PHYSICAL EVALUATION OF REHABILITATION WORKS IN BROKEN RIVER AND RYANS CREEK, NORTH EAST VICTORIA

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PREFACE

There is a tremendous demand to rehabilitate the physical and biological condition of Australian streams. As a consequence, the Cooperative Research Centre for Catchment Hydrology initiated a 'Stream Rehabilitation' project within its Waterways research program. This project has concentrated on the hydraulic, hydrologic, and geomorphic aspects of stream rehabilitation.

Stream rehabilitation efforts in Australia are being severely hampered by the almost total lack of physical and biological evaluation of rehabilitation projects. This report describes a unique study on the Broken River and Ryans Creek (NE Victoria) that was initiated by the former Broken River Management Board (now the Goulburn Catchment Catchment Management Authority) under the National Landcare Program. The project set-out, not only to design and build structures that would contribute to stream rehabilitation, but to evaluate whether they improved the ecological condition of the stream. This report describes the study done by Michael Stewardson into the physical changes that took place in the field sites. Not only is this a unique study in Australia, but it also explores some methods that could have wide application in the future evaluation of stream rehabilitation. Please note that the Department of Natural Resources and Environment, Victoria, is preparing a companion study into the biological changes that have occurred at the field sites.

Dr Ian Rutherfurd

(Project Leader)

SUMMARY

Background

In the past, efforts to rehabilitate Australian streams have focussed on the stability of the channel and management of riparian vegetation. More recently, rehabilitation projects have included manipulation of physical conditions within the channel to rehabilitate physical habitats. The increasing level of investment in such projects and the limited extent of current stream ecological and geomorphic knowledge demand a critical appraisal of past rehabilitation efforts. A few previous studies, mostly in North American streams, have evaluated physical response to rehabilitation based on (i) structural failure, (ii) changes in channel morphology, and (iii) changes in flow conditions. Despite differences in the methods used, these studies have consistently indicated an increase in the extent of pool habitat and hydraulic diversity in streams following the introduction instream structures. However, no study has provided adequate statistical testing of the significance of these results, and only one study has evaluated the response of an Australian stream to rehabilitation.

Methodology

Rehabilitation works were carried out in May 1996 along a 300 m reach of Broken River (a sand and gravel bed stream) and a 350 m reach of Ryans Creek (a cobble bed stream) in the Broken River catchment in north east Victoria. The works included the introduction of large woody debris (LWD), rip-rap along exposed banks, placement of boulders on the stream bed, and construction of rock riffles. Both projects were intended to stabilise the channel and enhance physical habitat diversity. It was hypothesized that increasing the diversity of physical habitats would result in increased biological diversity.

This report presents an evaluation of these two rehabilitation projects based on short-term changes in channel morphology, channel capacity and physical habitat conditions. The two project reaches were first surveyed in April 1996 prior to the rehabilitation work then re-surveyed several time between February 1997 and June 1998. Field surveys included longitudinal and cross-section profiles, measurements of velocity and depth, and observations of substrate type. Hydraulic modelling was used to estimate bank-full discharge and physical habitat conditions over a range of low to moderate discharges. In most cases, statistical testing was used to establish the significance of observed changes.

Evaluation of Rehabilitation Works

This study (and a companion biological study) tested the hypotheses that (i) works increased habitat diversity and (ii) increased habitat diversity lead to increased biological diversity. Results at the Broken River reach were consistent with these hypotheses. Both physical habitat and fish fauna diversity increased within two years of the rehabilitation works in the Broken River. At the Ryans Creek reach, habitat diversity decreased whilst the diversity of fish fauna was not significantly affected by the rehabilitation works. This suggests that physical habitat availability was not a key factor regulating fish fauna diversity at Ryans Creek. This is not unexpected given that the physical habitat diversity prior to rehabilitation works was higher than in many other streams. The introduction of LWD and boulders did not reduce the discharge capacity of either channel. In Broken River, flow resistance was unaffected by the works, probably because the structures were small relative to the size of the channel. In Ryans Creek, an increase in flow resistance was offset by an increase in channel size.

Based on these results, the following general conclusions can be made.

- **Whilst this study does not provide a general test of ecological theory its results are consistent with the hypothesis that low physical habitat diversity results in a low diversity of fish fauna.** However, changes in physical habitat diversity may not always influence biological diversity, particularly if physical habitat diversity is high.
- **The introduction of instream structures does not always increase the diversity of physical habitats.** An increase in habitat diversity is more likely to result if structures are designed to enhance the natural processes of pool and riffle formation, and habitat diversity prior to rehabilitation is low.
- **LWD and other features can be introduced into a channel without affecting channel capacity and flooding.**

It should be noted that that these conclusions are based on the evaluation of short-term changes in only two stream reaches. Considerably more research is required (including large-scale and replicated trials) to establish general principles to guide rehabilitation design.

Use of Rehabilitation Techniques

The hydraulic effect of LWD varies with discharge. The greatest hydraulic effect is likely to occur at intermediate discharges when blockage ratios of LWD items are at a maximum. The introduction of LWD appears to enhance pool areas and, in the absence of morphological change, increases hydraulic diversity. Morphological adjustments following the introduction of a high loading of LWD can result in reduced hydraulic diversity. However, a reduction in hydraulic diversity is less likely if hydraulic diversity prior to introduction of LWD is low and LWD placement is designed to enhance the natural process of pool development. LWD can be introduced without a reduction in channel capacity. Models used to predict changes in channel capacity with altered LWD loading that require the assumption of no channel change are unreliable in situations of high LWD loading.

The use of boulders to rehabilitate lowland and cobble-bed rivers is of questionable value given that they are unlikely to be a natural feature of the channel. Artificial riffles should use a downstream gradient similar to that of naturally occurring riffles, and should be located so as to enhance pre-existing pool-riffle features. Riffles with a gradient steeper than pre-existing riffles will result in a reduction in riffle area at lower discharges.

Physical Habitat Diversity as a Design Goal

In some situations, enhanced physical habitat diversity may be a useful goal for design of instream rehabilitation works. Results at Broken River are consistent with suggestions that an enhancement of habitat diversity will result in an increased diversity of fish fauna. However this relation remains largely untested and no widely accepted definition of habitat diversity is available. For this reason, a more appropriate goal is the hydraulic conditions of a comparable channel in a relatively natural state. Characteristics at a range of spatial scales should be considered to maximize the possibility of addressing habitat needs of the entire stream community.

ACKNOWLEDGMENTS

The project documented in this report is the result of collaboration between the Cooperative Research Centre for Catchment Hydrology (CRCCH) and the Marine and Freshwater Resources Institute (MAFRI). The project was supported by:

- The Cooperative Research Centre for Catchment Hydrology (Project W2),
- The (former) National Landcare Program (Project No. IFRS/95-3-2)
- The Mid-Goulburn Broken Implementation Committee of the Goulburn Catchment Management Authority (formerly The Broken River Management Board), and
- The Department of Natural Resources and Environment (Victoria).

Coordination of the project was undertaken by Ian Rutherfurd (CRCCH), Geoff Gooley (MAFRI), and Wayne Tennant (ID&A). The staff of MAFRI (Snobs Creek), Amanda Armitage (CRCCH) and Gerry Gerrish (CRCCH) provided field assistance. Paul Brown and John Douglas (MAFRI) provided advice regarding biological aspects of the project. Jill Glover (The University of Melbourne) assisted in the preparation of this final report and Chandra Jayasuria (The University of Melbourne) prepared the two locality maps. Early drafts of this report were reviewed by Rebecca Bartley, Paul Brown, Chris Gippel, Geoff Gooley, Tony Ladson, Russell Mein, Ian Rutherfurd, and Wayne Tennant. The final draft was reviewed by Richard Marchant and Bruce Abernethy.

The rehabilitation trials were undertaken on stream reaches adjacent to the properties of David Friday (Broken River) and Mr Rammage (Ryans Creek). The cooperation and involvement of these landowners are gratefully acknowledged.

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1 INTRODUCTION

1.1 Stream Rehabilitation and Project Evaluation

The rehabilitation of streams is currently an internationally expanding area of investment by public river and water management agencies (Sear 1994). In the past, efforts to rehabilitate Australian streams have focussed on the stability of the channel and riparian vegetation. More recently, rehabilitation projects have included altering physical conditions within the channel to rehabilitate physical habitats of the aquatic community. Conditions that are thought to influence stream communities include flow velocity and depth, and the type of cover and substrate. These rehabilitation projects include the provision of environmental flows, the re-introduction of large woody debris, and construction of artificial riffles. The increasing level of investment in such projects and the limited extent of current stream ecological and geomorphic knowledge, demand a critical appraisal of past rehabilitation efforts. However there have been few attempts to monitor and evaluate the performance of physical stream rehabilitation projects in Australia to date.

1.2 Overview of the Project

A three year project, beginning in July 1995, monitored the response of two rivers in the mid-Broken River catchment to rehabilitation works. Base-line monitoring was carried out over the first year of the project. Rehabilitation works were carried out following these baseline surveys. The biological and physical response of the channel was monitored for a period of two years following these works. The Marine and Freshwater Resources Institute (MAFRI) monitored fish and macroinvertebrate communities and the Cooperative Research Centre for Catchment Hydrology (CRCCH) monitored physical changes. This report describes the results of monitoring physical changes at these two reaches including:

- changes in channel morphology,
- flow capacity, and
- habitat conditions.

The results of the biological monitoring are documented by MAFRI. For completeness, preliminary biological results have been summarised in Chapter 7. However, readers specifically interested in the results of biological monitoring, should contact the Freshwater Division of MAFRI[1] to obtain their final report.

1.3 Why Conduct Physical Monitoring?

Biological monitoring alone is unlikely to provide sufficient evidence to support general principles for rehabilitation design. In this study, physical monitoring identified the effect of works on channel morphology and physical habitat conditions and provides evidence to support explanations of biological change. By understanding the causes of biological change, it is possible to make general recommendations regarding the design of rehabilitation works. In addition, there is some concern that instream rehabilitation works increase channel roughness and reduce channel flow capacity. In lowland streams this may result in increased flooding. To address this concern, this study evaluates the effect of the works on the flow capacity of the channel. The Ryans Creek channel is incised and flooding is unlikely to be a major issue influencing management of this river. Despite this, the effect of works in both rivers has been assessed to provide information for rehabilitation of rivers where flood protection is an important issue.

