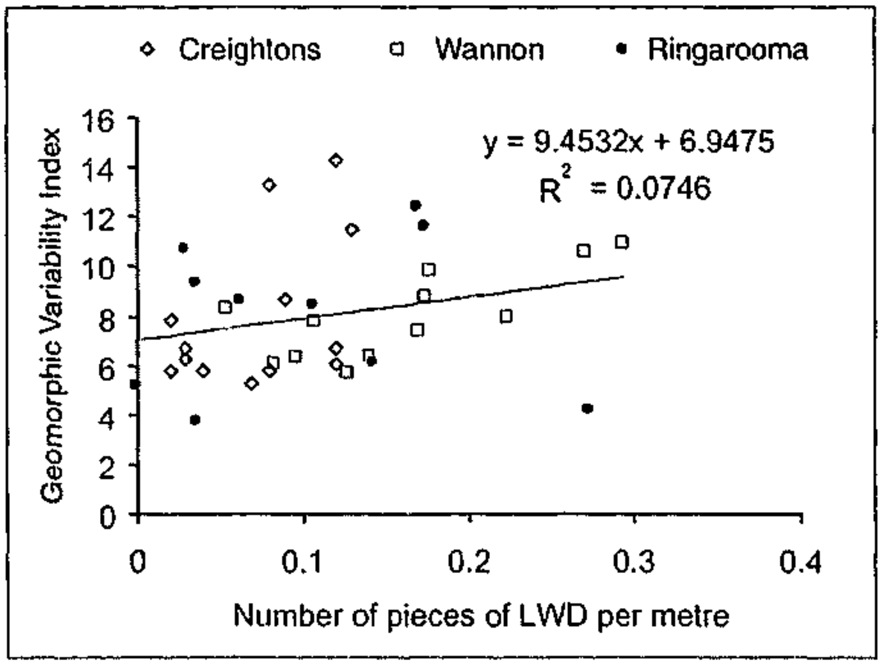


Figure 10.13: Relationship between LWD and Geomorphic Variability for the three study sites. The number of pieces of LWD were standardised to number of pieces of LWD per metre.

There are a number of possible reasons why the amount of LWD did not show a significant positive relationship with the level of Geomorphic Variability:

- LWD is a supply dependent feature of natural channels (Lisle, 1987), and there are considerable differences in the density of riparian vegetation both within and between reaches on the three study streams; with the Ringarooma having high densities of riparian vegetation, whilst the other sites have been extensively cleared. Since the volume of LWD in a reach is considered to be highly correlated with density of riparian vegetation of the banks (Marsh et al., 2001), it is possible that amount of LWD differed too much between sites and therefore its affect on the Geomorphic Variability was masked by other factors such as sediment depth changes and/or incision;
- There is also the issue of scale, as the effect that a piece of LWD will have on the complexity of a stream bed, will largely be related to the size of the channel. On the Ringarooma River, it may be that there is sufficient LWD being delivered to the

channel, however, the river is currently too wide (up to 100 m in sand places) for the LWD to have any affect on the Geomorphic Variability of the channel;

- It is uncertain as to whether LWD that is being re-exposed after being buried has the same influence as sediment that enters the channel from the bank. It may be that the position of the LWD, either partially buried under the sand, or on top of the sand, will have a different effect on the level of Geomorphic Variability measured;
- The results may also be confounded by historical influences. As discussed in Chapter 4, the Wannon River was subject to a large de-snagging program in the 1970's and this project is said to have removed up to 30% of the LWD in the lower Wannon. This process may or may not have had a dramatic influence on the Geomorphic Variability of the channel, and its subsequent relationship with LWD;
- The relationship between the Geomorphic Variability and LWD may have been confounded by the fact that the sediment depths are too great in many reaches (particularly on the Ringarooma River) for LWD to have an impact. It is uncertain if the large volumes of sediment will reduce the capacity of LWD to create significant scour in the channel bed. Further investigations into the role of LWD in slugged streams may reveal that LWD will play a more important role in creating diversity and habitat once the sediment depths are reduced to less than 20% of the reach volume. This appears to be occurring on Reach 6 of the Ringarooma River.

This study has shown that the level of Geomorphic Variability in each reach is controlled more by the amount of sediment, or more accurately the proportion of the reach that has been impacted by sediment, than by the amount of LWD in each reach. It is expected, however, that LWD would be an important influence on Geomorphic Variability as other studies have suggested that riparian vegetation will hasten the recover process considerably (eg. Wolman and Gerson, 1978). Further studies looking at the impact of LWD should specifically look at the amount, size, orientation, source and density of LWD, under more controlled experimental situations.

10.6 Theoretical and Methodological contributions of the Index of Geomorphic Variability

The development of the Geomorphic Variability Index has provided both theoretical and methodological contributions to the study of recovery in streams disturbed by sediment slugs. The Index:

- identified a threshold level of sediment that reduced the level of Geomorphic Variability in a stream reach. The presence of thresholds in fluvial systems is well established in the literature (eg. Schumm, 1973; Schumm, 1991). This threshold was identified in Figure 10.11 when all three streams were graphed together, as well as in the HCA for each of the individual streams. These results suggest that when the sediment volume is greater than ~20% of the total volume of the channel, the Geomorphic Variability of the channel is significantly reduced. Similarly, when the sediment is moving out of the channel, and the channel is recovering, the sediment has to be reduced to less than 20% of the channel volume before recovery can occur;
- allowed reaches from different streams to be graphed together and compared (as long as the variables that they are being compared against were scaled or non-dimensionalised eg. % of reach filled with sediment);
- provided an estimate of the recovery of each stream based on the synthesis of four important geomorphic variables (thalweg, cross-sections, sediment size and sediment stability). The synthesis of the variables provides an estimate of recovery for an entire reach, instead of for the individual variables within the reach;
- provided a methodological tool for future studies looking at the impact of sediment slug disturbance. The Index provides a good estimate of the recovery of the stream without having to use of all the data analysis techniques presented in this thesis.

10.7 Time scales of recovery for each of the three streams

In addition to understanding the recovery process using spatial data, it is helpful to have an idea of how long it takes a sediment slug to move through a stream. The application of ergodic theory or 'space for time substitution' has meant that the time frames relating to the response and recovery of each of the study streams have not been specifically addressed.

Without observing exactly when the physical recovery changes occurred on a stream, it is difficult to quantify the time scales of recovery. In this study, only one stream, the Ringarooma River, has made a full recovery according to the Geomorphic Variability measures used in this study. A discussion of the mechanisms and processes relating to the time scales of recovery are made for each of the three study streams below.

Review of the time scales of recovery for the Ringarooma River

The results of this study have shown the Ringarooma River is the only river that has made a full recovery, yet the exact time frame for recovery of specific reaches along the river is unclear. An estimate of recovery for the Ringarooma River was made by Knighton (1989), he suggested 'at least another 50 years will be required for the river to cleanse its channel of mining debris'. It is unclear exactly which sections of the stream Knighton was referring to, however, if he meant that the whole stream, it would take a series of very large flood events (assuming that floods are the main agent for sediment transport) to fully cleanse the remaining sediment slug from the entire length of the Ringarooma River in next 37 years (given that his paper was written 13 years ago).

It is also important to note that Knighton's recovery predictions were based on a model of the sediment transport potential of the Ringarooma (Figure 10.14). Whereas, the research in this thesis has specifically used the return of Geomorphic Variability as a measure of recovery, and the results have shown that there appears to be a close correlation between the return of the pre-disturbance bed level and the re-instatement of Geomorphic Variability on the Ringarooma River. Therefore, if the relative bed levels, and associated time scale of bed-level return can be predicted at different points along the Ringarooma River, then it would also be possible to predict the relative rates of recovery for Geomorphic Variability.

It appears that the bed levels have returned to their pre-disturbance levels according to Knighton's (1991) predictions (Figure 10.14). Therefore, if the recovery period is calculated from the time the sediment levels began to decline, through to the time at which the bed level is at its pre-disturbance level, then the time frame of recovery for the Derby (Briseis) area was ~40 years and at Herrick (Reach 6) it appears to be greater than 50 years (Figure 10.14).

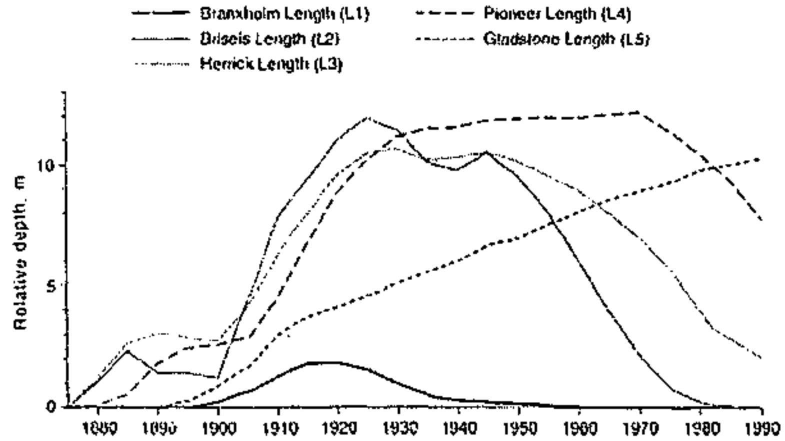


Figure 10.14: Relative sediment depths at the main mining areas as predicted by Knighton (1991).

Knighton (1989) suggested that recovery (of bed levels) will be increasingly sluggish with distance downstream, and it is therefore likely that the recovery of Geomorphic Variability will follow the same pattern. It is also possible that a lag effect will develop between bed level stabilisation and Geomorphic Variability recovery with increasing distance downstream. This will result from an increasing contribution of stored sediments during large flood events with distance downstream.

In saying this, it is expected that the lower reaches of the Ringarooma River (from Bell's Bridge down) will never make a full recovery. This is because this area has already undergone a number of channel changes in the form of avulsions and changes in channel course. It has now formed an important wetland system with Ramsar status (ie. international recognition as an area of ecological significance). This wetland area has been, and is currently undergoing change from both the increase in sediment delivery from the river, as well as from unstable coastal dune structures. The combination of these factors, as well as the significant colonisation of the area by vegetation and the sediment delivery still increasing, will mean that this part of the Ringarooma River will have difficulty returning to it pre-disturbance morphology (or anything similar). Given the new status of the area as a Ramsar wetland, many people (eg. DPIWE) are happy for the wetlands to remain intact. The recovery of the lower reaches cannot be predicted with any certainty and a total evacuation of mine tailings may never occur, particularly if incision produces perched terraces along the side of the river that are out of reach of even major flood events.

Overall, although Knighton's prediction of recovery for the Ringarooma River in the next 37 years is unlikely, the ability of the upstream reaches to recover their Geomorphic Variability at the same time as the bed level has stabilised, suggests that a recovery of Geomorphic Variability for much of the Ringarooma River will be possible within 50-100 years.

Review of the time scales of recovery for Creightons Creek

No estimates of the time scales of recovery have ever been made for Creightons Creek. This is probably due to doubt as to whether the upper incising reaches have stabilised or are still producing sediment (Davis and Finlayson, 2000). Estimating the recovery time scales for Creightons Creek is probably the most difficult of the three streams, due to the combination of incision and sediment production. Although incision is inherently a requirement for the recovery of many sites, the continued incision beyond the 'stable' level may act as a secondary disturbance; this makes estimating recovery time scales difficult. Therefore, unlike the Ringarooma River, it is not possible to use predictions of bed-level recovery to estimate the Recovery of Geomorphic Variability, as these two processes do not occur simultaneously on Creightons Creek. Monitoring of the changes along Creightons Creek should therefore be on-going, and then in the future more accurate predictions may be made.

Review of the time scales of recovery for the Wannon River

The recovery time scales are also difficult to predict on the Wannon River as there has not yet been a significant return of Geomorphic Variability despite the bed levels returning to near pre-disturbance levels. The time scales of recovery on the Wannon River are also dependent on the stream stabilising and not undergoing an incision process such as that occurring on adjacent streams such as Bryans Creek (Rutherfurd and Budahazy, 1996). Assuming that the bed level does stabilise (and does not incise) once the sediment evacuates, the recovery of the Wannon River will be dependent on the time it takes to re-develop appropriate variability eg. pools and riffles. As with Creightons Creek, the recovery process on the Wannon River should be monitored into the future so that the time it takes the stream to fully re-stabilise can be recorded and predicted for reaches further downstream.

Comparison with other recovery time scales

Some studies have been conducted looking at the time scales of recovery for macroinvertebrate and fish response to disturbance (eg. review in Fuchs and Statzner, 1990 and Milner, 1996). From a geomorphic perspective Wolman and Gerson (1978) estimated some of the recovery time scales for landslide events; however, very few studies have been able to put time scales on the geomorphic recovery of river systems.

Many of the estimates that have been made for geomorphic recovery have used the return to mean bed level as the recovery indicator. Some of these estimates include 100 years recovery time for a stream impacted by a sediment slug resulting from a large flood (Erskine, 1996); this estimate is considered to be slightly greater than the return period for the flood event itself. Whereas Lisle (1981) suggested that streams in Oregon that had been affected by flood induced sediment slugs will take at least two decades to recover. Madej and Ozaki (1996) showed that for Redwood Creek California, the recovery rate (specifically defined as the return to pre-disturbance bed level) varies from 8 years (when near to the disturbance source) to 15 years when 5 kilometres further downstream. Madej and Ozaki's (1996) estimates suggest that there will be considerable lag in the recovery of bed level with distance downstream. This supports Knighton's (1991) estimates for a lagged response in bed-level recovery on the Ringarooma River. Overall, there appears to be a great range in the rates and time scales of bed level recovery for streams disturbed by sediment slugs.

Summary of recovery time scale assessments

The variable time scales and rates of recovery observed in previous studies may be because the factors that contribute to the recovery of each stream are catchment specific. The results from this study suggest that it will be difficult to ever develop a generic predictive model of recovery. It may, however, be possible to roughly estimate the time scales of recovery for disturbed streams using factors such as geology, size of the bed sediments, flood frequency and vegetation cover.

This section has also highlighted that there is more scope for research of the 'rates' and 'time-scales' of recovery. There are a number of specific areas that would merit investigation:

- the possibilities for scaling the recovery response according to features or processes such as catchment area, stream width or flood frequency;
- understanding the lag time scales of response between the return of pre-disturbance bed-level and the recovery of Geomorphic Variability;
- determining if there are different recovery time scales for different sized slugs.

Investigation of these areas of recovery would require experiments to be set up over time (possibly many decades); answers could not be obtained using space for time substitution alone.

10.8 General summary of the response of streams disturbed by sediment slugs

10.8.1. Evaluation of the 'wave model' and limitations of the results

One of the main aims of this thesis was to evaluate the classic wave model of sediment slug movement and channel recovery (Chapter 3). This section now summarises the response of each of the streams to that model, and an evaluation is made as to the extrapability of the results of this thesis to other slugged stream systems.

One of the main hypotheses being tested in this study was whether the return of mean bed level equated to the recovery of a variable geomorphic structure capable of sustaining appropriate habitat. It was found that the return of bed levels similar to the pre-slugged condition did not necessarily lead to a recovery of Geomorphic Variability. It was also shown that bed level recovery was not the only indicator of recovery potential on a stream. The pre-disturbance stream condition and source of the sediment also appear to be very important factors. This result is supported by the study by Alexander and Hansen (1986), which is the only documented study that has been able to observe the full spectrum of sediment slug impact (ie. 5 years of pre-impact data, 5 years of impact data and 5 years of post-impact data). Alexander and Hansen's study used different variables to measure recovery, however, they determined that roughly 4 years after they ceased adding sediment to the stream, the bed levels had returned to levels similar to the pre-disturbance condition; however, they noted (through visual observation only) that the variability in channel form had not returned, subsequently neither had the fish populations.

Summary of the response of streams disturbed by sediment slugs

In earlier chapters (2 and 3), I discussed the application of ergodic theory to understanding recovery processes following large scale geomorphic disturbance. The final output from previous research using this approach was the formulation of schematic diagrams that showed that evolutionary (or ergodic) response of streams to incision and channelisation (eg. Hupp and Simon, 1991; Schumm et al., 1984).

The research in this thesis has gone beyond simply using ergodic theory to explain the response of streams disturbed by sediment slugs by incorporating the concepts of scale and variability into the analysis process. Nonetheless, a schematic diagram such as the one presented in Figure 10.15 is useful for summarising the various stages of disturbance and recovery discussed in earlier sections. Figure 10.15 shows the disturbance and recovery process in 5 main stages; the bottom of Figure 10.15 shows the different stages through space, according to the position of the sediment slug.

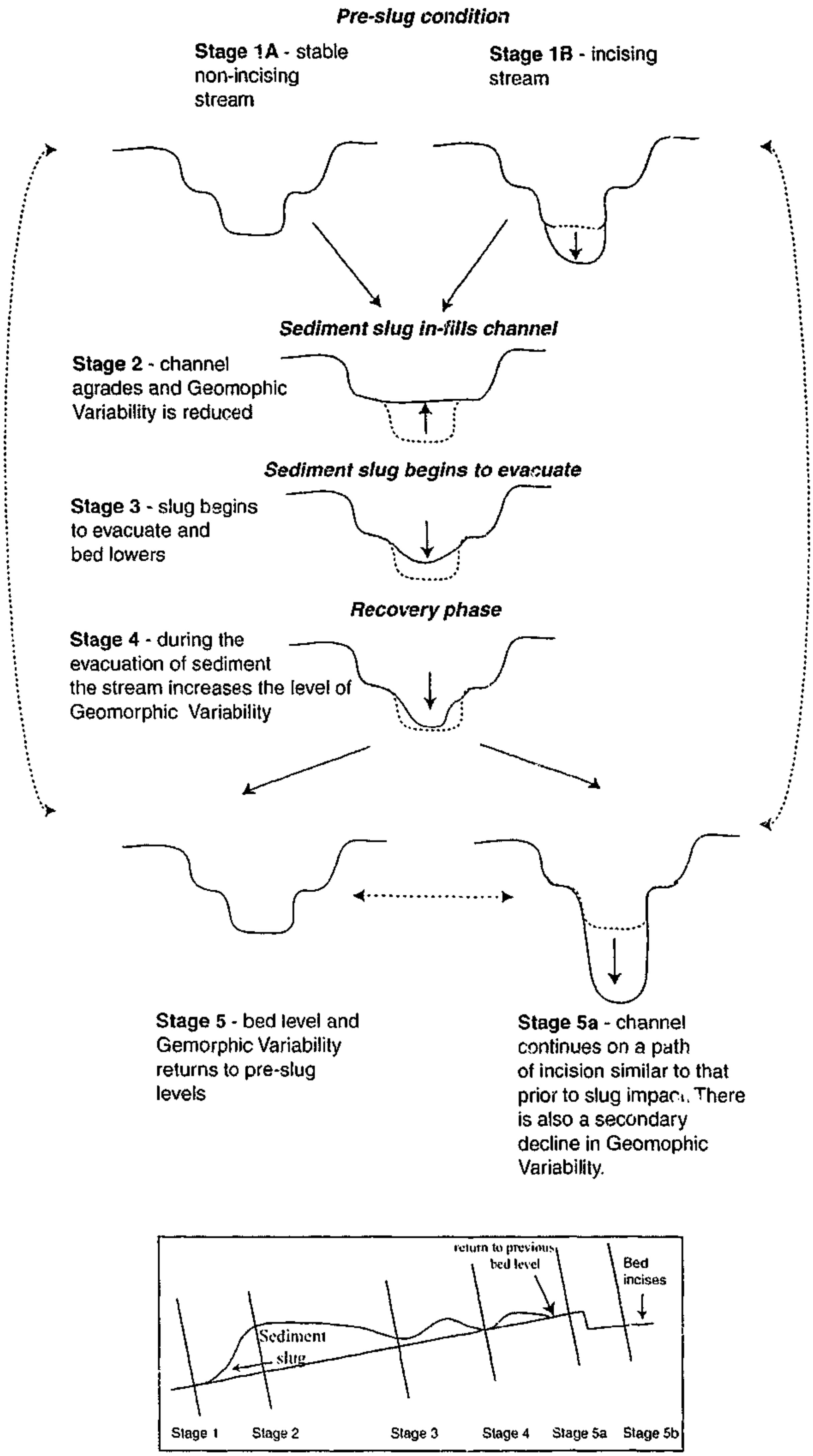


Figure 10.15: Schematic diagram showing the different recovery pathways for the three streams in this study.

Figure 10.15, Stage 1A and 1B represent the pre-disturbance condition. It was important to split this stage into two groups as this study showed that the antecedent or pre-slug condition was an important factor affecting the recovery potential of streams disturbed by sediment slugs. For example, on Creightons Creek, the fact that the stream was incising prior to disturbance has meant that the recovery process is more likely to involve elements of incision. Stage 1A represents a stream that is relatively stabile prior to sediment slug disturbance (eg. Ringarooma River) and Stage 1B is a stream that was incising prior to be in-filled by a sediment slug (eg. Creightons Creek). Stage 2 represents the stream once the sediment slug has aggraded the channel, and Stage 3 represents the sediment slug starting to evacuate the stream. Stage 4, is the first of the recovery phases and the sediment depths are almost at pre-disturbance levels. During this phase the actual level of Geomorphic Variability increases. On Creightons Creek and the Wannon River, this slight increase in variability was usually linked to the start of an incision phase. On the Ringarooma, the increase in variability was a function of the mixing of small amounts of finer sediment with the indigenous gravel bed-level which created high levels of variability.

Following Stage 4, there are two potential recovery pathways; Stage 5 is typical of the response of a stream such as the Ringarooma whereby the bed level restabilises to a level similar to that in Stage 1A, and the channel essentially 'recovers'. Stage 5a is typical of a stream such as Creightons Creek where the stream continues to incise in a similar manner to its pre-disturbance condition. The arrow linking Stage 5 and 5a is there to show that:

- the stable condition represented by Reach 5 may or may not incise in the future; and
- that once a stream in Stage 5a has ceased incising, it may stabilise to a condition similar to Stage 5; although this new stable condition will be different from the pre-disturbance condition

The Wannon River is situated part way between Stage 5 and 5a.

This model helps to conceptualise the range of responses that a stream goes through following sediment slug impact. This model (Figure 10.15) has extended existing research is the following ways:

- ♦ It has shown that Gilbert's (1917) model of sediment slug movement is too simple for many streams that have been disturbed by sediment slugs. The research in thesis has shown that there are multiple recovery pathways for streams impacted by sediment slugs, and streams may switch between the different pathways during the recovery phase;

- Previous research using space for time substitution to evaluate the recovery of streams to disturbance (eg. Hupp and Simon, 1991; Schumm et al., 1984) did not take into account scaling issues such as the position of the study reaches in the catchment. The affect of scale (eg. the size of slug vs channel size) appeared to be an important factor controlling the ability of streams to recover. In addition, the incised stream models only used mean conditions to assess recovery and variability was not evaluated.

The findings in this study also expand on the recent research by Madej (2001). Madej (2001) suggested that following sediment slug impact, 'the degree of regularity and organisation that develops in a channel depends on the time since disturbance (number of organising flows), the size of the sediment pulse, and the presence of forcing elements that can influence channel morphology' (p2269). Most of the examples used in Madej's (2001) study showed that there was an increase in bed variability through time, however, this research was focused specifically on gravel bed rivers. The research in this thesis, incorporated both fine grained alluvial streams as well as gravel bed/bedrock controlled streams. The study showed that the recovery trajectory initially produced an increase in bed variability, however, the long term trajectory suggests that in some streams (typically clay channels) there will be a second disturbance phase in the form of channel incision. It therefore appears that the recovery pathways will be closely related to morphological structure and sedimentary characteristics of the stream.

In light of the inappropriateness of the wave model to explain the geomorphic recovery of all streams disturbed sediment slugs, the next section will present a number of alternative models of channel response.

10.8.2. Alternative models of geomorphic recovery

In light of the results presented in Figure 10.15, it is appropriate to re-assess the Geomorphic Recovery Model presented in Chapter 3. The Geomorphic Recovery Model originally put forward by Gilbert (1917) and revised in Chapter 3, essentially follows the path of Stage 1A to Stage 5 in Figure 10.15 (ie not Stages 1B to 5a), and it does not include Stage 4. This implies that the Geomorphic Recovery Model is only suitable for streams that have been impacted by discrete sediment delivery events in channels that had a relatively stable antecedent conditions. Streams that have been impacted by slugs resulting from endogenous sources, such as many of the incised streams in Australia, appear to respond differently, and an alternative model may be required for these stream types.

Examples of more appropriate models are presented in Figure 10.16. These models assume that impact and recovery process is not symmetrical in either space or time.

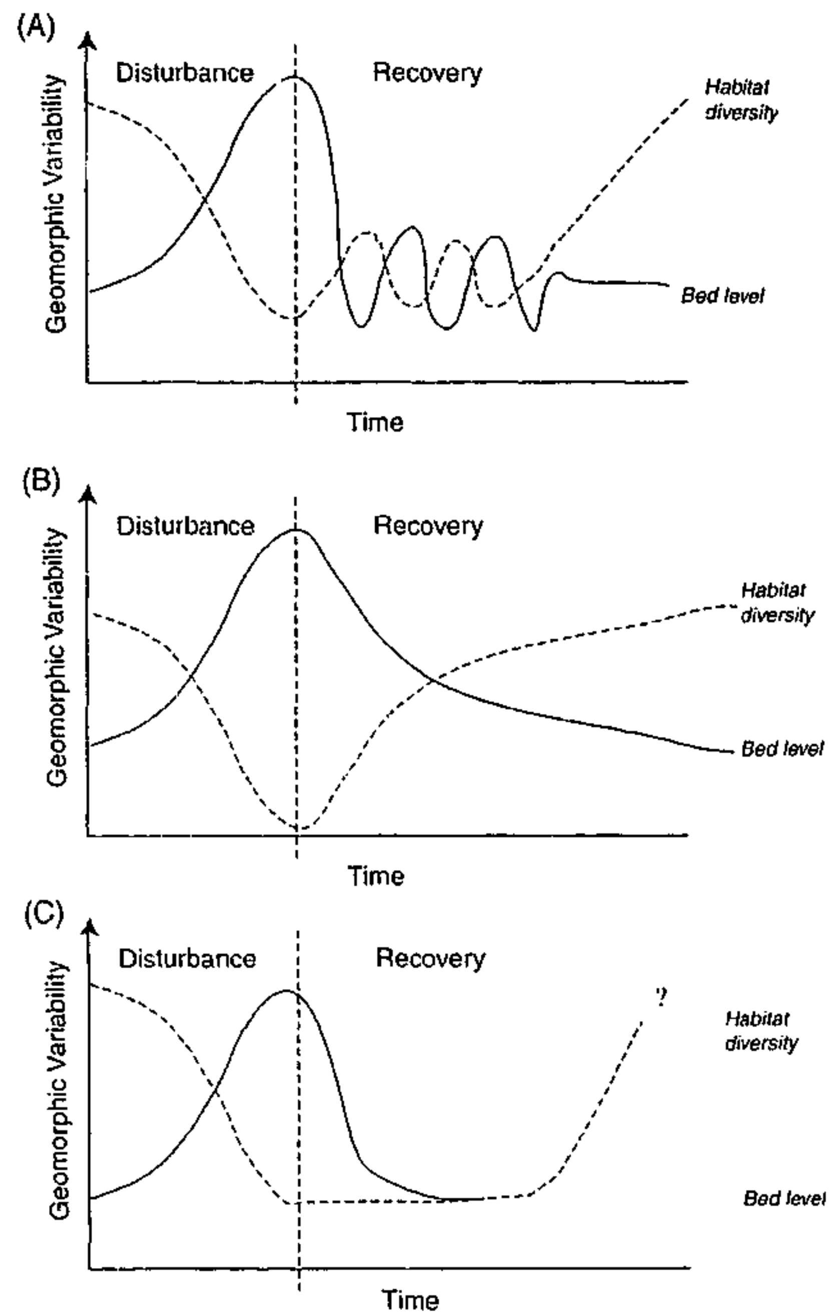


Figure 10.16: Alternative model of sediment slug impact and recovery: the asymmetrical model.