1.4 Methodology

Changes in channel morphology, flow capacity, and physical habitat conditions at the two project reaches have been assessed based on field surveys over a three year period. Projects like this one are rare and there is no standard evaluation methodology available. For this reason, previous approaches to evaluating rehabilitation projects are reviewed in Chapter 2. Based on this review and the specific requirements of this project, a physical assessment methodology was developed. This methodology includes field surveys, data processing, hydraulic modelling, and statistical significance testing. Assessment of the impact of works was based on a comparison of conditions before and after rehabilitation works. It is emphasised that this study is not a controlled experiment, rather it is an observational and exploratory study of the physical response of two rivers to rehabilitation works. The response to these works was super-imposed on other physical changes, such as those caused by the historical sequence of flows and changes within the catchment. Where possible, the contribution of works to observed changes was evaluated. In the case of channel changes in Ryans Creek, channel changes along the length of Ryans Creek were compared with changes at the rehabilitation reach to identify changes relating specifically to the works.

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[1] Marine and Freshwater Resources Institute (Snobs Creek), PO Box 20, Alexandra, Victoria, 3714

1.5 Interpretation of Results

This research project is one of the first exploratory studies of the environmental impacts of stream rehabilitation works. This report contributes to the knowledge of the physical impact of stream rehabilitation works. However, it should be remembered that it is limited to a three year study at two reaches. Considerably more monitoring and evaluation is required to develop general models of physical response for rehabilitation design. This report suggests improvements to stream rehabilitation design and provides a method for monitoring and evaluating the physical impacts of instream works. These results form the basis for interpreting the results of biological monitoring, reported in detail elsewhere, and summarised in Chapter 7.

2 BACKGROUND

2.1 Stream Rehabilitation

Stream rehabilitation can take two distinct forms. **Structural rehabilitation** involves the direct manipulation of physical aspects of the channel and can include the installation of artificial structures within the channel, the manipulation of channel morphology, and the manipulation of natural features of the channel such as large woody debris and substrate (National Research Council 1992). **Non-structural rehabilitation** refers to projects that do not directly disturb the channel, such as the release of an environmental flow, or changes to floodplain management practices. In general, non-structural rehabilitation is the preferred approach to rehabilitation of streams because:

- it addresses the cause of degradation, and
- it is more likely to be self-sustaining.

However, non-structural rehabilitation can often be impractical because of the costs involved.

Two critically important components of a Rehabilitation design are the **goal** and **hypothesis**. The **goal** is generally, although not always, expressed in terms of biological outcomes. The three different goals in common use are:

(i) increased abundance of particular target species,

(ii) increased diversity of species, and

(iii) increased similarity between the aquatic community of the project reach and some reference community (e.g. the pre-disturbance community).

The goal should reflect the values assigned to the river environment by stakeholders. There is no right or wrong goal for a rehabilitation project, as long as the goal is well defined and accepted by everyone involved in the project.

The **hypothesis** relates a proposed rehabilitation measure to the intended biological outcome. Three common hypotheses, corresponding to the three objectives given above, are:

(i) increasing the availability of physical habitat for a particular species will increase the abundance of the species,

(ii) increasing the diversity of physical habitats will increase biological diversity, and

(iii) increasing the physical similarity of two streams will increase the similarity of their stream communities.

Projects that seek to improve the environmental condition of streams by providing for the habitat needs of aquatic species are often described as **habitat enhancement.** In such projects, stream habitat degradation is thought to have progressed to the point where factors such as substrate, cover, and hydraulic conditions, have contributed to a decline in aquatic populations (Beschta et al. 1994; Gore and Shields 1995; Swales and O'Hara 1980; Wesche 1985). To be successful, these projects require that habitats for the target species at different life-stages are known (Hey 1992), and that factors currently limiting productivity are correctly identified (Andrus 1991; Hicks and Reeves 1994). However, stream rehabilitation is rarely based on sufficient knowledge of the physical habitat requirements of the biota (Borchadt 1993). Furthermore, rehabilitation design parameters for fluvial processes, site-specific hydraulics, and aquatic organisms have defied complete analysis, particularly at the finer scales (Newbury and Gaboury 1993a). It is also possible that efforts to enhance the habitat of a limited faunal group may ignore, or have a detrimental affect on, other members of the aquatic community (National Research Council, 1992).

An alternative to the habitat enhancement approach is to mimic the natural materials and dimensions of a **reference site**. The reference site may be the project reach in its pre-disturbance condition, the current condition of nearby lightly disturbed sites, or some idealized condition (Brookes and Shields 1996; Kondolf and Downs 1996; Newbury and Gaboury 1993a). It is claimed that the best habitat enhancement efforts imitate the geomorphology of a reference channel in the hope that natural restoration of biological integrity will follow (Kondolf and Downs 1996; Osborne et al. 1993).

Projects that aim to increase biological diversity by increasing **physical habitat diversity** steer a middle course between the habitat enhancement and reference site approaches, particularly if the assessment of habitat diversity is based on a comparison with a reference stream. This approach has been adopted in the design of rehabilitation works for Ryans Creek and Broken River. In this case, instream structural rehabilitation works were intended to create natural channel features that enhance physical habitat diversity and consequently, biological diversity. Practitioners should remember that with all three approaches, the links between management actions and biological outcomes are hypotheses. These hypotheses, although in common use, are rarely tested and may be highly unreliable.

2.2 Previous Studies of the Physical Impact of Structural Rehabilitation

Assessment Methods

There have been few documented studies evaluating physical response of streams to structural rehabilitation works. The few studies available include assessments based on structural failure, changes in channel morphology, and changes in flow conditions. The simplest studies consider structural integrity alone. For example, Andrus (1991) evaluated the performance of 1257 structural rehabilitation projects on the basis of whether they were functional at the time of survey. Only 2% of structures were found to have failed since construction. These studies provide no measure of the environmental benefit of works.

Some studies monitor changes in channel morphology. For example, Newbury and Gaboury (1993b) used a longitudinal bed profile to monitor pool development in Mink Creek following the construction of artificial riffles. Hansen et al. (1996) suggest that variability in channel width and depth should be used to assess structural rehabilitation works, as greater channel variability will contribute to greater diversity of hydraulic habitat conditions. No evidence is provided to support this claim. Hansen et al. (1996) also suggest that the spatial distribution of erosion and deposition should be monitored to assess the stability of rehabilitated rivers. McDowell and Magilligan (1997) monitored the impact of stock exclusion from streams using measurements of bank-full width, low flow depth, low flow width to depth ratio, and low flow pool area. This study did not identify desirable values for these channel characteristics. Although able to show morphological responses to works, these studies did not provide insight into changes in habitat conditions at finer scales. Of the approaches reviewed, the invert profile appeared to be the most reliable in detecting changes. These surveys allowed some inferences to be made regarding the presence of pools at low flows.

Shields et al. (1995) monitored physical response to structural rehabilitation works in a reach of Hotophia Creek, north-west Mississippi. In this study, 12 cross-sections and a invert profile were surveyed prior to, and following, rehabilitation works. Three bed sediment samples were also taken from each cross-section, and pool depths at mid-summer base flows were measured using a wading rod. Shields et al. (1995) also monitored changes in pool habitat based on observations of velocity (at 0.6 times depth above the bed), depth and substrate type during mid-summer base flows using a regularly spaced grid sampling. Between 5 and 7 observations were made across transects that were spaced 15-20 m apart. This transect spacing was found to be necessary to detect changes in the area of pool habitat. Pool habitat was defined in two ways: (i) depth > 0.2 m and velocity < 0.1 m/s, and (ii) Froude number < 0.15.

V.A. Poulin & Associates (1991) monitored physical response to 23 stream rehabilitation structures. A longitudinal bed profile was used to assess depth variability before and after rehabilitation. Depth variability was characterised by the standard deviation of the detrended invert profile. Cross-section surveys were used to estimate the spatial distribution of sediment deposition and erosion. Bed surface sediments were classified visually. Flow types (pool, riffle or glide) and fish cover types were mapped before and after rehabilitation to allow estimation of changes in the habitat composition along the reach. Inter-gravel permeability and gravel size distribution was measured at the location of each rehabilitation structure.

The effect of rehabilitation works on physical habitat diversity was assessed in a number of studies, with increases in diversity being considered a desirable outcome. Van Zyll de Jong et al. (1997) compared habitat enhancement works on the basis of increased variability in depth, substrate, cover, and current velocity. Unfortunately, the method of calculating variability was not documented. These authors identified a need to develop a model describing habitat heterogeneity and complexity at different spatial and temporal scales to explain changes in aquatic communities. Huusko and Yrjänä (1996) evaluated the effect of works on hydraulic diversity based on modelled velocity, depth and Froude number distributions before and after rehabilitation. Diversity was described as the range of values of these parameters. V.A. Poulin & Associates (1991) provide a more sophisticated definition of hydraulic diversity based on the composition of flow types (pool, riffle and glide) observed in a stream reach.

Some studies have focussed on assessing changes in the area of habitat for one or more life-stage. The physical response to channel modifications in Douglas Creek, Wyoming, was assessed based on changes in depth, velocity, hydraulic radius, cross-sectional area, and wetted perimeter at individual cross-sections (Cooper and Wesche 1976). For this study, deeper water and higher velocities were assumed to result in increased abundance of trout. Koehn (1987) monitored changes in hydraulic conditions as a result of structural works in Ovens River, Victoria. An evaluation of these changes was based on comparison of distributions of velocity and depth measurements. Increases in the area of blackfish rearing habitat was considered a desirable outcome of the project, where this habitat was defined by areas with velocity less than 0.2 m/s and depth greater than 0.2 m. Elliott et al. (1996), and Huusko and Yrjänä (1996) modeled habitat area before and after structural rehabilitation works using the PHABSIM model. In this approach, habitat of a particular species life stage is related to velocity, depth, and substrate type.