The model in Figure 10.16 (A) suggests that recovery may fluctuate between phases of aggradation and incision many times before re-establishing former bed levels (eg. Creightons Creek or the Wannon River). Alternatively, Figure 10.16 (B) describes a lagged response which incorporates sediment storage which is applicable to both exogenous and endogenous sediment slug impacts. These models are more akin to the research conducted by James (1991; 1999). Figure 10.16 (C) suggests that there is a lagged response between the time that the bed level returns to pre-disturbance levels and the time at which Geomorphic Variability is re-instated. This type of model would have implications for assessing the time frames between the return of mean conditions (eg. bed level) versus habitat (eg. Geomorphic Variability). Further research would be needed to determine if such models would be more appropriate for streams impacted by sediment slugs.

Despite the inappropriateness of the Geomorphic Recovery Model for describing the recovery of *all* streams disturbed by sediment slugs, the research in this thesis has determined a number of indicators that would be considered useful for identifying whether a stream will recover. Streams with the following factors appear to be more likely to recover over shorter time periods:

- streams with gravel bed and/or bedrock morphology;
- sections of stream with high stream powers;
- streams with intact riparian vegetation;
- streams with stable morphology (eg. not undergoing processes such as channel incision).

10.9 Unique findings of study

The literature reviews in Chapters 2 and 3 identified that disturbance and recovery are important issues facing geomorphic systems. The reviews also identified that the current approaches for evaluating the response and recovery of streams to disturbance such as sediment slugs were not appropriate. This thesis provided unique research findings in four main areas:

1. The use of Geomorphic Variability as an indicator of recovery;
2. Understanding the role of scale in geomorphic response;
3. Ergodic theory;
4. The study of recovery in streams disturbed by sediment slugs

The use of Geomorphic Variability as an indicator of recovery

Understanding how the variability, as well as changes in mean conditions are affected in response to disturbance, has been highlighted as an important research need by many authors (eg. Chapman and Underwood, 2000; Palmer and Poff, 1997). This thesis has responded to this need by developing a unique method for evaluating the response of streams disturbed by sediment slugs. The term Geomorphic Variability was developed to describe the geomorphic structure of a stream reach. Associated experimental design, field work and data analysis techniques were also developed so that Geomorphic Variability could be used to evaluate the condition of a stream at different stages of disturbance (and recovery). The use of small scale variability in the physical condition of a stream has presented a new research approach in geomorphic studies, which replaces traditional measures based on mean conditions.

As well as using variability (rather than mean conditions) to evaluate the recovery of streams to disturbance, the research in this thesis measured the response using more than one variable. Often cross-sections have been the dominant variable used to evaluate the response. This study used four main variables (thalweg, cross-sections, sediment size and sediment stability) which were assessed both individually, and combined into an index.

In association with each of these variables a new range of data analysis techniques were presented and evaluated. A discrete range of variables have now been identified for use in further studies attempting to quantify the Geomorphic Variability of streams. The use of multiple variables also enabled the response of the streams to be assessed from a range of scales and dimensions.

The role of scale

Geomorphic research looking at large scale disturbance is predominantly conducted using the single catchment case study approach, and the process-response mechanisms have been directly related to specific catchment conditions. The work on scale conducted in this thesis has provided some more generic solutions to understanding how 'all' streams respond. Such techniques include:

- the empirical approach to predicting pre-disturbance pool depth; and
- scaling sediment depths according to stream size.

This type of research will become increasingly important as control sites become more difficult to find. They also allow reaches that are spatially dissimilar (ie. in different parts of the catchment) to be compared, as the data can be evaluated with respect to its position along the stream. The approaches taken in this thesis present a more holistic approach to understanding how streams respond to change.

Ergodic Theory

Ergodic theory has been extensively used in geomorphic studies for evaluating streams disturbed by channelisation and incision. This is one of the first studies that has rigorously employed the ergodic approach to the study of sediment slugs. The findings (presented in earlier sections of this chapter) suggest that the recovery process in streams impacted by sediment slugs is more complicated than those that are impacted by incision.

The application of ergodic theory in this thesis has also been enhanced through the use of multiple study sites, statistical analysis procedures and the evaluation of scale. Future studies employing the use of ergodic theory should incorporate the following elements:

- the use of reaches instead of single cross-sectional sites. Within the reaches, multiple data samples should be collected so that the variability can be incorporated into the assessment of change;
- control reaches that have not undergone disturbance need to be incorporated into the design and used as benchmarks against which changes in the impact areas can be measured;
- the position of the reach relative to its position in the catchment should be assessed and all data collected should be scaled accordingly. This scaling process provides an estimate of the conditions that would expected at different points along the stream in the absence of disturbance. It will also help determine if the changes occurring on the stream are actually a result of the impact or simply a function of natural variability.

The study of recovery in streams disturbed by sediment slugs

An assessment of the recovery pathways and process for streams that have been disturbed by sediment slugs has never been rigorously evaluated using the space for time approach. This study has successfully applied this method to streams disturbed by sediment slugs, and in the process determined that the space for time approach is a useful tool, however, further research will need to incorporate temporal modelling of sediment movement, including the lag times associated with sediment storage. A combination of both spatial and temporal data would enhance any further investigation of disturbance and recovery in streams disturbed by sediment slugs.

10.10 Discussion

This chapter has presented the final evaluation of each of the streams according to the Geomorphic Recovery Model. The final evaluation was made using an Index of Geomorphic Variability. This Index was then used to evaluate the response of each stream to the different phases and volumes of the sediment slug. Evaluation of the results was then presented in relation to the wave model and ergodic theory, and the major research contributions of this thesis were presented.

The main points from Chapter 10 can be summarised as follows:

- No individual variable was able to rigorously evaluate the overall response of streams to sediment slugs, therefore an Index of Geomorphic Variability was developed. An additive framework was employed. The Index was then used to evaluate the response of each of the streams according the Geomorphic Recovery Model. The index was also used to evaluate the effect of sediment and LWD on the level of variability in each reach.
- Hierarchical cluster analysis was then applied to assess if the Geomorphic Variability Index could be used to differentiate between the different impact groups. It was shown that it could successfully group reaches that have similar sediment depths; those with greater than 20% of their reach volume impacted by sediment were usually grouped together, and those with less than 20% grouped together.
- A final evaluation of the Geomorphic Recovery Model was then made for each of the 3 streams. It was found that:
  - Creightons Creek has not yet made a full recovery mainly due to the incision process in the recovery reaches;
  - The Wannon River appears to be moving into a secondary phase of disturbance due to channel incision;
  - The Ringarooma River appears to have made a full recovery.
- The distinctive features that have resulted in the recovery of the Ringarooma River (rather than Creightons Creek or the Wannon River) include the bedrock/gravel bed nature of the stream, the high stream powers in many of the confined valleys, the relatively stable catchment and vegetated riparian zones and the exogenous rather than endogenous source of sediment;
- It was found that there is a negative power function relationship formed when the sediment depth is plotted against Geomorphic Variability for all of the streams. It was also determined that there is a significant negative correlation between the % of the reach impacted by sediment and the level of Geomorphic Variability.
- There was a negative correlation between the percentage of the stream filled with sediment and the level of Geomorphic Variability in each reach. This result also highlighted that there appears to be a threshold depth that affects variability; that threshold occurs between 20 and 25% of the reach volume. This threshold value was found to correspond to the proportion of the reach that is represented by pools, and when sediment volumes increase beyond 20%, pool features are drowned out;
- There was no significant correlation between the level of Geomorphic Variability and LWD. However, this result is considered to be related more to the variation in sediment supply rather than LWD having no influence on the stream;

- A schematic space for time model of the recovery of streams disturbed by sediment slugs was presented. This model is similar to the incised stream models that employed ergodic theory to describe the recovery process, and is the first model of its kind used to explain the recovery of streams disturbed by sediment slugs;
- The wave model was evaluated for its ability to explain the recovery of streams disturbed by sediment slugs and it was found that it was only effective at explaining the response of some streams. Three alternative models of recovery were proposed in light of the findings in this chapter and it is expected that geomorphic recovery, particularly for incised streams, would be more appropriately explained by an asymmetrical and/or time-lagged wave model.
- A summary of the main research contributions of this thesis were presented and the significant contributions were made in quantifying Geomorphic Variability, understanding the role of scale in geomorphic response and using ergodic theory to evaluate the response of streams disturbed by sediment slugs.

The next chapter presents the final discussion and conclusions for the thesis.

Chapter 11

Conclusions, outcomes and suggestions for further research

11. Chapter 11 - Conclusions, outcomes and suggestions for further research

11.1 Summary of research

A basic question in geomorphology is understanding how streams respond to major changes in water and sediment inputs. The major contribution of this thesis has been an increase in the understanding of how streams respond and recover from increased sediment load (in the form of sediment slugs) at the reach scale. This research has relevance not only to geomorphological theory, but it also provides important outcomes which can be used to help rehabilitate many streams that have been disturbed by sediment slugs. Understanding the processes of recovery in disturbed stream systems has been identified as an important research need in the field of stream rehabilitation (Downs et al., 1999; Fryirs and Brierley, 2000; Fuchs and Statzner, 1990; Gore et al., 1990; Hupp, 1997; Rutherfurd et al., 2000; Simon, 1995). Understanding the pathways of recovery in disturbed streams has the potential to save millions of dollars of stream restoration funding by providing management intervention at the appropriate stage of the natural recovery cycle. The lack of knowledge of the recovery pathways of disturbed streams provided the motivation for this study.

To better understand and quantify the recovery process, an assimilation of the concepts of recovery used by fluvial geomorphologists and aquatic ecologists is needed. The concept of Geomorphic Variability was developed here for this purpose. The main factors that contribute to Geomorphic Variability are thalweg variability, cross-sectional variability, sediment size variation and sediment stability. A rigorous statistically based field work program was developed to enable changes in Geomorphic Variability to be measured in disturbed stream systems.

To observe the change in Geomorphic Variability and, thus, recovery, a specific example of a disturbance was required; the process of recovery on streams impacted by sediment slugs was chosen for this thesis. Processes such as land-clearing, sheep and cattle grazing and mining have increased erosion in stream networks, resulting in an increased delivery of sediment to stream systems. When enough coarse sediment gathers in the stream bed, it forms a sediment slug. These slugs tend to move down stream channels as an attenuating wave, getting longer and lower as they proceed. Thus, many slugs have a relatively well defined back-end, making them suitable for studying the progressive recovery of Geomorphic Variability, using a space for time approach.

Current models used to describe the recovery of streams disturbed by sediment slugs are based on using average conditions. Seeing that species abundance and diversity is one of the main indicators of stream health, and species diversity has been linked to habitat diversity and geomorphological structure, it seems more appropriate to measure recovery using indicators such as Geomorphic Variability.

To this end, a model of Geomorphic Recovery was proposed (Figure 11.1). This model was based on a review of literature which describes a variety of approaches for assessing the recovery of streams that had been disturbed by sediment slugs. Previous research had used the return of average conditions, such as mean bed levels, as a measure of recovery. The model proposed in this thesis used Geomorphic Variability as an indicator of recovery and change: this was considered to be a more eco-compatible approach. Thus, the adapted model proposed in this thesis provided an opportunity to determine if a return to pre-disturbance bed levels occurred simultaneously, or gradually, with the return of a more variable geomorphic structure. Due to long time scales over which sediment slugs move and evolve in streams, space for time substitution (or ergodicy) was the method chosen to evaluate the recovery model.