Results

Changes in physical habitat conditions with instream structural works have been assessed in a number of studies using methods similar to those used to assess changes in Broken River and

Ryans Creek (Cooper and Wesche 1976; Koehn 1987; Shields et al. 1995; Shields and Smith 1992; V.A. Poulin and Associates 1991). In all cases, except Shields and Smith (1992), these studies compared hydraulic conditions before and after structural rehabilitation works. Shields and Smith (1992) compared conditions in reaches that had been subject to Large Woody Debris (LWD) removal with conditions in undisturbed reaches. The river type, nature of works and changes in physical conditions detected in each of these studies are summarised in Table 1. Observed changes in pool area and physical habitat diversity are discussed in the following paragraphs.

Table 1: Studies of change in pool area (*P*) and habitat diversity (Δ) at low flows with instream works

Reference	*River name*	*Width (m)*	*Bed material*	*Nature of works*	*P**	*Δ**
Cooper and Wesche (1976)	Main channel Douglas Creek, Wyoming	15-18	Coarse	Deflectors, spur dams, check dams, barriers, artificial overhangs	0	
	Side channel, Douglas Creek, Wyoming	4-10	Coarse	As above	+	
Koehn (1987)	Ovens River, Victoria	20	Coarse	Log weir pool	+	
		17	Coarse	Boulders	+	
V.A. Poulin and Associates (1991)	Sachs Creek	5-7	Coarse	Log structures	+	0
	Macmillan Creek	20-30	Coarse		+	+
	Southbay Dump Cr	2-3	Coarse		+	+
Shields and Smith (1992)	South Fork Obion River, Tennessee	12-17	Sand	Removal of LWD	-	-
Shields et al. (1995)	Hutophia Creek, Mississippi	44-77	Sand	Spur dikes	+	
(Van Zyll de Jong et al. 1997)	Joe Farrell’s Brook, Newfoundland	8-13	Coarse	Bolder clusters, V-dams, half-log covers	+	+

* The “+” symbol indicates an increase and “–“ indicates a decrease following instream works

The changes in pool area were detected in, or inferred from, these studies (see Table 1) using a range of methods for measuring pool area. Shields et al. (1995) defined pools as (i) area with depth greater than 0.2 m and velocity less than 0.1 m/s, and (ii) areas with Froude number less than 0.15. Koehn (1987) defined pool habitats as areas with depth greater than 0.2 m and velocity less than 0.2 m/s. Both of these studies report a substantial increase in pool areas, although neither included a statistical test of the significance of these changes. V.A. Poulin and Associates (1991) and Van Zyll de Jong et al. (1997) identified pools using an unspecified method of visual assessment and did not test the significance of changes. Changes in pool areas were not explicitly assessed by Cooper and Wesche (1976) but can be inferred from changes in cross-sectional Froude numbers calculated using mean depth and velocity values for transects (data included in their report). Median Froude numbers reduced in both the main and side channels following works. Using a jackknife test, the reduction was significant in the side-channel ($p=0.05$) but not significant in the main channel. Shields and Smith (1992) did not explicitly assess changes in pool area but found that removal of LWD led to a reduction in low velocity habitat. Despite differences in methods used to assess changes in pool areas, all studies indicated an increase in the extent of pool habitat in streams with structures and LWD.

V.A. Poulin and Associates (1991), Shields and Smith (1992), and Van Zyll de Jong (1997) assessed the effect of structural rehabilitation works on habitat diversity. V.A. Poulin and Associates (1991) used the Brillouin index (Magurran 1988) applied to proportional areas of different flow types (pool, riffle, glide etc.) and did not include any tests of the statistical significance of changes in diversity. The results indicated an increase in diversity at two out of the three sites examined in this study. At the third site there was no change in habitat diversity. No explanation was given for these changes. Shields and Smith (1992) used the Shannon diversity index based on velocity and depth measurements across transects and assessed the significance of changes in this index using a two-tailed t-test for unpaired data. Unfortunately this test violated the requirement of the t-test that measurements are independent (Magurran 1988). The existence of spatial correlation in the measured data means that this test is not applicable to data collected along cross-sections. This study indicated that there was a decrease in habitat diversity following removal of LWD from South Fork Obion River. Van Zyll de Jong (1997) noted an increase in physical habitat diversity following structural rehabilitation but did not describe the method of calculating diversity. These three studies all suggest that structural elements in streams can enhance hydraulic diversity. However, no study has provided an adequate statistical test of the significance of their results.

Discussion

A number of studies included longitudinal invert profiles and cross-sections as part of the physical evaluation program. Surveys of the invert profile seem particularly well suited for assessing changes in bed topography and provide a basis for inferring changes in pool distribution and depth at low flows. Cross-section surveys appear to have been less useful, particularly in cases where major changes in bank-full channel geometry did not occur. Qualitative assessments of bed sediments were conducted in a number of studies although they contributed little to the studies' conclusions. The diversity of hydraulic conditions has been used to assess benefits of rehabilitation structures with higher diversity considered a desirable outcome. The justification for selecting this performance criterion is generally not provided. There is some variation in the method of calculating hydraulic diversity. A number of studies suggest that an increase in the availability of pool habitat is a desirable outcome based on the assumption that pool habitat availability limits the population of one or more fish species. Evidence to support this claim is frequently not provided. Some more sophisticated habitat modelling approaches have also been used. These approaches are only applicable to cases where the physical habitat characteristics of the target species are known and physical habitat availability limits the abundance of the species.

There has been a range of methods used to evaluate changes in physical habitat conditions. Changes in pool area and hydraulic diversity are the most common characteristics considered although the method of surveying and calculating these characteristics varies between studies. Only one study included a statistical test to assess the significance of changes in physical habitat conditions and in this case, the test was inappropriately applied. These studies consistently indicate that instream structures and LWD contribute to increases in pool area and enhance physical habitat diversity. However, these results must be interpreted with care given the lack of statistical testing.

3 PROJECT REACHES AND EVALUATION METHODOLOGY

3.1 The Catchment

The Broken River rises in the Great Dividing Range, and flows north across undulating land to join its major tributaries, Holland Creek and Moonee Creek. Although the main channel changes direction to the west to eventually discharge into the Goulburn River at Shepparton, flood flows continue north in Broken Creek which discharges to the Murray River in the basins' north-west (Department of Water Resources 1989a; Department of Water Resources 1989b). Ryans Creek flows north then west, joining Holland Creek approximately 10 km upstream of its junction with Broken River. Annual rainfall in the basin varies from 1400 mm high in the catchment, to between 400 and 700 mm across the alluvial plains. Pasture covers 69% of the catchment, intensive agriculture another 13%, leaving 18% with native vegetation.

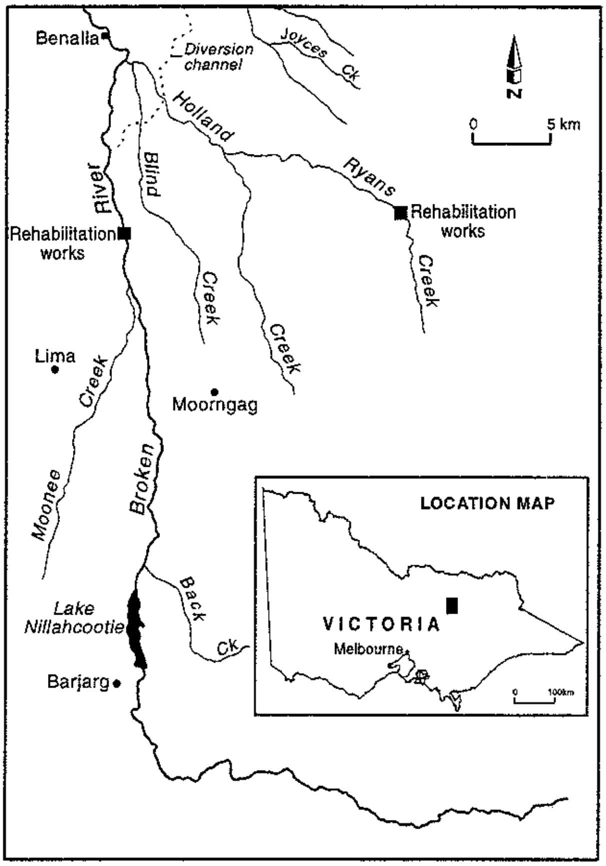

Figure 1: Location of project reaches

Approximately 100,000 ML of runoff from the catchment is harvested for irrigation and urban water supply. Lake Nillahcootie is a major irrigation storage on the Broken River with a capacity of 40,000 ML (Figure 1). A smaller storage, Loombah Weir, is situated on Upper Ryans Creek and provides water for the township of Benalla. Loombah Weir has a storage capacity of 678 ML (Australian National Committee on Large Dams 1990).

River management activities have been common throughout the basin. Holland, Five Mile and Moonee Creeks have been reported to suffer from eroding banks, sedimentation in the stream channel, and loss of riparian vegetation (Department of Water Resources 1989b). Bank erosion has been seen as a major problem along the Broken River, particularly the lower reaches. Sediment from Holland and Moonee Creek has been identified as causing degradation at downstream locations.

3.2 Project Reaches

The focus of this study are rehabilitation works undertaken in 1996 along a 300 m reach of Broken River and a 350 m reach of Ryans Creek (Figure 1). The Broken River reach is a low-gradient stream with a broad floodplain and a sand and gravel bed. Prior to rehabilitation works, stock access was permitted along both banks and there was evidence of bank erosion along the length of the reach. A gravel and sand point bar had developed in the middle section of the reach. The lack of mature vegetation on this bar and the presence of unvegetated sand deposits on natural channel levees suggest that bed material is mobile at flood flows and sand is carried as wash load.

Table 1: Characteristics of the Broken River and Ryans Creek reaches

	Broken River	*Ryans Creek*
Channel gradient	0.0012	0.006
Mean channel width (m)	20	10
Bed material	Sand and gravel	Cobble and sand

The Ryans Creek reach has a steeper gradient than the Broken River reach and a cobble bed. An extreme flood in 1993 caused an abrupt change in the morphology of Ryans Creek. Anecdotal reports suggest that flooding caused an enlargement of the channel and removal of riparian vegetation. Soon after this event, a uniform channel was excavated with the intention of assisting in the channel recovery process. In 1996 a 10 m wide stream flowed within a larger channel of approximately 50 m width. Vegetation was becoming established within the larger channel along the banks of the inner channel. Cattle access was possible at some points along the reach. High vertical exposed banks occurred at the upstream end of the reach and downstream of the reach. There was no large woody debris within the channel prior to rehabilitation works. A pool-riffle morphology is evident in base-line surveys.

3.3 Rehabilitation Works

Rehabilitation works were carried out in April and May 1996 to stabilise the channel and enhance physical habitat conditions at the two project reaches. Works at the Broken River reach included the placement of 8 logs (keyed into the bank), rip-rap along exposed banks, and placement of boulders on the stream bed (Figure 2). One log was placed across the channel, the remainder were attached to one bank and oriented downstream. Approximately eight boulders with a diameter of greater than 1 m were placed on the stream bed in two clusters of four. Boulders were aligned diagonally upstream of bank-attached logs.

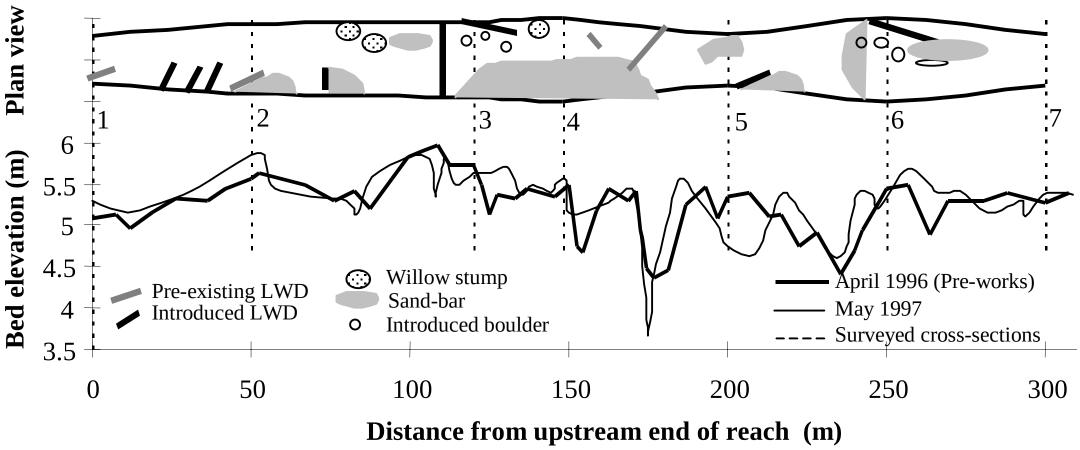

Figure 2: Plan view and longitudinal bed profile at the Broken Stream rehabilitation reach at David Friday's property (features and channel width on plan view diagram are not to scale)

Works at Ryans Creek included the placement of eight logs and boulders within the channel and the construction of two rock chutes (Figure 3). Downstream of the project reach a third rock chute was constructed and upstream of the project reach a number of additional logs were added to the channel. Rock chutes were constructed over existing riffles. One log extended across the width of the channel in a pool. Five others were attached to alternate banks and oriented downstream at a riffle, creating a "herring bone" configuration. The remaining two were placed in isolation along the channel and not attached to the bank. Rock boulders were mostly located in a cluster downstream of the log that spanned the channel. In addition to instream works, the two reaches were fenced to exclude stock and willows were removed from streambanks and replaced by native vegetation.

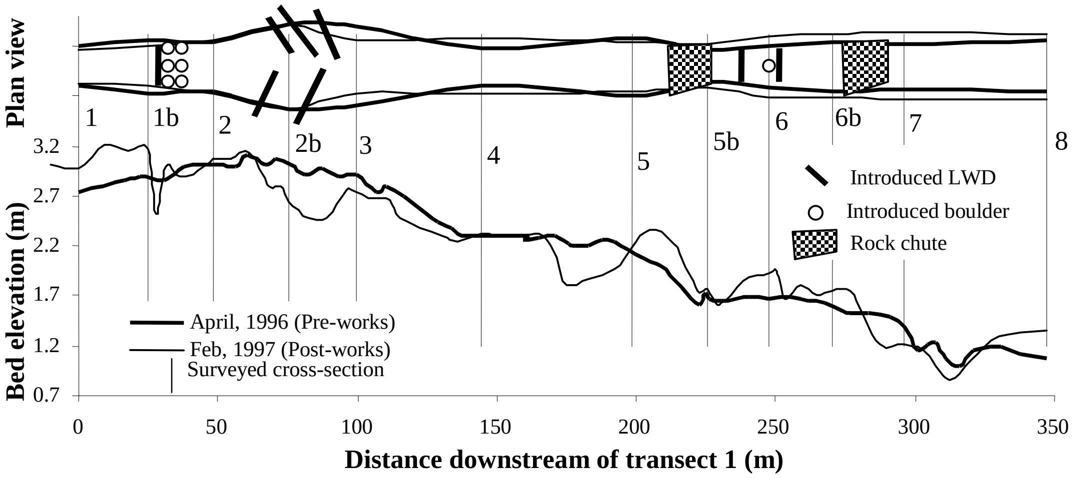

Figure 3: Plan view and longitudinal bed profile at the Ryans Creek rehabilitation reach (features and channel width on plan view diagram are not to scale)

3.4 Field Program

Rehabilitation works were carried out at the two project reaches in April and May, 1996. The reaches were surveyed in April 1996 prior to works. The Broken River reach was re-surveyed four times between February 1997 and June 1998 and the Ryans Creek reach was re-surveyed three times over this post-works period (Table 2). A longitudinal profile of the channel invert (ie. the lowest point of the channel cross-section) and water surface was surveyed during most of these field visits (Table 2 indicates exceptions). The longitudinal profiles were surveyed along the channel invert using a dumpy level and measuring tape. The distance between bed survey points was between 1 m and 10 m with points located at breaks in the slope of the bed. In retrospect, locating bed survey points at a regular interval would simplify the analysis of changes in bed topography and is recommended for future studies.

Seven and twelve cross-section transects were spaced along the Broken River and Ryans Creek reaches respectively. An additional four transects were located at 25 m spacing (ie. half way between in the initial transects) at the Ryans Creek reach in sections that were to be a focus of rehabilitation works (Figure 10). No claim is made of the representativeness of these cross-sections of conditions throughout the river. Rather, these cross-sections are intended to measure changes over the period of monitoring in the vicinity of the rehabilitation works.

Water depth, substrate type, and velocity (at 0.4 times the depth above the bed) were measured across each cross-section at intervals of 1.0 m in Broken River and 0.5 m in Ryans Creek. Each cross-section was located using survey pegs placed on both banks.

Table 2: Surveys conducted in Broken River and Ryans Creek

Broken River		**Ryans Creek**	
Flow (ML/d)	**Date**	**Flow (ML/d)**	**Date**
34	29 April 1996	26	16 April 1996
Works	*Undertaken*	*Works*	*Undertaken*
176	13 February 1997*	14	12 February 1997
233	23 April 1997*	8	22 April 1997*
48	22 May 1997	3	17 June 1998
36	18 June 1998		

* Reach surveys that did not include longitudinal bed and water surface profiles.

Additional longitudinal profiles were surveyed along large sections of Ryans Creek in February 1994, April 1996, and February 1997 by ID&A (Wayne Tennant, ID&A, pers. Comm., October 1998). These surveys followed the channel invert. Level measurements were taken every 50 m with some additional measurements at high and low points in the bed topography. Each survey was conducted along a different reach of the river (Figure 4) and with a different frequency of measurement points (Table 3).

Table 3: Timing, extent and resolution of invert profile surveys in Ryans Creek upstream of the Watchbox Creek confluence

Date	*Extent of survey (m)**	*Points /100m*
February 1994	0 to 13700	4.1
January 1996	3000 to 4500	11.8
July 1997	3500 to 13700	3.4

*Distances are measured along the channel upstream from the confluence with Watchbox Creek (refer to Figure 4)

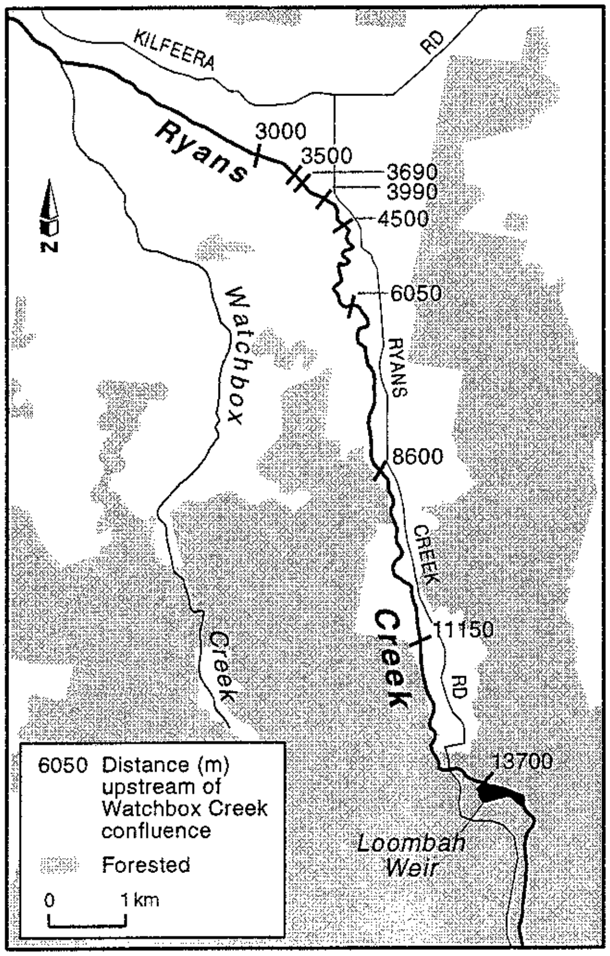

Figure 4: Location of surveys along Ryans Creek

3.5 Assessment of Environmental Impacts

Changes in channel morphology, flow capacity, and physical habitat conditions at the Broken River and Ryans Creek reaches are described in the following three chapters. Changes in channel morphology were assessed directly from longitudinal and cross-section surveys of the channel. Hydraulic modelling was used to estimate bank-full discharge and physical habitat conditions over a range of low to moderate discharges. The parameters calculated using field survey and modelled data were selected from those used in the literature. In most cases, statistical methods have been used to test the significance of observed changes in physical parameters. The influence of model uncertainty has not been considered as no estimate of model error is available.