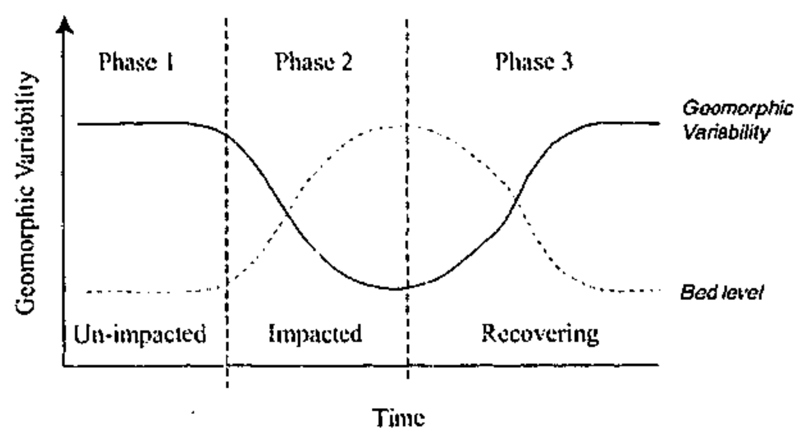


Figure 11.1: Geomorphic Recovery Model tested in this thesis

To test the model of Geomorphic Recovery, a number of field sites were required. Some 20 streams in SE Australia containing sediment slugs were identified; three were chosen mainly because considerable work had been carried out on these streams by other researchers. Each stream also had control sites, and the back-end (or recovering section) of the stream could be identified. The selected streams were Creightons Creek, the Wannon

River (both in Victoria) and the Ringarooma River (Tasmania). Each of the sites had a different sedimentation history, thus providing a range of tests for the Geomorphic Recovery Model.

Following the collection and presentation of data from each of the three study sites, analysis was undertaken to determine if differences in Geomorphic Variability between study reaches were due to the presence of the sediment slug, or the result of natural variation. This was a novel approach in geomorphology, whereby the current or observed condition, was assessed against the expected, or predisturbance condition. This approach was more rigorous than the standard space for time approach. A range of data analysis techniques were then used to quantify each of the Geomorphic Variability measures: thalweg, cross-sections, sediment size and sediment variability.

The results of these analyses were assessed for each of the individual factors, then integrated into a Geomorphic Variability Index. This index provided an 'overall' estimate of Geomorphic Variability which was then used to evaluate the Geomorphic Recovery Model on each stream. The major findings resulting from this study are outlined below.

11.2 Thesis findings

Evaluation of general thesis aims

Chapter 1 presented a number of thesis aims. These findings in relation to each aim are outlined below.

1. *To review the role of morphology in stream health and habitat studies and thus identify appropriate factors for quantifying the Geomorphic Variability of a stream reach.*

Review of the geomorphic and ecological literature determined that variability of the thalweg, cross-sections, sediment size, and sediment stability were important factors affecting both the geomorphic and habitat conditions in a stream (at the reach scale).

2. *To evaluate existing models of Geomorphic Recovery (for streams impacted by sediment slugs) and adapt them to provide a more 'eco-compatible' approach.*

Gilbert's (1917) wave model of sediment movement and recovery formed the basis of the Geomorphic Recovery Model tested in this thesis. Gilbert's model used mean conditions as a measure of recovery; this was found inappropriate due to large spatial scale used, and the difficulty of linking such a model to smaller scale habitat studies. Geomorphic Variability was considered a more appropriate indicator of recovery, and provided a more eco-compatible approach for measuring recovery in streams disturbed by sediment slugs.

3. *To identify a range of suitable techniques for quantifying the variability of geomorphic field data, and thus habitat.*

A number of new approaches (as well as the application of existing approaches) made it possible to differentiate between changes that were a function of the presence of the sediment slug, and those that were a result of natural variation. The most important of these techniques were:

- an empirical technique to estimate pre-disturbance pool depth;
- the use of the Co-efficient of Variation (CoV) (a dimensionless value), to estimate channel change between control and impacted cross-sections;

A range of novel data analysis techniques was evaluated, and the most appropriate technique for analysing each of the variables that make up Geomorphic Variability selected. The research showed that:

- the standard deviation (SD) of depths method was the most appropriate for quantifying thalweg variability; although in future studies the wiggliness factor (w) and fractal dimensions (D) methods would also be suitable;
- the sum of squared height deviations (Σdh^2) method was the most appropriate for quantifying cross-sectional variability;
- sorting was found to be the most appropriate method for quantifying sediment size variability;
- an adaptation of Shields shear stress equation was suitable to estimate the percentage time the median grain size is entrained during the flow duration curve. This method was used to estimate sediment stability.

<u>Evaluation of Thesis Hypotheses</u>

In addition to the general thesis aims above, a number of more specific hypotheses were presented in Section 3.7.1; these were designed to evaluate the Geomorphic Recovery Model. Each of the hypotheses are restated below, and a detailed description of how the research presented in this thesis addressed each of the hypotheses is presented.

(i) *Ergodic theory is a suitable approach for evaluating the recovery of streams disturbed by sediment slugs.*

In this thesis I identified a fundamental weakness in past applications of ergodic approaches in geomorphology, that is, ergodic approaches can only be applied if an estimate can be made of the natural variation that would have existed in the absence of the disturbance. In this thesis, I employed an 'observed versus expected' approach to estimate the predisturbance condition of each of the variables (Chapter 7). Thus, future studies that use ergodic theory need to address the issues of scale, as well as have an estimate of the pre-disturbance condition. Scale relationships needs to be assessed when collecting field data (in terms of the location of study reaches and scaling the data from each reach accordingly), as well as in the assessment of the size of the sediment slug (and its relationship with the size of the channel).

This study is also the first to use variability (rather than a change in mean conditions) as a measure of recovery using a space for time approach. The use of variability means that the results are compatible with both geomorphic and habitat scale studies. To summarise the response of streams disturbed by sediment slugs using the ergodic approach, a schematic diagram of the various stages of sediment slug impact and recovery was developed (Figure 10.15). This diagram presents the results in a similar fashion to previous researchers looking at the recovery of incised streams following disturbance (eg. Hupp and Simon, 1991; Schumm et al., 1984);

(ii) *That the return of the pre-disturbance bed level following impact by a sediment slug is a good measure of the return of Geomorphic Variability to a stream.*

It was found that the return of a stream to its pre-slugged bed levels does not necessarily mean that there is an associated recovery of Geomorphic Variability. The Ringarooma River was the only stream that showed a recovery of Geomorphic Variability at the time of bed-level re-establishment. Creightons Creek and the Wannon River have not yet recovered, due to channel incision. It was identified, however, that there appeared to be an initial increase in Geomorphic Variability once the sediment slug evacuates the stream; this occurred on all study streams (and was incorporated into the model presented in Figure 10.15). The subsequent decline in Geomorphic Variability that occurred on the other streams (mainly the Wannon River) was a result of the channel incision occurring in the areas where the slug has evacuated the system. Hence, these results suggest that the recovery process is threshold based (eg. Brunsden and Thornes, 1979; Schumm, 1973). In addition, the rate and timing of the recovery process will be highly dependent on local conditions such as other disturbances operating within the stream.

(iii) *That the Geomorphic Recovery Model proposed in this thesis accurately predicts the response of streams disturbed by sediment slugs.*

I determined that the Geomorphic Recovery Model was applicable for certain stream types, but it did not accurately predict the recovery process for all streams, particularly those disturbed by endoslugs. For all of the study sites, it is likely that the recovery of streams disturbed by sediment slugs would be more appropriately explained using an asymmetrical or lagged wave model (such as that presented in James, 1989). The distinctive features that have resulted in the recovery of the Ringarooma River, rather than Creightons Creek or the Wannon River, include the bedrock/gravel bed morphology of the stream, the high stream powers in many of the confined valleys, well vegetated riparian zones and the exogenous rather than endogenous source of sediment.

General thesis findings - predictive tools for further research:

In addition to findings presented above, there were a number of other general findings, as listed below:

- Geomorphic Variability decreases with increasing sediment depth according to a power function relationship;
- once the percentage of a reach filled with sediment increased beyond 20%, there is a significant negative decline in Geomorphic Variability. The 20% value has both a statistical and physical basis; it was found that pools represent less than 20% of the reach volume, therefore sediment volumes greater than 20% tend to drown out and smother pools and all associated variability;
- the Geomorphic Variability Index, based on the characteristics of the thalweg, cross-sections, sediment size and sediment stability, provided a more holistic look at how streams change in response to sediment slug impact. The Index could be used in future studies that want to estimate the level of Geomorphic Variability or diversity in a stream reach;
- the Index of Geomorphic Variability is able to group the different reaches according to their sediment volumes. The Geomorphic Variability Index can therefore be used to distinguish between areas with different levels of variability (and sediment depth) in future studies.

11.3 Research Appraisal

The research presented in thesis used a number of new and novel approaches to evaluating the response of streams impacted by sediment slugs. *In this thesis I have made five new contributions to the science of geomorphology.* The research in this thesis built on the methods and findings of previous geomorphological research, and the new contributions are outlined below:

- this study used an eco-geomorphic approach to evaluate the recovery of streams disturbed by sediment slugs at a scale that is relevant to both ecology and geomorphology;
- this study developed a rigorous statistically based framework for data collection and analysis so that more quantitative results could be used to describe the recovery of streams;
- this study incorporated data analysis techniques from a variety of scientific disciplines (including marine ecology and econometrics) to quantify the variability of geomorphic data. These techniques would be applicable to future studies wanting to quantify geomorphic diversity at the reach scale;
- this study incorporated the issues of scale (eg. catchment area and slug size) in the process of evaluating the response of streams to sediment slug impact. This involved the development of a number of original scaling techniques, which in some cases, allowed the data to be evaluated against the pre-disturbance condition. These techniques also allow reaches from different parts of the catchment to be compared (eg. scaling channel size against sediment volume). Such techniques could be used in future studies to evaluate the disturbance of different reaches, and rivers, within and between catchments. This will provide an estimate of the relative levels of disturbance and allow prioritisation of funding and rehabilitation;
- this study successfully employed ergodic theorem (in combination with scaling and statistical techniques) to evaluate the recovery of streams disturbed by sediment slugs.

11.4 Implications for the management of disturbed streams

In future studies looking at quantifying the Geomorphic Variability of streams, it wouldn't be necessary for researchers or managers to go through all of the analysis procedures conducted in this study. The following points summarise the procedure for future studies looking at how Geomorphic Variability changes in response to disturbance:

(1) locate control, impacted, and recovering sections along the stream (control sections may need to located on another stream if suitable sites cannot be found on the impacted stream);

(2) select representative reaches within the three sections;

(3) measure the four variables that represent Geomorphic Variability (thalweg, cross-sections, sediment size and sediment stability);

(4) use the scaling procedures (Chapter 7) to determine if the impact (ie. sediment slug) has actually altered the mean conditions in the stream or if the differences are simply a function of natural variability. If there are significant differences then move onto (5);
(5) calculate the variability of each of the factors using the four techniques identified in Chapter 10 (ie. SD of depths, Σdh^2, sorting and percentage time the sediment is stable, respectively);
(6) combine the data into the form of the Geomorphic Variability Index and determine the overall level of variability for each reach;
(7) identify which reaches have recovered, or will recover on their own, and determine which reaches will be suitable for rehabilitation.

Once the level of Geomorphic Variability has been calculated for the streams of interest, there are a number of ways in which it could be used in stream management. For example, it will now be easier to determine which stream types are more likely to recover from disturbance by sediment slugs. As discussed in Chapter 1, disturbed streams can be broken into one of three groups:
(1) streams that will recover independently of human intervention (ie. heal themselves);
(2) streams that will require some human intervention to accelerate the recovery; and
(3) streams that are not likely to recover (within human life spans).
This thesis has identified that the Ringarooma River is a category (1) stream, whereas, Creightons Creek and the Wannon River are more likely to be category (2) streams. Thus, the results and methods developed in this thesis will help prioritise streams for rehabilitation, resulting in more efficient and effective allocation of funding.

There is also the potential to use these results to revise the current guidelines for sand and gravel extraction (eg. DWR, 1992), particularly in streams that have been impacted by sediment slugs. Such revisions may suggest that sediment depths of non-indigenous material should be kept to less than 20% of the reach volume so that suitable habitat is maintained.

The results of this research could also be used to update texts such as the Stream Rehabilitation Manual for Australian Streams (Rutherfurd et al., 2000) and Stream Analysis and Fish Habitat Design (Newbury and Gaboury, 1993) to incorporate a more rigorous statistical approach and provide some new methods for quantifying physical instream habitat.

On a more local scale, current research being conducted by ecological agencies within Australia could now use the results of this research. For example, the Cooperative Research Centre for Freshwater Ecology is currently undertaking a macroinvertebrate and fish surveys along Creightons Creek. The results of this work will provide them with information on the level of physical habitat diversity found at different locations along the creek. This may help explain some of their ecological data (eg. high vs low macroinvertebrate abundances).

11.5 Suggestions for further research

During the course of this investigation, a number of further areas of research were identified. These are outlined as follows:

- Future studies looking at the recovery of Geomorphic Variability would be enhanced by incorporating biological data. Despite the wealth of evidence suggesting that habitat diversity leads to species diversity, there have been very few ecological studies carried out in conjunction with a geomorphological study at this scale. It is necessary to rigorously assess if there is a correlation between physical diversity and species diversity for the specific variables used in this study, particularly in the context of Australian streams. This will allow the variables used in this thesis to be applied with more confidence in future studies;
- Further research is required to develop empirical relationships that can be used to predict channel change at the reach scale. For example, the empirical relationship between mean pool depth and catchment area developed in this study requires further work. This would involve collecting more data on a wider variety of stream types. Empirical relationships will become increasingly important as a predictor of 'appropriate' stream condition for rehabilitation projects particularly in areas where there are no control sites remaining;
- There is definite scope for the Geomorphic Recovery Model and the methods employed in this thesis to be applied to other disturbances (eg. downstream of dams) to assess the potential for recovery. Assessing the Geomorphic Recovery Model using Geomorphic Variability will determine whether the model is applicable to other geomorphic disturbances, or if it is suitable only for streams disturbed by sediment slugs;
- Research is also required to look at appropriate tools for accelerating or prompting recovery within streams disturbed by sediment slugs. Such activities should involve experimenting with increasing structural diversity within disturbed reaches using

features such as logs and/or rocks. Field based experiments also need to be conducted to develop appropriate methods for stabilising sediment stores within the stream;

- There is also the need to set up a number of long term monitoring projects (such as those conducted on Redwood Creek, California, eg. Madej and Ozaki, 1996; Nolan *et al.*, 1995 and the 15 year study by Alexander, 1986), to look at changes in recovery over time and not just space. The long term monitoring projects are also required on streams that have been impacted by sediment slugs to obtain more appropriate data on sediment slug movement and bedload transport.