4 CHANNEL MORPHOLOGY

Although the rehabilitation works carried out in the two reaches did not include direct manipulation of channel morphology, the instream works resulted in channel changes by influencing sediment movement. These secondary morphological effects could influence stream biota by altering the pattern of hydraulic conditions and substrate within the project reaches. Morphological change can also affect channel capacity and flooding through changes in cross-section area, shape and flow resistance. This chapter provides a description of the morphological impact of the rehabilitation works based on descriptions of bank-full channel geometry, the longitudinal bed profile, and bed surface sediments. The effects of these changes on flooding and physical habitat conditions are discussed in chapters 5 and 6 respectively.

4.1 Bank-full Channel Cross-Section Geometry

The mean shape and size of the bank-full channel influences channel flow capacity. Irregularities in channel geometry may also enhance flow resistance by creating local flow accelerations. Many lowland rivers, particularly in urban areas, have been straightened and re-shaped to a uniform cross-section to enhance their flow capacity and reduce upstream flooding. However, it has been suggested that longitudinal variability in channel cross-section geometry is responsible for the diversity of hydraulic habitat conditions in rivers (Hansen et al. 1996; Western et al. 1997). There is concern that a loss of channel variability through flood mitigation schemes reduces hydraulic habitat diversity and adversely affects aquatic communities. For this reason, many channel rehabilitation works include enhancement of channel irregularities through measures such as the reintroduction of large woody debris and construction of riffles. It is important to note that the contribution of channel variability to hydraulic habitat diversity has not yet been demonstrated. Hydraulic variability, however defined, is likely to be scale-dependant and the relationship between hydraulic variability at different scales may not be a simple one. Furthermore, changes in bank-full channel geometry may have a relatively minor effect on low flow hydraulic conditions.

The bank-full channel geometry can be characterised by the bank-full cross-sectional area (A), surface width (W), wetted perimeter (P), hydraulic radius (A/W) maximum depth (D), width to depth ratio (W/D) and a shape parameter ($W \times D / A$) suggested by Western et al. (1997). The ranges in these parameters provide a practical method of characterising longitudinal variability in channel geometry (Western et al. 1997). The mean and range (maximum and minimum values) of these parameters were estimated for each reach using cross-section surveys. Results are presented in Figures 5 to 7. The bank-full stage was identified at the Broken River reach as the level of the surrounding floodplain. The bank-full stage was not clearly defined at the Ryans Creek reach because the channel is incised. To overcome this difficulty, a water surface profile was modelled for a flow of 520 ML/d for the pre-rehabilitation channel. The stage at this discharge was used as the bank-full level for the morphological analysis.

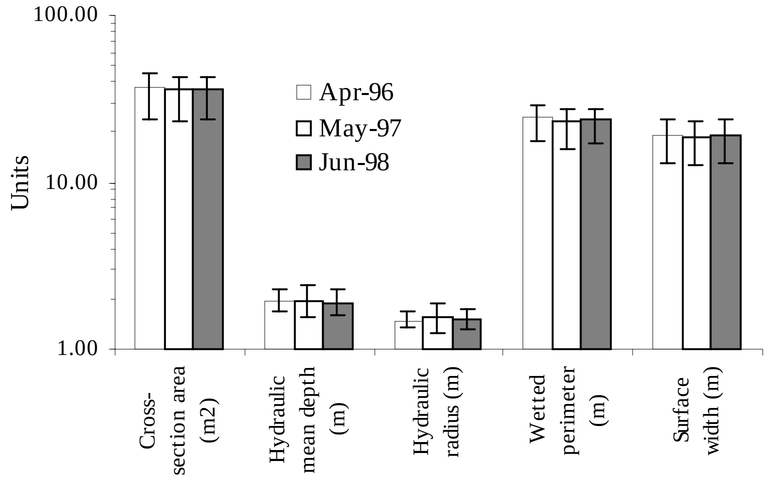

Figure 5: Mean and range of bank-full channel cross-section area and dimensions at the Broken Stream rehabilitation reach

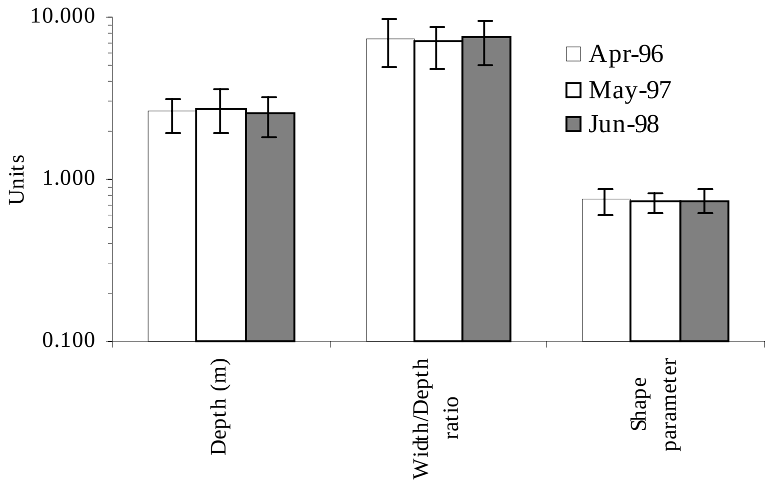

Figure 6: Mean and range of bank-full channel cross-section depth and shape parameters at the Broken Stream rehabilitation reach

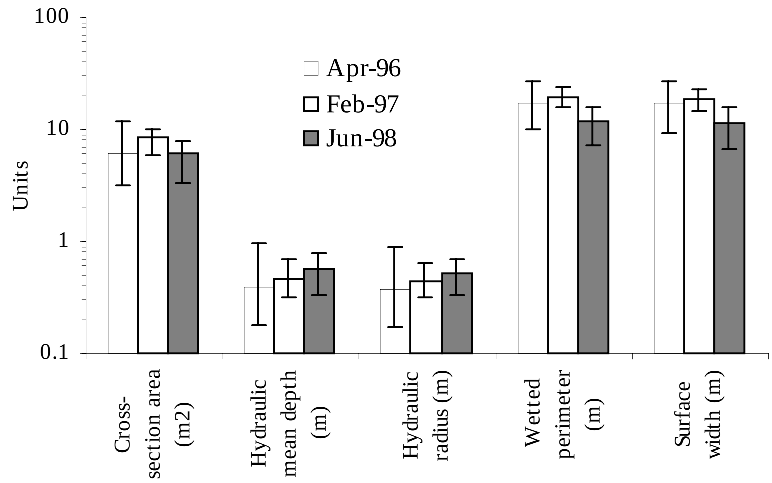

Figure 7: Mean and range of bank-full channel cross-section area and dimensions at the Ryans Creek Rehabilitation reach

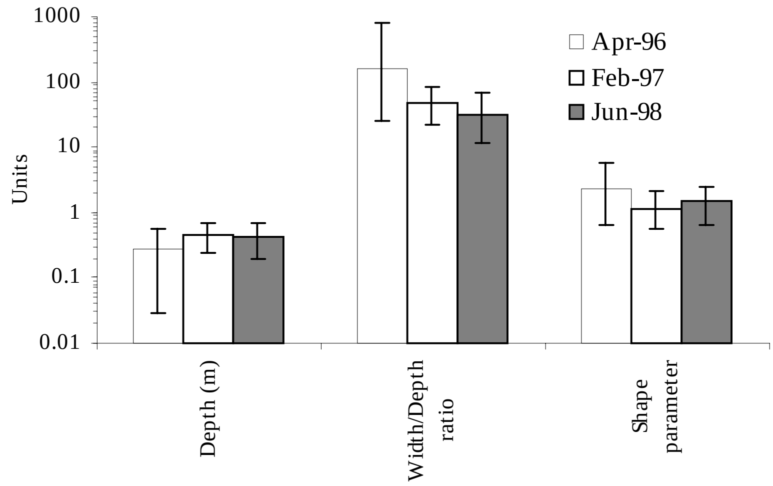

Figure 8: Mean and range of bank-full channel cross-section depth and shape parameters at the Ryans Creek Rehabilitation reach

The rehabilitation works at the Broken River reach did not have any measurable effect on mean cross-section geometry. At the Ryans Creek reach, changes in mean channel geometry are not statistical significant (paired t-test, p=0.05, this test is described in Appendix I). A test of equality of two variances described by Snedecor and Cochran (1989) (also described in Appendix I) was used to assess changes in channel variability at Ryans Creek. There was a significant (p=0.05) reduction in the variability of the hydraulic radius and mean depth between 1996 and 1997 and in the variability of the wetted perimeter between 1996 and 1998. There was no significant change in channel variability between 1997 and 1998. The reduction in channel variability at Ryans Creek between pre- and post-rehabilitation works surveys was the only significant change in bank-full channel cross-section geometry detected by this study.

4.2 Invert Profile

Longitudinal variability in bed topography influences hydraulic habitat conditions, particularly at low flows. Topographic high points generally form riffle crests with an upstream backwater profile forming a pool and a steeper, shallower region downstream of the riffle crest. Variability in bed topography is not well described by the bank-full cross-section geometry. For this reason, bed topography is described separately based on a longitudinal profile along the channel invert. Invert profile surveys for the rehabilitation reaches are shown in Figure 9 and Figure 10. Note that these diagrams show a detrended profile. To generate these profiles, a linear regression is fitted to the invert profiles (shown in Figure 2 and Figure 3). The detrended profiles show the residual or difference between the invert profile and the linear regression. The profiles are detrended so that the oscillations in the bed topography of streams with different mean bed gradient can be compared.