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Appendix A - Developing a Flood Frequency Curve

The technique used to develop the flood frequency curves presented in Chapter 4 were based on the methods described in Newbury and Gaboury (1993) and Rutherfurd et al., (2000), which are abbreviated versions typically derived from texts such as Pilgrim (1987).

The technique used to develop the flood frequency curves required that the gauge record be at least 10 years old. From the record, an annual series plot can be developed which requires the annual maximum flood for each record year to be identified. The annual maximum flood is taken here as the mean daily flow in megalitres (ML). The following steps outline the development of a flood frequency curve.

Step 1:

The annual flood series is ranked in descending order from the largest flood first, to the smallest flood on record, last.

Step 2:

The plotting position (PP) is then calculated from the annual flood series using Equation 1.

$$PP(m) = \frac{m \pm \alpha}{N + 1 - 2\alpha} \times 100 \qquad \text{Equation 1}$$

Where m is rank of the flood in the series (the largest flood has a rank of 1), N is the number of years of the record, α is constant (adopted as 0.4 after McMahon and Srikanthan, 1981). Substituting in these values, the plotting position for each flood is thus given by Equation 2.

$$PP(m) = \frac{m - 0.4}{N + 0.2} \times 100 \qquad \text{Equation 2}$$

Step 3:

A flood frequency curve is then developed by plotting the PP(m) for each flood (x-axis) against the discharge (ML/day) (y-axis), using a log-normal graph.

Step 4:

To use the flood frequency plot, a curve is usually fit to the data points by eye (or using a Log Pearson type 3 distribution) so that % probability values can be read off the graph. In this thesis, the data points were interpolated within Excel™ and the discharge values for the 50%, 67% and 90% recurrence interval were calculated. It was the 50% recurrence interval or 1 in 2 year event was that of the most interest in this study.

The resulting flood frequency curves for Creightons Creek, the Wannon River and the Ringarooma River were presented in Chapter 4

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Appendix B - Example calculation of the application of Manning's Equation for calculating bankfull on Creightons Creek

This appendix presents an example of the numerical calculations used to calculate the bankfull stage on the upstream reaches of Creightons Creek. The data from Reach 9 will be used to describe the process. The process can be broken into 4 steps, which are summarised below:

Step 1: Use the method described in Grayson *et al.* (1996) (and presented in Section 5.5.5.1) for extending flow records to ungauged catchments to calculate the bankfull discharge (Q_2) at Reach 9;

Step 2: Select a uniform, representative cross-section from the reach and develop a graph of $AR^{2/3}$ against depth ($\bar{y}$). Calculate a relationship between these two variables (power function);

Step 3: Calculate the value of $AR^{2/3}$ for the cross-section using Manning's equation using the known Q_2;

Step 4: Substitute the calculated value of $AR^{2/3}$ back into the equation derived in Step 2 to calculate the bankfull stage (or depth).

The numerical calculations involved in each of the 4 steps are outlined in more detail below.

Step 1:

This method was described in sufficient detail in Section 5.5.5.1.

Step 2:

The data presented in Table 1 is used to construct a relationship between hydraulic depth ($\bar{y}$) and $AR^{2/3}$, where A is cross-sectional area and R is hydraulic radius.

Table 1: Values used to construct a curve of $AR^{2/3}$ against depth for Reach 9 on Creightons Creek

STAGE (m)	AREA (m)	R	AR^0.67
0.10	0.26	0.06	0.04
0.20	0.76	0.14	0.20
0.30	1.32	0.22	0.48
0.40	1.94	0.29	0.85
0.50	2.62	0.35	1.30
0.60	3.37	0.42	1.88
0.70	4.16	0.50	2.61
0.80	4.97	0.57	3.41
0.90	5.81	0.64	4.31
1.00	6.69	0.71	5.32
1.10	7.61	0.77	6.39
1.20	8.56	0.83	7.56
1.30	9.55	0.88	8.77
1.40	10.60	0.93	10.10
1.50	11.70	0.98	11.54
1.60	12.84	1.03	13.10
1.70	14.02	1.08	14.76
1.80	15.25	1.13	16.55
1.90	16.53	1.18	18.47
2.00	17.86	1.22	20.41
2.10	19.25	1.26	22.47
2.20	20.74	1.23	23.83
2.30	22.33	1.31	26.76
2.40	23.93	1.39	29.84
2.50	25.55	1.46	32.92
2.60	27.19	1.53	36.15
2.70	28.87	1.59	39.39
2.80	30.60	1.62	42.28
2.90	32.43	1.61	44.62

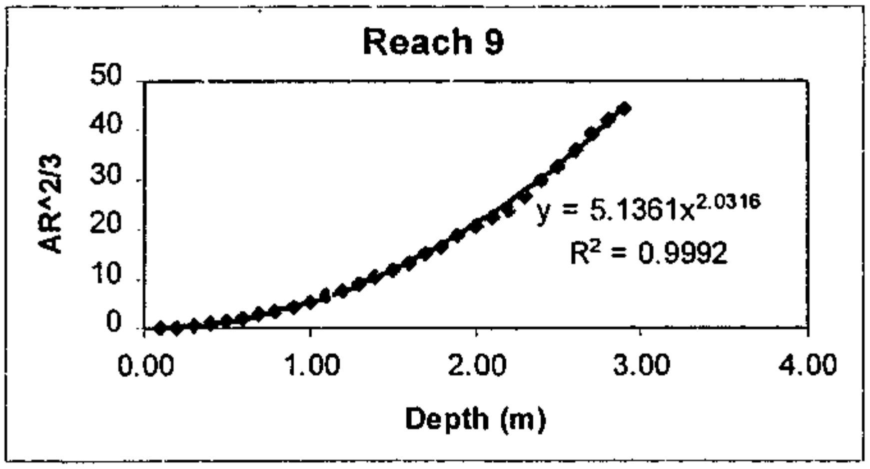

Figure 1: Graph formed from the data in Table 1 for Reach 9

The relationship formed from the data in Table 1 and Figure 1 can be expressed using Equation 1.

$$\text{Depth}\ (\bar{y}) = 5.14 * (AR^{2/3})^{2.0316} \qquad \text{Equation 1}$$

<u>Step 3:</u>

The following values were calculated for Reach 9 from field data and are used in subsequent calculations:

Q_2 (bankfull discharge)	= 10.02 m^3/s
V (mean velocity)	= 0.523 m/s
A (cross-sectional area)	= 0.785 m^2
WP (wetted perimeter)	= 5.036 m
R (hydraulic radius, A/WP)	= 0.156 m

Manipulations of Manning's equation (Equation 2) can be used to determine the value of $s^{1/2}/n$.

$$v = \frac{s^{1/2}}{n} R^{2/3} \quad \Rightarrow \quad \frac{s^{1/2}}{n} = \frac{v}{R^{2/3}} \qquad \text{Equation 2}$$

where v is the average velocity at each cross-section, s is slope, and n is Manning's n. Then substituting the value of $v/R^{2/3}$ for $s^{1/2}/n$ into Mannings equation as shown in Equation 3, it is possible to obtain a value of $AR^{2/3}$ (where R = area/wetted perimeter).

$$Q_2 = \left(\frac{s^{1/2}}{n}\right) AR^{2/3} \Rightarrow Q_2 = \left(\frac{v}{R^{2/3}}\right) AR^{2/3}$$ Equation 3

$10.02 = (0.523/0.156^{0.67}) * AR^{2/3}$

$AR^{2/3} = 5.51$

Step 4:

Then substituting the value of $AR^{2/3}$ into the equation derived in Step 2, it is possible to calculate a depth value for the bankfull stage. In this case the stage that corresponds to the bankfull discharge (Q_2) for Reach 9 is 1.04 m.

Appendix C - sediment size analysis

Particle size analysis of sand and clay fractions

To determine the particle size distribution and calculate the D_{50} within each reach, the sediment samples underwent sizing analysis. The analysis procedure used was based on procedures outlined in Australian Standard 1289 (SAA AS 1289, 1991). In each case, the sediment samples were all less than 1000g and the samples that contained significant clay were between 300-500g (Briggs, 1977).

Procedure:

1) All samples were oven dried at 105^0C to obtain a constant mass. Organic matter was removed by hand prior to drying where possible.
2) Where the samples were predominantly sand (95% by eye) the dried samples were weighed and set aside for sieving. Where the samples contained a considerable clay content, further treatment was required.
3) The clay dominated samples were weighed, then covered with dispersing solution (sodium hexametaphosphate $(Na(PO_3)_n.Na_2O)$.
4) The clay samples were then wet sieved using a 63 μm sieve. The remaining coarse fraction was then placed in the oven at 105^0C and dried.
5) The sand samples and coarse fraction of the clay samples were then dried sieved using a mechanical shaker. The sieve sizes used were: 8 mm (-3ϕ); 4 mm (-2ϕ); 2mm (-1ϕ); 1 mm (0ϕ); 500 μm (1ϕ); 250 μm (2ϕ); 125 μm (3ϕ); 63 μm (4ϕ). Each sample was shaken for 10 minutes.
6) The data were collated and used to calculate the percentage passing the 63 μm sieve (i.e. the percentage of clay and silt), as well the particle size distribution of the coarse fraction (> 63 μm).

References:

Briggs, D., 1977. Sediments (sources and methods in geography). Butterworths & Co., London.

Appendix D - Flow duration curves for each site

Flow duration curves display the relationship between the streamflow and the percentage of time it is exceeded (Gordon et al., 1992). For this thesis, flow duration curves were constructed by ranking all of the mean daily flow values from each st... am gauge profile in ascending order. The ranked data were then divided into 26 class intervals. The total number of occurrences greater than the given class value is then computed, and the points plotted to create a cumulative frequency curve. The flow duration curves for Creightons Creek, the Wannon River and the Ringarooma River are given in Figure 1, Figure 2 and Figure 3, respectively.

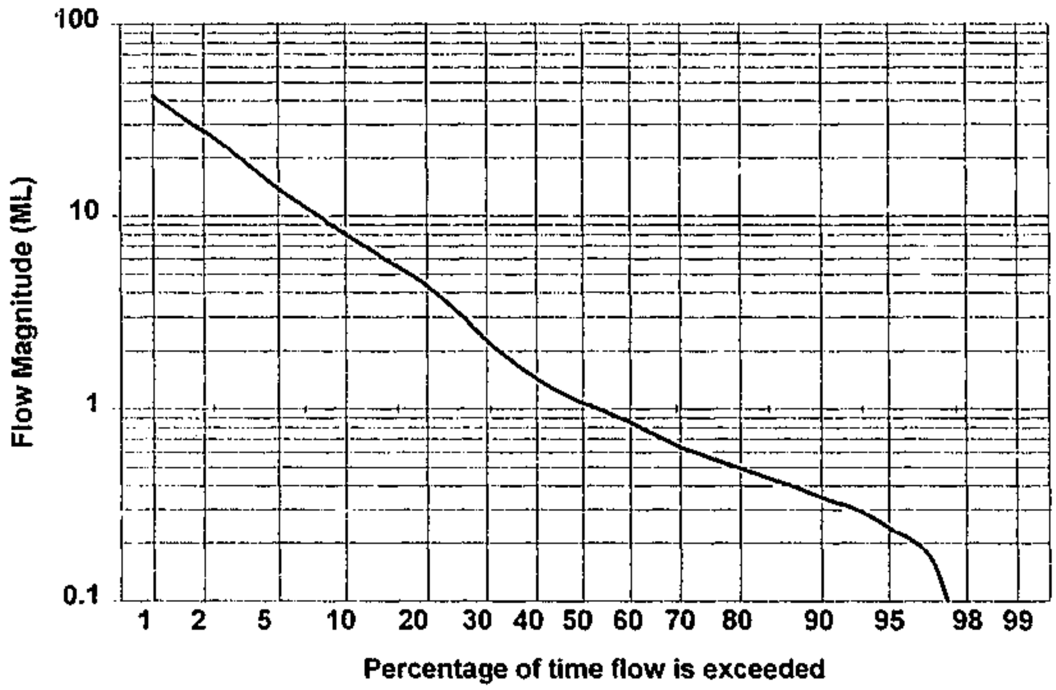

Figure 1: Flow duration curve for Creightons Creek

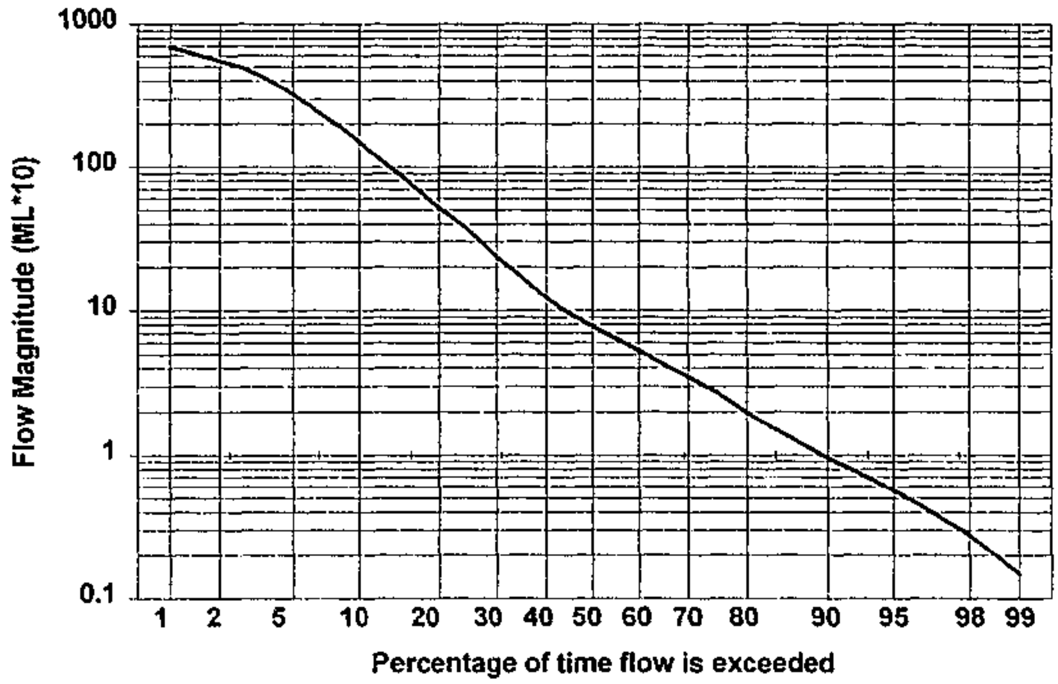

Figure 2: Flow duration curve for the Wannon River

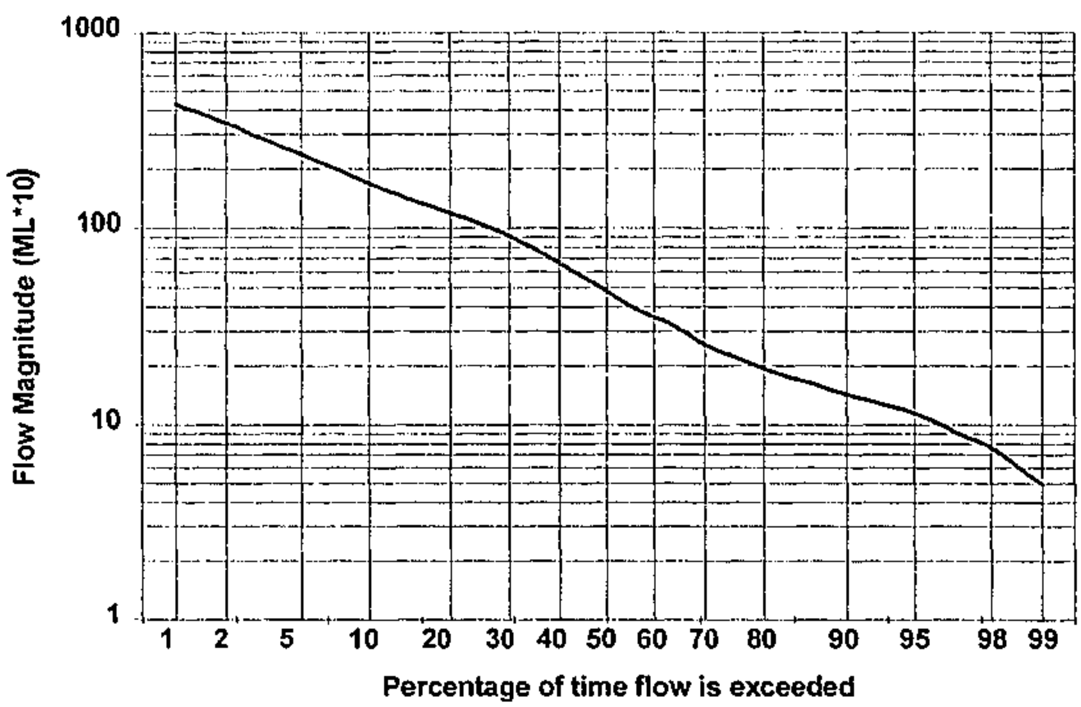

Figure 3: Flow duration curve for the Ringarooma River

<u>References:</u>

Gordon, N.D., McMahon, T.A. and Finlayson, B.L., 1992. Stream Hydrology (An Introduction for Ecologists). John Wiley and Sons, England.

Appendix E - Cross-sectional data for Creightons Creek

Reach 1	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	13.20	2.40	20.76	15.50	1.34	5.50
	2	16.00	2.25	16.35	16.84	0.97	7.13
	3	17.00	2.18	24.54	17.78	1.46	7.82
	4	17.90	2.29	22.04	17.12	1.24	7.82
	5	14.90	2.76	28.56	16.45	1.67	5.40
	6	9.50	1.65	9.35	10.62	0.57	5.76
	7	9.90	2.34	15.47	11.70	1.46	4.24
	8	8.70	1.99	11.56	9.86	0.99	4.38
	9	14.00	2.09	18.46	16.41	1.87	6.70
	10	12.00	1.07	8.95	12.84	0.55	11.21
Reach average		13.31	2.10	17.60	14.51	1.21	6.60
Standard deviation		3.23	0.46	6.53	2.96	0.44	2.07
Co-efficient of variation		0.24	0.22	0.37	0.20	0.36	0.31

Reach 2	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	14.00	1.71	14.68	14.95	0.98	8.21
	2	13.50	2.58	22.44	14.55	1.54	5.23
	3	11.20	2.46	13.12	10.87	0.90	4.55
	4	10.50	2.50	15.76	12.19	1.45	4.20
	5	9.50	1.45	5.97	10.40	0.49	6.57
	6	9.00	1.59	8.60	10.77	0.83	5.66
	7	9.90	1.79	11.34	10.51	1.05	5.55
	8	9.50	2.53	16.15	12.17	1.54	3.75
	9	10.30	2.45	13.41	11.05	1.10	4.21
	10	11.00	2.50	17.33	12.92	1.57	4.40
Reach average		10.84	2.15	13.88	12.04	1.15	5.23
Standard deviation		1.68	0.46	4.62	1.65	0.37	1.35
Co-efficient of variation		0.16	0.21	0.33	0.14	0.32	0.26

Reach 3	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	12.00	2.13	19.93	13.31	1.50	5.63
	2	10.50	2.09	15.75	11.80	1.33	5.04
	3	11.00	1.59	11.31	12.53	0.96	6.92
	4	12.70	2.58	22.69	14.22	1.81	4.93
	5	9.00	2.06	12.53	10.45	0.88	4.38
	6	8.50	2.01	12.79	10.29	1.22	4.23
	7	10.30	2.22	18.93	12.02	1.84	4.64
	8	10.00	2.62	18.21	11.99	1.51	3.82
	9	10.00	2.58	18.31	12.00	1.53	3.88
	10	9.00	1.63	9.98	10.30	0.83	5.54
Reach average		10.30	2.15	16.04	11.89	1.34	4.90
Standard deviation		1.33	0.37	4.21	1.29	0.36	0.94
Co-efficient of variation		0.13	0.17	0.26	0.11	0.27	0.19

Reach 4	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	9.00	1.89	11.12	10.11	1.10	4.77
	2	9.50	2.21	14.02	11.19	1.25	4.30
	3	10.50	2.07	15.37	12.31	1.37	5.07
	4	10.50	1.95	14.49	11.85	1.18	5.40
	5	7.70	1.36	6.95	8.31	0.59	5.68
	6	9.50	1.67	10.80	10.27	1.30	5.71
	7	9.00	1.99	12.17	10.35	1.19	4.52
	8	10.70	1.57	10.24	11.22	0.99	6.84
	9	10.00	1.72	12.05	11.44	1.07	5.81
	10	8.00	2.09	10.84	9.15	0.95	3.83
Reach average		9.44	1.85	11.81	10.62	1.10	5.19
Standard deviation		1.04	0.27	2.44	1.23	0.22	0.88
Co-efficient of variation		0.11	0.14	0.21	0.12	0.20	0.17

Reach 5	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	10.30	1.26	5.86	9.37	0.63	8.17
	2	12.10	0.90	5.03	9.58	0.53	13.44
	3	14.50	1.47	11.52	15.28	1.20	9.86
	4	16.50	1.44	7.99	17.29	0.52	11.46
	5	12.00	1.38	12.86	13.23	0.74	8.70
	6	8.60	1.15	4.93	9.29	0.37	7.48
	7	11.50	1.23	9.50	12.42	1.02	9.35
	8	10.50	1.11	7.42	10.90	0.60	9.50
	9	9.40	1.02	10.74	9.93	0.99	9.22
	10	9.10	1.10	6.54	9.02	0.66	8.27
Reach average		11.45	1.21	8.24	11.63	0.73	9.55
Standard deviation		2.49	0.19	2.80	2.86	0.26	1.75
Co-efficient of variation		0.22	0.15	0.34	0.25	0.36	0.18

Reach 6	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	13.04	1.45	8.52	13.78	0.62	8.99
	2	13.09	1.05	10.85	13.21	0.82	12.53
	3	12.60	1.06	10.45	13.13	0.79	11.89
	4	11.85	1.72	9.63	12.28	0.73	6.91
	5	12.00	1.06	12.79	13.31	1.04	11.30
	6	14.40	1.35	11.67	15.16	0.88	10.67
	7	14.80	1.52	16.31	15.47	1.08	9.74
	8	10.46	1.25	10.83	11.12	0.70	8.40
	9	10.73	1.28	10.60	11.57	0.95	8.38
	10	10.00	1.32	6.52	7.48	0.56	7.58
Reach average		12.30	1.30	10.82	12.65	0.82	9.64
Standard deviation		1.61	0.22	2.58	2.28	0.17	1.90
Co-efficient of variation		0.13	0.17	0.24	0.18	0.21	0.20

Reach 7	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	9.60	0.95	6.04	9.44	0.64	10.16
	2	10.30	1.01	9.05	11.12	0.81	10.25
	3	10.00	1.08	9.26	10.81	0.83	9.26
	4	9.82	0.81	6.19	10.36	0.57	12.12
	5	9.50	0.98	7.62	9.98	0.74	9.74
	6	11.00	0.96	8.23	10.92	0.82	11.46
	7	9.57	1.22	7.77	9.97	0.71	7.84
	8	9.35	1.10	7.26	9.80	0.73	8.50
	9	11.80	1.09	6.90	9.01	0.70	10.88
	10	15.75	1.16	7.68	9.51	0.85	13.64
Reach average		10.67	1.03	7.60	10.09	0.74	10.38
Standard deviation		1.94	0.12	1.07	0.70	0.09	1.72
Co-efficient of variation		0.18	0.11	0.14	0.07	0.12	0.17

Reach 8	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio	Mean velocity (11/10/00), m^3/s
	1	16.00	1.19	12.05	16.44	0.73	13.50	
	2	12.50	1.27	9.99	13.[illegible]6	0.76	9.84	
	3	12.00	1.39	12.03	12.85	0.91	8.63	
	4	12.50	1.55	12.63	14.80	0.98	8.06	
	5	9.50	1.30	8.99	10.10	0.61	7.31	
	6	11.00	1.04	8.37	11.59	0.83	10.63	
	7	16.00	1.34	14.18	17.19	1.22	11.94	
	8	22.50	1.30	17.64	23.02	1.03	17.31	
	9	17.50	1.27	11.38	18.03	0.49	13.78	
	10	11.15	1.28	10.44	12.09	0.58	8.71	
Reach average		14.07	1.29	11.77	14.93	0.81	10.97	0.45
Standard deviation		3.92	0.13	2.70	3.84	0.23	3.15	
Co-efficient of variation		0.28	0.10	0.23	0.26	0.28	0.29	

Reach 9	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio	Mean velocity (11/10/00), m^3/s
	1	11.00	1.04	6.19	11.45	0.54	10.58	
	2	11.00	0.98	6.96	11.34	0.61	11.22	
	3	9.00	0.97	4.99	9.63	0.44	9.28	
	4	9.00	1.08	5.59	9.33	0.58	8.37	
	5	13.50	1.06	7.75	13.97	0.83	12.80	
	6	13.00	0.95	7.06	13.43	0.51	13.63	
	7	13.50	1.04	9.33	13.77	0.69	12.98	
	8	11.00	1.46	13.50	12.25	0.98	7.53	
	9	11.50	1.28	11.05	12.37	0.90	8.98	
	10	12.00	1.06	7.74	12.27	0.63	11.37	
Reach average		11.45	1.09	8.02	11.98	0.67	10.68	0.52
Standard deviation		1.62	0.16	2.62	1.59	0.18	2.10	
Co-efficient of variation		0.14	0.15	0.33	0.13	0.27	0.20	

Reach 10	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio	Mean velocity (11/10/00), m^3/s
	1	10.50	1.07	8.75	11.20	0.78	9.81	
	2	11.00	0.77	5.99	11.36	0.53	14.29	
	3	10.50	1.30	11.06	11.45	0.97	8.08	
	4	9.00	1.20	8.95	9.97	0.78	7.50	
	5	7.50	1.47	8.03	8.94	0.81	5.12	
	6	7.50	1.34	7.55	8.68	0.84	5.62	
	7	12.50	1.15	9.52	13.09	1.10	10.87	
	8	12.00	1.13	9.27	12.59	0.71	10.62	
	9	12.50	1.24	12.53	13.29	1.00	10.12	
	10	10.50	1.06	8.69	11.07	0.65	9.91	
Reach average		10.35	1.17	9.03	11.16	0.82	9.19	0.52
Standard deviation		1.84	0.19	1.80	1.60	0.17	2.71	
Co-efficient of variation		0.18	0.16	0.20	0.14	0.21	0.29	