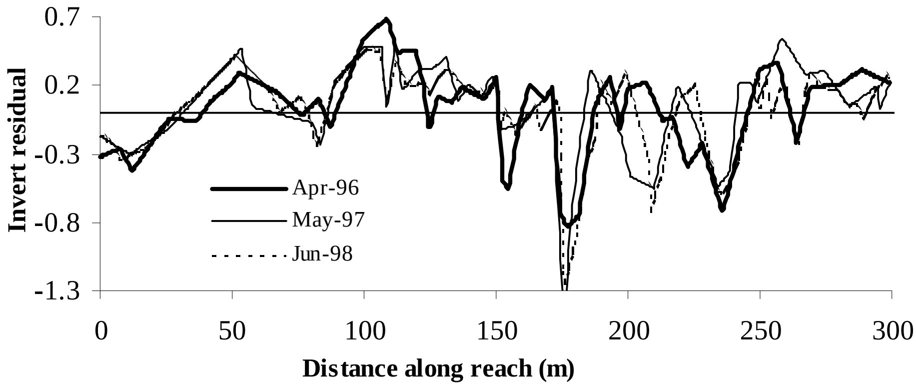

Figure 9: Detrended invert profile along the Broken River reach

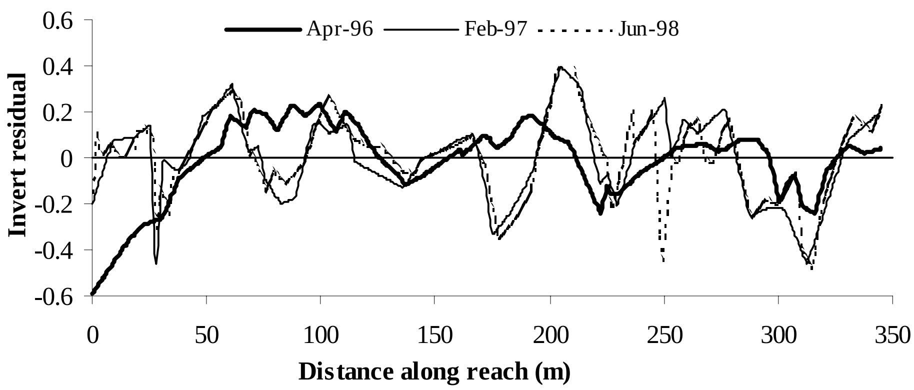

Figure 10: Detrended invert profile along the Ryans Creek reach

Local changes in the Broken River invert profile occurred between surveys, but with no general pattern to this change (Figure 9). There appears to have been bed scour at some sections where large woody debris (LWD) was added (ie. 110 m, 120 m and 210 m) and scour pools were apparent at pre-existing items of LWD (ie. 155 m and 175 m). Four LWD items introduced into the channel between 20 m and 80 m did not result in scour of the invert. This may be due to the location of these items in a pool and at a greater distance above the bed than other LWD. Boulders were added to the channel at two locations (120 m and 250 m). There has been enhanced deposition of sediments downstream of both of these boulder clusters since the works were carried out.

Figure 11 shows the standard deviation in the detrended invert profile for each survey and suggests that there was no change in topographic variability of the bed over the period of monitoring. The standard deviation provides a measure of the amplitude of oscillations in bed topography but will not indicate changes in the wavelength (or frequency) of these oscillations. Richards (1976) uses lag correlation to analyze bed oscillations associated with pool and riffle bedform. Lag correlation is the correlation coefficient calculated for all pairs of points separated by a particular “lag” distance. Generally, lag correlation decreases with increasing lag distance. The relation between lag correlation and lag distance (often referred to as a correlogram) for the detrended bed profiles describes the continuity or wavelength of bed oscillations. Lag correlation coefficients were calculated for a range of lag distances (up to 50 m) to investigate changes in continuity of the bed profiles along the two reaches (Figure 12). If the frequency of oscillations decreased (ie, pools and riffles become longer) then lag correlation coefficients should increase indicating greater longitudinal continuity in the bed topography. Figure 12 suggests that there has been no real change in the continuity of the bed topography of the Broken River reach since rehabilitation works.

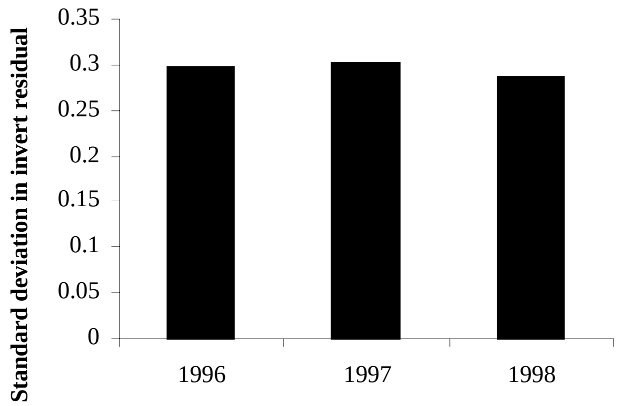

Figure 11: Standard deviation of detrended invert profile along the Broken River reach

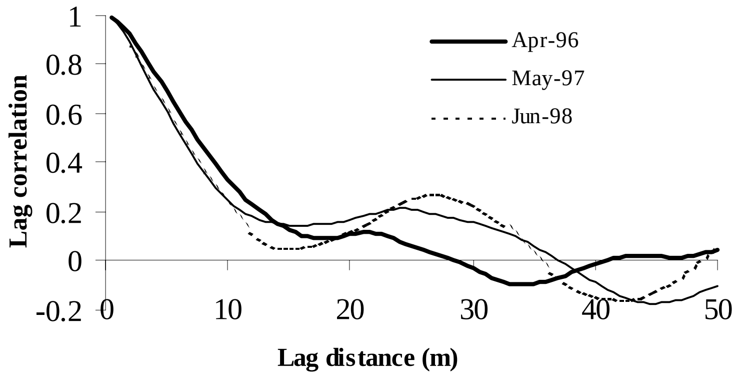

Figure 12: Correlogram for detrended invert profile in the Broken River reach

Invert profile surveys along the Ryans Creek rehabilitation reach indicated substantial changes in bed topography following rehabilitation works (Figure 10). Sediment accumulation at the upstream end of the reach (0 m to 20 m) was probably the result of scour around a large multi-stem LWD item placed in the channel upstream of the first transect. A scour pool developed below and downstream of a channel spanning item of LWD at 25 m. Prior to rehabilitation works, a riffle was observed at 80 m to 120 m. Five LWD items were placed on this riffle attached to each bank and oriented downstream. Scour of the riffle following rehabilitation works appeared to be the result of locally increased velocities through the flow constriction created by these LWD items. There was no change in bed topography between 120 m and 170 m, a section of the reach along which no structural works occurred. A loosely packed boulder riffle was constructed between 210 m to 220 m locally raising the elevation of the bed. A pool developed upstream of this riffle within a year of its construction. This pool is located on the outside of a mild bend in the channel and may have resulted from the secondary currents through the bend at higher flows. A second riffle was constructed at 280 m to 290 m and appeared to have resulted in the enlargement of a scour pool downstream of the riffle. Enhanced deposition at 330 m to 350 m was probably the result of a backwater from the riffle constructed downstream the rehabilitation reach.

Despite the substantial changes in bed topography, the amplitude of oscillations were unaffected by the rehabilitation works (Figure 13). However, there has been a decrease in continuity of the bed topography (Figure 14) suggesting greater frequency of bed oscillations. This is indicated in Figure 10 by an increase in the number of scour pools within the reach. A systematic change in the topography of the bed along the Ryans Creek reach has resulted in a greater frequency of bed oscillations.

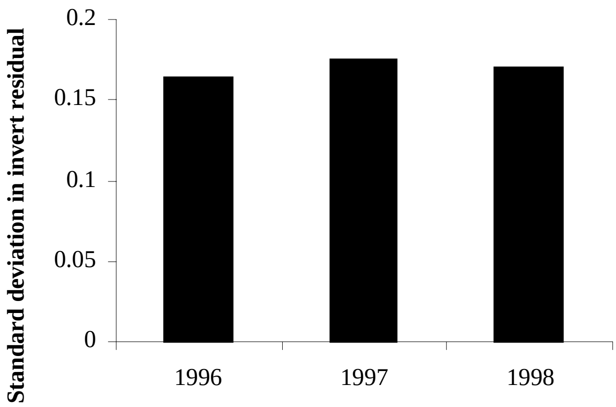

Figure 13: Standard deviation of detrended invert profile along the Ryans Creek reach

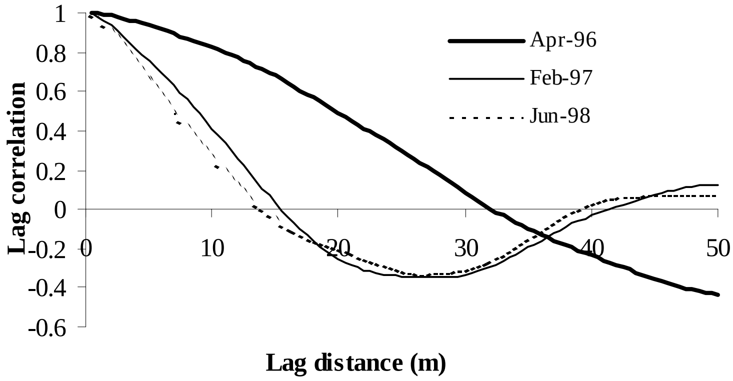

Figure 14: Correlogram for detrended invert profile in the Ryans Creek reach

It is possible that the changes in bed topography observed at the Ryans Creek reach were a response to channel change during the 1993 flood. To test this possibility, changes in bed topography at the rehabilitation reach were compared with changes along the length of Ryans Creek over the same period. The lag correlations for lag distances of 25 m, 50 m, 75 m, 100 m, 125 m and 150 m were calculated for invert profile surveys conducted in February 1994 and January 1996 along Ryans Creek between Loombah weir and 3.5 km upstream of the Watchbox Creek confluence (Figure 4). These surveys indicated a relatively small increase in continuity over this period (Figure 15) compared to the decrease in continuity observed at the rehabilitation reach. To further confirm the general trend toward increasing continuity, these surveys were broken into four sub-reaches. The 50 m and 100 m lag correlation for each sub-reach (Figure 16) show that lag correlation for all four reaches generally increased between February 1994 and January 1997. The reduction in continuity at the rehabilitation reach is in opposition to a general trend of increasing continuity along the creek. Based on this evidence it is concluded that channel changes observed at the Ryans Creek reach were the result of rehabilitation works and not a response to channel change during the 1993 flood.

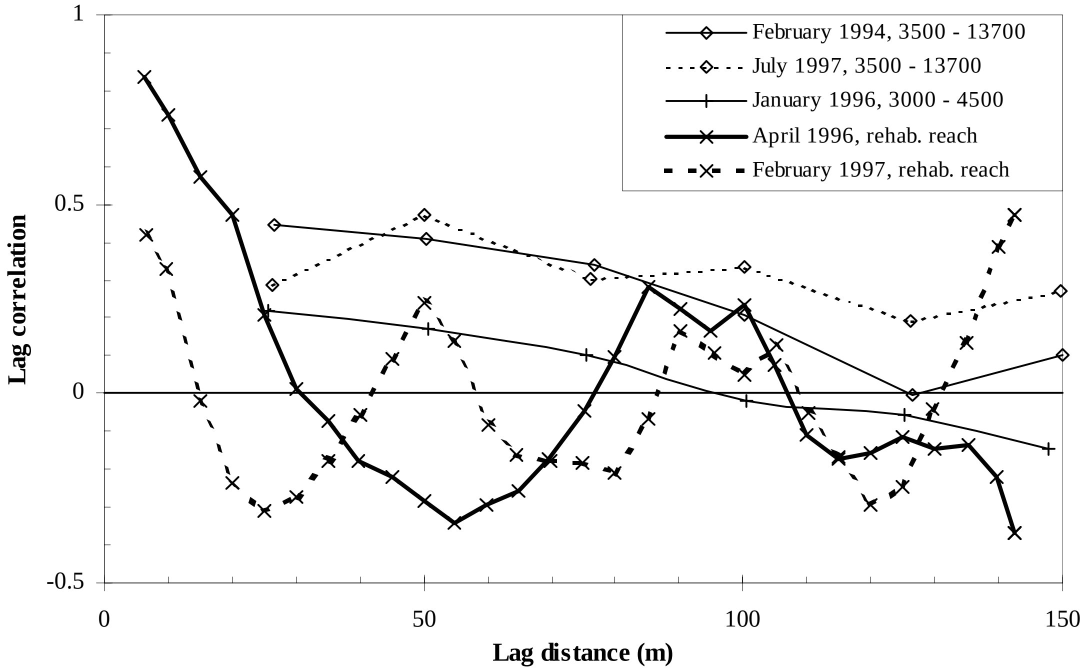

Figure 15: Lag correlations based on invert profile surveys in Ryans Creek

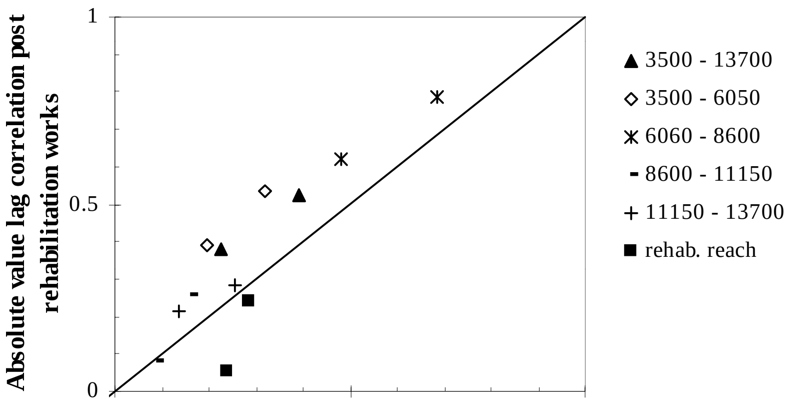

Figure 16: The 50 m and 100 m lag correlation coefficients for reaches of Ryans Creek before and after rehabilitation works in April 1996

4.3 Surface Sediments

Surface sediments within stream channels consist of inorganic material and organic detritus on the channel bed and banks. Stream substrate is often highly heterogeneous (Allan 1995) and has an important influence on the distribution of aquatic organisms. The size and packing of inorganic sediments influence sediment stability and may have implications for biota attached to the sediments. Other factors that are thought to be of biological importance are the porosity and surface texture of particles.

Surface sediments were visually classified at regular intervals across transects as

- aquatic plants,
- clay,
- sand,
- cobbles, or
- a matrix of cobbles and finer material.

The classification of aquatic plants was used when vegetation substantially covered the inorganic sediments. The author carried out classifications on every occasion to minimise the confounding effects associated with subjective assessments by different personnel. The proportion of the stream bed covered with each of the five types of substrate types was calculated for each survey (Figure 17 and Figure 18). There was no consistent change in substrate composition following rehabilitation works at the Broken River reach. Surveys in April 1996 and June 1998 show almost identical percentages of the different substrate types.

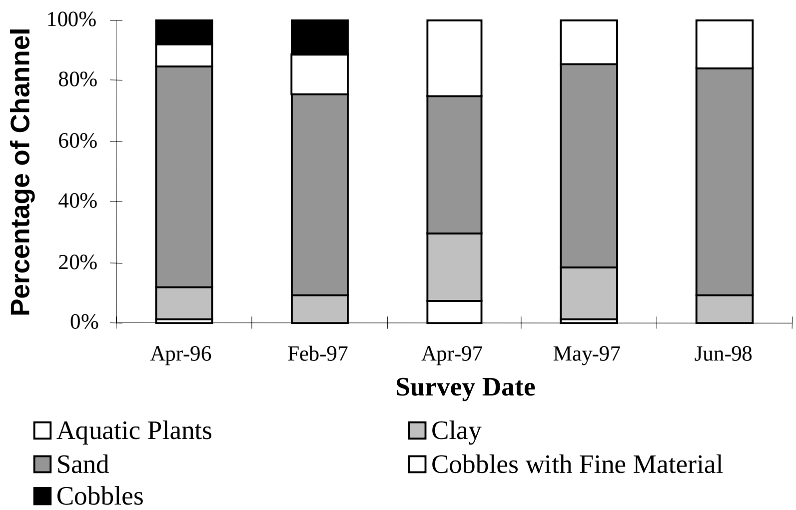

Figure 17: Percentage area of different substrate types along the Broken River reach

At the Ryans Creek reach, changes in substrate composition were statistically significant (according to the χ^2 test, p=0.05, this test is described in Appendix I) between the April 1996 and February 1997 surveys and between the April 1997 and June 1998 surveys. No change was detected between February 1997 and April 1997. The area of cobble substrate reduced over the three years of this project. The area of cobble and fine material matrix increased between April 1996 and February 1997. The extent of aquatic vegetation decreased from April 1996 to February 1997 and increased between April 1997 and June 1998. Given that changes were on-going at this reach and the lack of any data from control reaches, it is possible that observed changes in substrate composition are influenced by factors other than rehabilitation works. For example, the increases in aquatic vegetation in June 1998 may be the result of annual weather patterns.

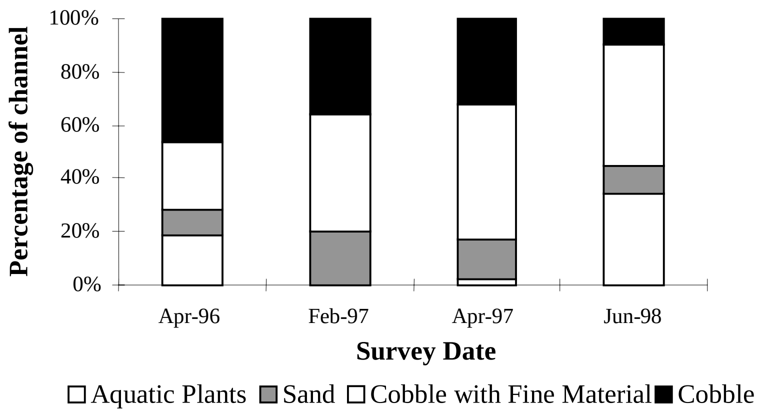

Figure 18: Percentage area of different substrate types along the Ryans Creek reach

4.4 Discussion

No change in morphology or substrate was detected at the Broken River reach other than local scour at items of LWD and accumulation of sediments downstream of boulder clusters. However, this redistribution of sediments did not influence the variability or continuity of the bed topography. In contrast, changes in variability of the cross-section geometry and continuity of bed topography were detected at the Ryans Creek reach. The relative severity of the morphological impact of works at Ryans Creek may have been due to the larger scale of works relative to the size of the channel. Mean bank-full cross-section area in Ryans Creek is 6 m^2 compared to 36 m^2 in Broken River. A similar number of LWD items and isolated boulders were added to both channels and in addition to these works, two riffles were constructed at Ryans Creek.

At the Broken River reach, sediments accumulated downstream of the two boulder clusters. With the exception of a scour pool in the middle of the Ryans Creek reach, bed scour occurred at and downstream of LWD located in shallower section of the channel and downstream of rock chutes. A decrease in continuity of the bed profile was detected at the rehabilitation reach of Ryans Creek, which was opposite to the general trend of increased continuity along Ryans Creek over the period of rehabilitation. The available evidence supports the claim that morphological changes at the Ryans Creek reach were primarily the result of rehabilitation works. However, changes in surface sediment composition at this reach may have been affected by other factors such as annual weather patterns.

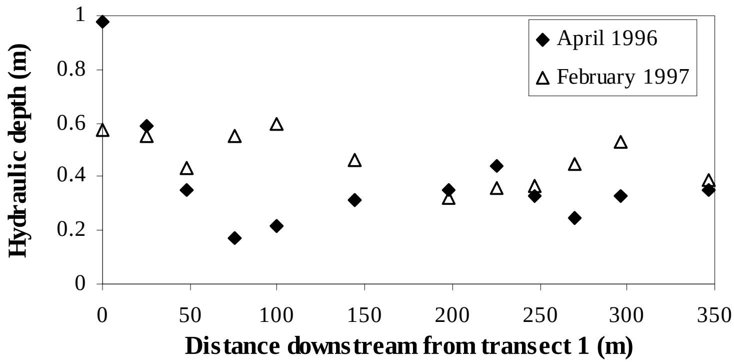

Figure 19: Hydraulic depth at bank-full flow along the Ryans Creek reach

It is often suggested that addition of isolated structures into a channel increases channel variability as a result of local scour around these structures. However, observations at Ryans Creek show a reduction in channel variability following structural rehabilitation. Channel changes were the result of sediment deposition within pools, or scour of riffles. In particular, infilling of a pool at transect 1 and erosion of riffles at transects 2b and 6b have resulted in less variability in cross-section depth (Figure 19). It would appear from these observations that installation of instream structures can reduce longitudinal variability in cross-section shape. A possible explanation for this is that energy dissipated through turbulance around the installed structures is no longer available for sediment transport and the formation of a large-scale bedform. However, hydrodynamic forces around these structures have resulted in the development of local scour and deposition. Prior to rehabilitation works, the process leading to bed scour and deposition were pool-riffle development. Since rehabilitation works, scour and deposition associated with the instream structures appears to be the dominant process creating variations in bed topography. As a result of the works, the amplitude of large-scale topographical variations in the channel bed was reduced. Large-scale oscillations were replaced by smaller-scale oscillations associated with instream structures. This may explain the observed reduction in channel variability at Ryans Creek.