Reach 11	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio	Mean velocity (11/10/00), m^3/s
	1	9.00	1.19	7.41	10.01	0.74	7.56	
	2	10.50	1.12	8.71	11.22	0.78	9.42	
	3	13.00	1.11	8.72	13.84	0.78	11.71	
	4	15.50	1.17	11.28	16.16	0.82	13.30	
	5	13.50	1.10	10.05	14.03	0.62	12.33	
	6	13.00	1.11	8.43	14.09	0.60	11.71	
	7	11.50	1.06	8.16	12.14	0.58	10.85	
	8	11.50	0.86	6.20	11.94	0.51	13.37	
	9	15.00	1.09	10.81	15.34	0.91	13.76	
	10	16.00	1.13	12.20	16.38	0.80	14.22	
Reach average		12.85	1.09	9.20	13.52	0.71	11.82	0.42
Standard deviation		2.26	0.09	1.86	2.14	0.13	2.09	
Co-efficient of variation		0.18	0.08	0.20	0.16	0.18	0.18	

Reach 12	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio	Mean velocity (11/10/00), m^3/s
	1	9.50	1.99	15.92	10.78	1.48	4.77	
	2	9.50	1.80	24.69	11.87	2.08	5.28	
	3	11.00	1.65	31.40	13.76	2.65	6.67	
	4	11.50	1.88	32.15	13.96	2.34	6.12	
	5	11.50	1.50	31.82	15.62	2.28	7.66	
	6	13.50	2.00	31.04	15.40	1.99	6.75	
	7	13.50	1.87	37.67	16.14	2.45	7.22	
	8	17.50	1.87	40.17	19.92	2.49	9.36	
	9	14.00	2.30	30.30	16.48	1.52	6.09	
	10	14.50	2.09	28.36	15.90	1.72	6.93	
Reach average		12.60	1.90	30.35	14.98	2.10	6.68	0.21
Standard deviation		2.48	0.22	6.68	2.57	0.41	1.28	
Co-efficient of variation		0.20	0.12	0.22	0.17	0.20	0.19	

Reach 13	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio	Mean velocity (11/10/00), m^3/s
	1	8.50	0.87	4.42	7.99	0.55	9.77	
	2	6.00	1.06	4.44	6.72	0.66	5.66	
	3	4.50	0.66	1.62	4.74	0.24	6.82	
	4	6.50	0.74	3.00	7.08	0.63	8.78	
	5	5.50	0.76	2.43	5.83	0.34	7.24	
	6	4.50	0.83	2.43	5.04	0.42	5.45	
	7	8.00	0.96	5.15	8.77	1.02	8.38	
	8	10.50	0.74	5.59	10.73	0.64	14.19	
	9	6.50	0.58	2.79	6.80	0.26	11.21	
	10	8.00	0.91	4.47	8.51	0.66	8.79	
Reach average		6.85	0.81	3.63	7.22	0.54	8.63	0.45
Standard deviation		1.90	0.14	1.34	1.83	0.24	2.65	
Co-efficient of variation		0.28	0.18	0.37	0.25	0.43	0.31	

Appendix F - Cross-sectional data for the Wannon River

Reach 1	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	38.50	2.03	43.50	28.09	1.55	18.97
	2	32.50	3.79	66.16	30.16	2.19	8.58
	3	46.50	3.17	96.57	43.38	3.20	14.67
	4	38.00	3.98	102.35	33.61	2.36	9.55
	5	34.50	3.38	80.22	32.28	2.39	10.21
	6	45.50	3.85	92.52	32.15	2.87	11.82
	7	49.00	4.06	80.28	27.04	2.50	12.07
	8	44.00	3.00	54.32	24.44	2.01	14.67
	9	48.00	2.98	74.57	33.36	3.05	16.11
	10	45.50	3.25	71.75	31.50	2.15	14.00
Reach average		42.20	3.35	76.22	31.60	2.43	13.06
Standard deviation		5.85	0.61	18.47	5.09	0.50	3.22
Co-efficient of variation		0.14	0.18	0.24	0.16	0.21	0.25

Reach 2	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	31.00	5.13	106.31	34.00	3.13	6.04
	2	31.00	5.61	93.57	34.21	2.74	5.53
	3	30.50	4.89	86.56	33.15	2.53	6.24
	4	30.50	5.17	81.69	33.13	2.46	5.90
	5	35.00	4.81	88.34	33.48	2.67	7.28
	6	32.50	5.08	66.98	35.16	1.79	6.40
	7	27.50	6.05	70.21	30.83	2.00	4.55
	8	28.00	6.77	76.45	31.99	2.48	4.14
	9	24.50	5.87	65.55	28.15	2.05	4.17
	10	27.00	5.90	70.23	30.14	2.49	4.58
Reach average		29.75	5.53	80.59	32.82	2.43	5.48
Standard deviation		3.03	0.62	13.21	2.67	0.39	1.07
Co-efficient of variation		0.10	0.11	0.16	0.08	0.16	0.20

Reach 3	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	32.50	4.47	87.46	35.46	2.47	7.27
	2	34.50	3.13	58.59	36.35	1.61	11.02
	3	29.00	3.41	47.97	31.36	1.32	8.50
	4	33.50	4.61	63.82	35.74	2.04	7.27
	5	27.50	5.34	68.55	30.69	1.92	5.15
	6	24.50	3.31	35.56	26.47	1.16	7.40
	7	35.50	4.45	83.34	37.43	3.15	7.98
	8	35.50	4.41	77.50	37.54	2.07	8.05
	9	25.50	3.65	48.78	27.82	1.30	6.99
	10	29.50	3.68	49.51	32.12	1.78	8.02
Reach average		30.75	4.05	62.11	33.10	1.88	7.76
Standard deviation		4.10	0.71	17.09	3.99	0.60	1.47
Co-efficient of variation		0.13	0.18	0.28	0.12	0.32	0.19

Reach 4	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	33.50	2.34	46.90	34.21	1.37	14.32
	2	32.50	1.88	37.57	33.00	1.14	17.29
	3	34.50	2.73	46.14	35.39	1.40	12.64
	4	31.50	2.21	39.70	32.21	1.12	14.25
	5	31.00	2.89	42.00	32.05	1.30	10.73
	6	40.50	2.65	56.89	41.45	1.78	15.28
	7	36.50	2.89	57.26	37.42	1.38	12.63
	8	35.00	2.67	43.05	36.22	1.15	13.11
	9	32.00	3.71	49.24	33.78	1.36	8.63
	10	36.50	2.89	52.82	33.64	1.56	12.63
Reach average		34.35	2.69	47.16	34.94	1.36	13.15
Standard deviation		2.92	0.49	6.87	2.86	0.20	2.39
Co-efficient of variation		0.08	0.18	0.15	0.08	0.15	0.18

Reach 5	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	29.00	3.22	51.00	30.48	1.67	9.01
	2	39.50	3.58	58.35	40.84	1.43	11.03
	3	43.00	3.31	72.37	44.02	1.77	12.99
	4	44.00	3.14	63.22	44.95	1.44	14.01
	5	46.50	5.12	113.37	48.91	2.52	9.08
	6	46.50	4.93	111.82	48.61	2.29	9.43
	7	36.50	3.36	46.91	37.84	0.97	10.86
	8	35.00	3.93	55.61	37.03	1.47	8.91
	9	28.00	3.55	38.68	29.75	1.04	7.89
	10	33.50	3.23	48.35	34.66	1.63	10.37
Reach average		38.15	3.74	65.97	39.71	1.62	10.36
Standard deviation		6.83	0.72	26.26	6.93	0.49	1.93
Co-efficient of variation		0.18	0.19	0.40	0.17	0.30	0.19

Reach 6	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	35.50	3.58	92.03	37.19	2.47	9.92
	2	37.50	3.71	105.20	39.18	2.69	0.11
	3	41.00	3.78	94.85	42.66	2.42	10.85
	4	39.50	4.38	116.78	42.11	2.74	9.02
	5	37.50	3.80	111.95	40.15	2.66	9.87
	6	38.50	4.10	122.51	41.27	3.05	9.39
	7	37.50	3.37	88.33	42.44	2.14	11.13
	8	38.50	4.20	109.74	41.50	2.59	9.17
	9	32.00	3.62	76.07	33.65	1.83	8.84
	10	31.00	3.79	79.14	32.69	2.35	8.18
Reach average		36.85	3.83	99.66	39.28	2.49	9.65
Standard deviation		3.17	0.31	15.94	3.63	0.34	0.91
Co-efficient of variation		0.09	0.08	0.16	0.09	0.14	0.09

Reach 7	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	28.00	3.72	61.07	30.22	2.02	7.53
	2	16.00	3.91	111.02	35.83	3.10	4.09
	3	36.50	2.94	76.76	38.43	2.14	12.41
	4	32.50	3.01	69.81	33.69	1.82	10.80
	5	28.00	3.60	69.25	30.37	2.06	7.78
	6	32.50	3.49	73.49	33.84	2.42	9.31
	7	16.00	5.14	54.99	20.25	1.63	3.11
	8	15.50	4.60	49.12	19.94	2.43	3.37
	9	19.50	3.30	48.77	21.74	2.45	5.91
	10	21.50	3.06	44.13	22.86	2.03	7.03
Reach average		24.60	3.68	65.84	28.72	2.21	7.13
Standard deviation		7.86	0.71	19.52	6.93	0.41	3.12
Co-efficient of variation		0.32	0.19	0.30	0.24	0.19	0.44

Reach 8	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	28.50	3.86	73.51	30.81	2.39	7.[illegible]
	2	32.00	5.02	111.62	35.16	3.17	6.37
	3	29.00	5.90	101.43	32.97	2.88	4.92
	4	27.00	5.07	96.15	30.46	2.92	5.33
	5	30.00	3.33	71.83	31.42	2.36	9.01
	6	32.50	4.34	100.27	34.56	3.19	7.49
	7	30.50	4.53	87.58	32.81	2.53	6.73
	8	30.00	4.32	89.84	32.30	2.74	6.94
	9	25.50	4.08	89.84	30.80	2.78	6.25
	10	27.00	5.48	100.04	30.73	3.25	4.93
Reach average		29.20	4.59	92.21	32.20	2.82	6.54
Standard deviation		2.25	0.78	12.48	1.67	0.33	1.28
Co-efficient of variation		0.08	0.17	0.14	0.05	0.12	0.20

Reach 9	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	35.00	5.45	124.72	38.42	3.25	6.42
	2	28.00	5.68	106.07	32.26	3.29	4.93
	3	26.00	5.30	104.33	29.98	3.23	4.91
	4	30.50	5.54	119.23	33.96	3.98	5.51
	5	36.50	5.31	135.57	39.04	3.99	6.87
	6	36.50	5.26	135.14	40.10	3.46	6.94
	7	36.00	5.40	179.84	40.44	4.48	6.67
	8	37.00	5.07	131.88	40.39	3.26	7.30
	9	29.00	5.13	108.10	32.20	2.68	5.65
	10	37.00	5.93	123.57	41.86	3.84	6.24
Reach average		33.15	5.41	126.85	36.87	3.55	6.14
Standard deviation		4.29	0.26	21.96	4.30	0.52	0.85
Co-efficient of variation		0.13	0.05	0.17	0.12	0.15	0.14

Reach 10	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	45.00	5.43	176.91	47.57	3.72	8.29
	2	40.00	5.44	161.43	43.96	3.67	7.35
	3	37.50	5.60	162.51	41.97	3.70	6.70
	4	33.00	6.18	136.20	37.54	3.25	5.34
	5	42.50	8.01	218.49	47.52	5.82	5.31
	6	39.50	6.78	173.38	44.33	3.65	5.83
	7	37.50	6.65	154.81	41.42	3.49	5.64
	8	36.50	5.00	114.94	42.32	2.77	7.30
	9	42.50	5.86	149.13	45.54	3.52	7.25
	10	35.00	6.01	144.37	39.39	3.17	5.82
Reach average		38.90	6.10	159.22	43.16	3.68	6.48
Standard deviation		3.72	0.87	27.64	3.28	0.81	1.03
Co-efficient of variation		0.10	0.14	0.17	0.08	0.22	0.16

Reach 11	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	52.50	6.53	211.54	55.16	3.84	8.04
	2	42.00	6.21	178.49	46.24	3.86	6.76
	3	43.50	5.87	169.06	49.69	3.66	7.41
	4	40.00	6.64	171.34	43.64	3.45	6.02
	5	42.00	6.55	177.56	45.51	4.07	6.41
	6	43.50	7.18	192.68	47.38	4.23	6.06
	7	34.00	6.75	157.13	38.36	3.32	5.04
	8	54.50	6.88	210.23	57.52	5.48	7.92
	9	52.50	6.62	246.80	56.27	4.29	7.93
	10	38.50	5.94	148.64	41.51	2.64	6.48
Reach average		44.30	6.52	186.35	48.13	3.88	6.81
Standard deviation		6.74	0.41	29.51	6.47	0.74	1.00
Co-efficient of variation		0.15	0.06	0.16	0.13	0.19	0.15

Reach 12	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	38.00	7.22	186.78	42.32	4.41	5.26
	2	40.50	6.86	187.18	44.19	4.24	5.90
	3	41.00	6.18	166.78	44.92	3.77	6.63
	4	35.00	6.09	148.90	38.95	3.31	5.75
	5	35.50	7.11	177.41	40.46	4.55	4.99
	6	40.00	6.29	167.61	43.88	4.14	6.36
	7	41.50	7.10	187.29	45.68	4.27	5.85
	8	40.00	6.55	169.79	43.97	3.72	6.11
	9	38.50	6.39	175.66	42.58	3.99	6.03
	10	37.50	6.45	170.40	42.11	4.00	5.81
Reach average		38.75	6.62	173.78	38.91	11.65	5.87
Standard deviation		2.25	0.42	11.93	13.02	24.20	0.48
Co-efficient of variation		0.06	0.06	0.07	0.33	2.08	0.08

Appendix G - Cross-sectional data for the Ringarooma River

Reach 1	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	16.00	1.63	19.70	17.20	1.15	9.82
	2	18.50	1.25	16.29	19.13	0.85	14.80
	3	20.00	1.86	25.35	20.67	1.33	10.75
	4	15.00	1.02	9.66	15.64	0.47	14.71
	5	14.50	1.09	10.12	14.96	0.65	13.30
	6	18.50	1.99	13.23	19.12	0.88	9.30
	7	14.50	0.68	10.21	14.90	0.53	21.32
	8	16.50	1.00	9.16	16.81	0.61	16.55
	9	12.00	0.64	7.36	12.37	0.44	18.75
	10	20.00	1.66	16.41	20.95	1.33	12.05
Reach average		16.55	1.28	13.75	17.18	0.82	14.13
Standard deviation		2.65	0.48	5.66	2.78	0.34	3.92
Co-efficient of variation		0.16	0.37	0.41	0.16	0.41	0.28

Reach 2	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	19.00	1.73	21.59	20.07	1.08	10.98
	2	31.00	0.85	15.07	31.37	0.48	36.47
	3	35.50	2.58	39.62	36.45	1.26	13.76
	4	17.00	2.09	15.13	17.93	0.42	8.13
	5	24.50	2.05	33.27	25.54	1.86	11.95
	6	17.50	1.82	23.34	18.39	0.91	9.62
	7	22.50	1.94	28.37	23.33	1.54	11.60
	8	22.00	1.65	19.62	23.18	0.84	13.33
	9	22.00	2.08	32.33	23.36	1.39	10.58
	10	22.00	1.24	15.00	22.57	0.64	17.74
Reach average		23.30	1.80	24.33	24.22	1.04	14.42
Standard deviation		5.84	0.48	8.71	5.76	0.47	8.18
Co-efficient of variation		0.25	0.27	0.36	0.24	0.45	0.57

Reach 3	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	35.50	3.58	77.40	38.07	2.03	9.92
	2	29.00	1.46	29.39	29.51	1.00	19.86
	3	34.00	1.82	44.27	34.50	1.50	18.68
	4	26.50	1.14	19.45	26.70	0.56	23.25
	5	28.00	1.35	23.29	28.32	0.87	20.74
	6	32.00	1.45	26.91	32.25	0.95	22.07
	7	37.00	2.82	53.57	37.86	1.66	13.12
	8	31.00	2.41	41.73	31.91	1.10	12.86
	9	39.50	3.16	67.60	40.67	2.12	12.50
	10	29.50	2.53	42.91	30.49	1.06	11.66
Reach average		32.20	2.17	42.65	33.03	1.29	16.47
Standard deviation		4.21	0.85	19.12	4.62	0.52	4.92
Co-efficient of variation		0.13	0.39	0.45	0.14	0.40	0.30

Reach 4	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	50.00	4.05	99.59	51.62	1.93	12.35
	2	37.50	2.94	50.25	39.73	1.26	12.76
	3	38.00	2.34	62.64	38.73	1.58	16.24
	4	55.00	1.75	69.28	55.53	1.79	31.43
	5	56.00	1.34	52.33	58.10	0.94	41.79
	6	59.00	2.73	85.40	60.08	1.47	21.61
	7	38.00	2.53	64.61	38.95	1.08	15.02
	8	34.00	1.64	35.61	34.42	0.91	20.73
	9	40.50	2.14	58.83	41.30	1.71	18.93
	10	42.50	2.86	71.72	47.57	1.74	14.86
Reach average		45.05	2.43	65.03	46.60	1.44	20.57
Standard deviation		9.09	0.78	18.14	9.21	0.37	9.33
Co-efficient of variation		0.20	0.32	0.28	0.20	0.26	0.45

Reach 5	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	33.50	1.88	37.85	34.08	1.11	17.82
	2	30.00	2.01	39.11	30.74	1.27	14.93
	3	29.00	1.93	30.63	29.87	1.00	15.03
	4	35.50	1.59	28.48	35.84	0.95	22.33
	5	28.00	2.25	44.61	29.29	1.24	12.44
	6	26.50	1.87	27.91	27.76	0.95	14.17
	7	27.50	2.08	37.62	28.52	1.36	13.22
	8	27.50	1.93	45.34	28.35	1.59	14.25
	9	32.50	1.88	51.58	33.65	1.82	17.29
	10	29.50	1.82	40.15	30.52	1.19	16.21
Reach average		29.95	1.92	38.33	30.86	1.25	15.77
Standard deviation		2.96	0.17	7.70	2.75	0.28	2.86
Co-efficient of variation		0.10	0.09	0.20	0.09	0.23	0.18

Reach 6	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	55.00	1.60	63.78	55.52	1.15	34.38
	2	65.00	3.18	157.09	67.17	2.34	20.44
	3	67.00	2.52	123.99	68.20	1.85	26.59
	4	51.00	2.48	90.15	52.09	1.32	20.56
	5	60.00	2.55	102.34	61.31	1.96	23.53
	6	56.00	3.25	121.92	57.93	1.99	17.23
	7	47.00	3.50	109.47	48.26	1.89	13.43
	8	48.00	4.38	134.00	51.09	2.78	10.96
	9	70.50	3.93	145.14	72.23	2.84	17.94
	10	61.00	4.33	181.72	63.07	2.52	14.09
Reach average		58.05	3.17	122.96	59.69	2.06	19.91
Standard deviation		8.04	0.90	34.03	8.05	0.56	6.95
Co-efficient of variation		0.14	0.28	0.28	0.13	0.27	0.35

Reach 7	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	36.00	1.44	34.45	36.67	0.94	25.00
	2	38.00	2.59	71.80	39.20	1.83	14.67
	3	39.00	1.82	43.54	39.65	1.11	21.43
	4	42.50	1.52	47.59	42.98	1.20	27.96
	5	51.00	2.21	85.74	51.81	1.99	23.08
	6	46.50	2.24	78.38	47.40	1.51	20.76
	7	46.00	2.29	77.08	46.82	1.63	20.09
	8	40.00	2.60	66.52	41.35	1.42	15.38
	9	45.00	2.63	67.25	46.27	1.63	17.11
	10	45.00	2.40	60.77	45.78	1.31	18.75
Reach average		42.90	2.17	63.31	43.79	1.46	20.42
Standard deviation		4.62	0.44	16.65	4.62	0.33	4.19
Co-efficient of variation		0.11	0.20	0.26	0.11	0.22	0.21

Reach 8	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	53.50	3.13	88.95	54.74	1.62	17.09
	2	55.50	2.74	80.53	56.39	1.43	20.26
	3	51.00	2.97	76.43	52.39	1.36	17.17
	4	62.00	1.40	51.40	62.50	0.98	44.29
	5	61.00	0.99	40.71	61.28	0.65	61.62
	6	66.50	2.28	79.34	67.40	1.29	29.17
	7	84.00	2.60	82.85	85.02	1.23	32.31
	8	65.00	2.66	80.72	66.44	0.95	24.44
	9	64.00	3.20	101.05	65.41	1.52	20.00
	10	52.50	1.98	69.58	63.19	1.06	26.52
Reach average		61.50	2.40	75.16	63.48	1.21	29.28
Standard deviation		9.67	0.74	17.58	9.11	0.30	14.04
Co-efficient of variation		0.16	0.31	0.23	0.14	0.25	0.48

Reach 9	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	62.50	2.66	104.69	63.55	1.65	23.50
	2	58.50	1.38	43.46	59.13	0.73	42.39
	3	61.50	2.45	129.25	62.67	2.19	25.10
	4	59.00	2.77	134.54	60.20	2.15	21.30
	5	53.50	2.39	80.17	52.44	1.33	22.38
	6	56.00	2.94	207.14	58.55	3.95	19.05
	7	52.50	1.43	126.45	54.38	2.16	36.71
	8	50.00	1.50	49.67	50.58	0.91	33.33
	9	50.50	2.04	50.47	51.19	1.00	24.75
	10	59.50	2.30	74.82	59.49	1.46	25.87
Reach average		56.35	2.19	100.07	57.22	1.75	27.44
Standard deviation		4.52	0.57	51.05	4.72	0.94	7.52
Co-efficient of variation		0.08	0.26	0.51	0.08	0.54	0.27

Reach 10	Cross-section	Width$_{bf}$ (w), m	Depth$_{bf}$ (d), m	Area (m2)	Wetted Perimeter (P), m	Hydraulic radius (R), m	Width/ Depth ratio
	1	50.00	2.36	37.96	51.00	0.74	21.19
	2	47.00	1.96	45.46	48.34	0.94	23.98
	3	48.00	2.40	50.68	49.99	1.05	20.00
	4	48.50	2.19	40.38	49.75	0.81	22.15
	5	53.00	1.59	54.83	54.09	1.10	33.33
	6	45.50	2.38	51.78	41.20	0.96	19.12
	7	47.50	2.80	6[illegible].64	49.00	1.59	16.96
	8	42.00	2.08	44.69	43.12	0.91	20.19
	9	38.00	2.34	58.28	39.39	1.35	16.24
	10	40.00	1.56	45.97	40.84	1.17	25.64
Reach average		45.95	2.17	49.57	46.67	1.06	21.88
Standard deviation		4.65	0.38	8.44	5.08	0.26	4.95
Co-efficient of variation		0.10	0.18	0.17	0.11	0.24	0.23

Appendix H - Publications

This appendix contains a list of book chapters, conference papers and magazine articles that have been written and presented based on the research in this thesis.

Book chapters:

- Bartley, R. and Rutherfurd, I. (2001) Ringarooma River (a case study of sediment delivery and recovery). In Marutani, T., Brierley, G., Trustrum, N., Page, M. "Source-to-Sink Sedimentary Cascades in Pacific Rim Geo-systems". Published by Nippon Alps Sabo Center, Ministry of Land, Infrastructure and Transport, Tokyo, p 132-139.
- Bartley, R., Rutherfurd, I., Davis, J. and Finlayson, B. (2001) Creightons Creek (a case study of sediment delivery and recovery). In Marutani, T., Brierley, G., Trustrum, N., Page, M. "Source-to-Sink Sedimentary Cascades in Pacific Rim Geo-systems". Published by Nippon Alps Sabo Center, Ministry of Land, Infrastructure and Transport, Tokyo, p 140-147.

Conference Papers and Abstracts:

- Bartley, R. and Rutherfurd, I., (2001). Statistics, snags and sand: measuring the geomorphic recovery of streams disturbed by sediment slugs. In: I. Rutherfurd, F. Sheldon, G. Brierley and C. Kenyon (Editors), Proceedings of the Third Australian Stream Management Conference. Cooperative Research Centre for Catchment Hydrology, Brisbane, p15-21, Volume 1.
- Bartley, R. (2001). Predicting pre-disturbance pool depth: a tool for stream rehabilitation, 29th International Association of Hydraulic Research (IAHR) Congress, Beijing, Sept 2001, p166 - 177, J.F. Kennedy Student Paper Competition, Guifen LI (Ed).
- Bartley, R. and Rutherfurd, I. (2001). Quantifying the geomorphic recovery of streams disturbed by anthropogenically produced sediment slugs. *Proceedings of the 5th International Conference on Geomorphology*, Tokyo, August 2001.
- Bartley, R. (2001). Quantifying the recovery potential of disturbed river systems: a tool for stream rehabilitation, Australian Water Association 19th Federal Convention. AWA, Ozwater, Canberra, pp. 242-249. (Winner of the CRC Young Water Scientist of the Year Award).
- Rutherfurd, I. and Bartley, R. (2000) Physio-therapy for your stream: the dangers and potential of geomorphic models of stream disturbance and recovery in stream

rehabilitation. *Murrumbidgee 2000 Conference*, Charles Sturt University, Wagga Wagga, July 2000.

- Bartley, R. and Rutherfurd, I. (1999). The recovery of geomorphic complexity in disturbed streams: using migrating sand slugs as a model. In, Rutherfurd, I. and Bartley, R. (Eds) *Proceedings of the Second Australian Stream Management Conference,* Adelaide. CRC for Catchment Hydrology, Melbourne. p 39-44.
- Bartley, R. and Rutherfurd, I (1999) What is the impact of sediment slugs on the geomorphic variability of streams? *Australian and New Zealand Society for Limnology Biannual Conference*, Lake Taupo, New Zealand.

Other publications

- Bartley, R., Rutherfurd, I., Hairsine, P., Prosser, I., Wallbrink, P., and Perry, D. (2001) 'Australia is on the move…down the creek'. Australian Landcare Farm Journal, December, 2001.