5 FLOODING

The discharge that can be carried within a lowland channel directly affects the frequency and duration of flooding. In the past many lowland river channels have been modified to increase their capacity, and thereby reduce the risk of flooding. There is a concern that rehabilitation works including the reintroduction of large woody debris will reduce channel capacity by enhancing flow resistance within the channel. In this chapter, the hydraulic impact of rehabilitation works in Ryans Creek and Broken River is assessed to identify any contribution to flooding. The Ryans Creek reach is incised and flooding is unlikely to be a management issue. However, in the interests of developing knowledge that may be applied elsewhere, the effect of works on flow resistance at this site has been considered.

5.1 Hydraulic Modelling

Flow capacity of the channel along the two project reaches was estimated using the Darcy-Weisbach equation, which gives discharge as

$$Q = A\sqrt{\frac{8gRs_f}{f}}$$

where, A is the cross-section area, R is the hydraulic radius, s_f is the average energy gradient, g is acceleration due to gravity, and f is a friction factor. The average energy gradient over the length of the reach was assumed to be unaffected by rehabilitation works. Changes in A and R associated with rehabilitation were calculated directly as the average values for cross-section surveys conducted before and after rehabilitation. In Ryans Creek, a suitable bank-full stage could not be estimated from cross-section geometry due to channel incision. To overcome this difficulty, a linear regression fitted to the water surface profile modelled for a discharge of 520 ML/d (prior to rehabilitation works) was used as a hypothetical bank-full stage. Although arbitrary, it is argued that this approach is satisfactory for comparison of pre- and post-regulation channel capacity.

The friction factor f, at bank-full was calculated using the logarithmic function of relative roughness given by Keulegan (1938) as

$$\frac{1}{\sqrt{f}} = 2\log_{10}\frac{R}{k}.$$

The average channel roughness k, was determined by calibrated using water surface profiles surveyed at discharges less than bankfull. In order to estimate channel capacity it was necessary to assume that the roughness parameter was invariant with discharge, as no method is available to estimate changes in roughness with discharge. A detailed study including surveys during flood events is required to test the validity of this assumption.

5.2 Changes in Channel Capacity

This analysis indicated that the capacity of the channel at both rehabilitation reaches increased following rehabilitation works (Table 4). At the Broken River reach, the increase in channel capacity was associated with a reduction in the calibrated friction factor rather than changes in channel cross-section shape. The overall change in channel capacity was small and unlikely to be significant. Calibrated roughness values increased substantially in Ryans Creek. However the effect of this on channel capacity was offset by an increase in channel size.

Table 4: Data used to estimate percentage change in channel capacity in Broken River and Ryans Creek following rehabilitation

	1996	1997	1998
BROKEN RIVER			
Average cross-section area (m^2)	36.6	36.0	35.9
Average hydraulic radius (m)	1.95	1.94	1.90
Average calibrated roughness parameter	0.084	0.070	0.062
Friction factor	0.13	0.12	0.11
Percentage increase in channel capacity (relative to 1996 values)		**4%**	**5%**
RYANS CREEK			
Cross-section area (m^2)	6.00	8.50	6.09
Hydraulic radius (m)	0.37	0.44	0.52
Calibrated roughness parameter	0.015	0.047	0.062
Friction factor	0.60	0.72	0.74
Percentage increase in channel capacity (relative to 1996 values)		**41%**	**9%**

5.3 Discussion

Instream rehabilitation works did not reduce the flow capacity of the two reaches. At the Broken River reach, this appeared to be because flow resistance introduced by the structural works was small relative to total resistance for the channel. In total, eight logs were added to a 300 m long channel. If the LWD items have an average volume of 5 m^3, the volume of introduced LWD was less than 0.5% of the total volume of the channel. The maximum blockage ratio created by any introduced item of LWD was approximately 0.15 (area of LWD item = 5 m^2, channel cross-section = 36 m^2). Average Froude number for the channel at bank-full flow were 0.27. Using the method described by Gippel et al. (1996) the maximum afflux induced by the introduced LWD was estimated as 0.1 m. Note that this is the maximum increase in stage, elsewhere in the channel stage would have been less affected by rehabilitation works. This relatively minor increase in stage at bank-full flow supports modelling results, showing no major change in average capacity of the Broken River channel following rehabilitation.

There was a consistent increase in the bank-full friction factor for the Ryans Creek channel from 1996 levels shown by surveys in 1997 and 1998. However, both the average cross-section dimensions and channel roughness changed between 1997 and 1998. Despite these changes, bank-full channel capacity modelled for both 1997 and 1998 was greater than that modelled for the pre-rehabilitation works channel. The primary reason for this increased channel capacity was an increase in average cross-section dimensions. The model of Gippel at al. (1996) for estimating changes in stage as a result of introducing LWD was not applicable to the Ryans Creek reach because the model does not represent the significant morphological response of the channel. Because of this limitation, the model predicted substantial local increases in flood stage associated with high blockage ratios at introduced LWD. In reality, increases in channel dimensions offset the effects of the initially, high blockage ratios.

6 PHYSICAL HABITAT CONDITIONS

Flow velocity, depth and associated hydrodynamic forces are widely considered to be key factors influencing the distribution of fish, invertebrate, and other lotic species (Allan 1995; Koehn and O'Connor 1990). The spatial distribution of velocity, depth and substrate type is often thought to define the distribution of habitats within a stream. A stream reach with predominantly shallow, fast flowing water would be expected to have a different fauna from one with deep, slow flowing water. Some species are thought to have a preference for a particular range of hydraulic conditions. Changes to hydraulic conditions can effect the availability of habitat, abundance of aquatic species and composition of aquatic communities. In this chapter, changes in physical habitat conditions at the two reaches are discussed.

6.1 Hydraulic Distributions

The approach used in this study for analysing changed in velocity and depth distributions was adopted from Gorman and Karr (1978). This approach has also been used by Schlosser (1982) and Shields and Smith (1992). Velocity and depth measurements were grouped into ranges (Table 5). The proportion of the channel in each range is used as a description of the physical habitat conditions for the reach.

Table 5: Hydraulic ranges used by Gorman and Karr (1978)

Depth		**Velocity**	
Range (m)	Description	Range (m/s)	Description
<0.05	Very shallow	<0.05	Very slow
0.05-0.2	Shallow	0.05-0.2	Slow
0.2-0.5	Moderate	0.2-0.4	Moderate
>0.5	Deep	0.4-1	Fast
		>1	Torrent

Velocity and depth surveys were carried out at different discharges. Variations in hydraulic conditions between surveys may have been the result of rehabilitation works or changes in discharge between the times of survey. To overcome this difficulty, a model was used to estimate hydraulic conditions at the same discharge for each of the surveys (Figure 20, Figure 21, Figure 23, and Figure 24). The model used a gradually varied flow, backwater procedure to estimate water surface profiles and a conveyance procedure to distribute flow across the channel (Henderson 1966). Roughness values for each cell across the channel were calibrated based on surveyed velocity and depths. Changes in flow resistance with stage were represented using the Keulegan's (1938) logarithmic function (given in Section 5.1).

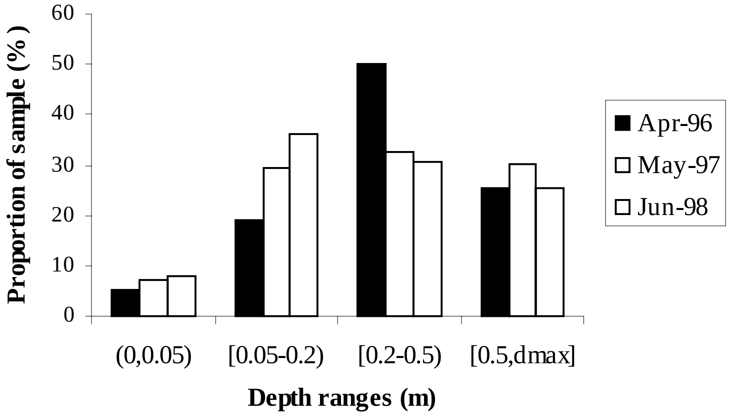

Figure 20: Depth distribution in Broken River at 34 ML/d

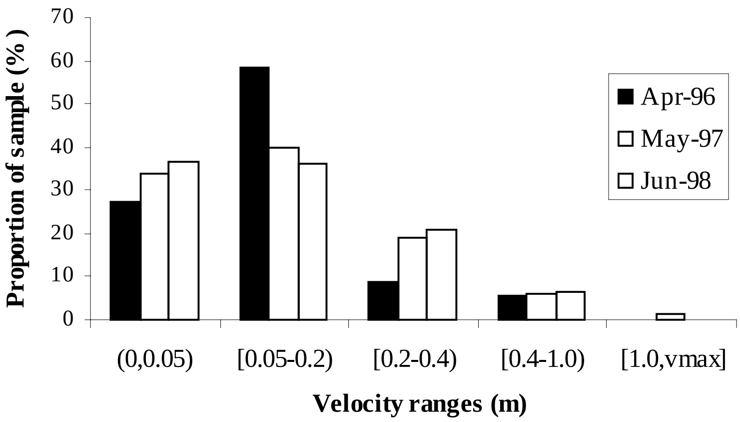

Figure 21: Velocity distribution in Broken River at 34 ML/d

Depth and velocity distributions in the Broken River appear to have changed following rehabilitation works. The area of channel with moderate depths and slow flowing water has decreased whilst the area of shallow and moderate flowing water increased. The area of deep and very shallow water was unaffected by the works as was the area of channel with fast and very slow water. The works appear to have mostly influenced the mid-range of the velocity and depth distributions.

The greatest changes in velocity distributions occurred at cross-sections 3, 4, 6, and 7 (Figure 22). These sections are at, or immediately downstream of the location of works along the reach. Velocity profiles at cross-sections 4, 6, and 7 show an increase in velocities. There was only a slight decrease in velocities at cross-section 3. It is not surprising that an increase in velocity accompanied a decrease in depth.

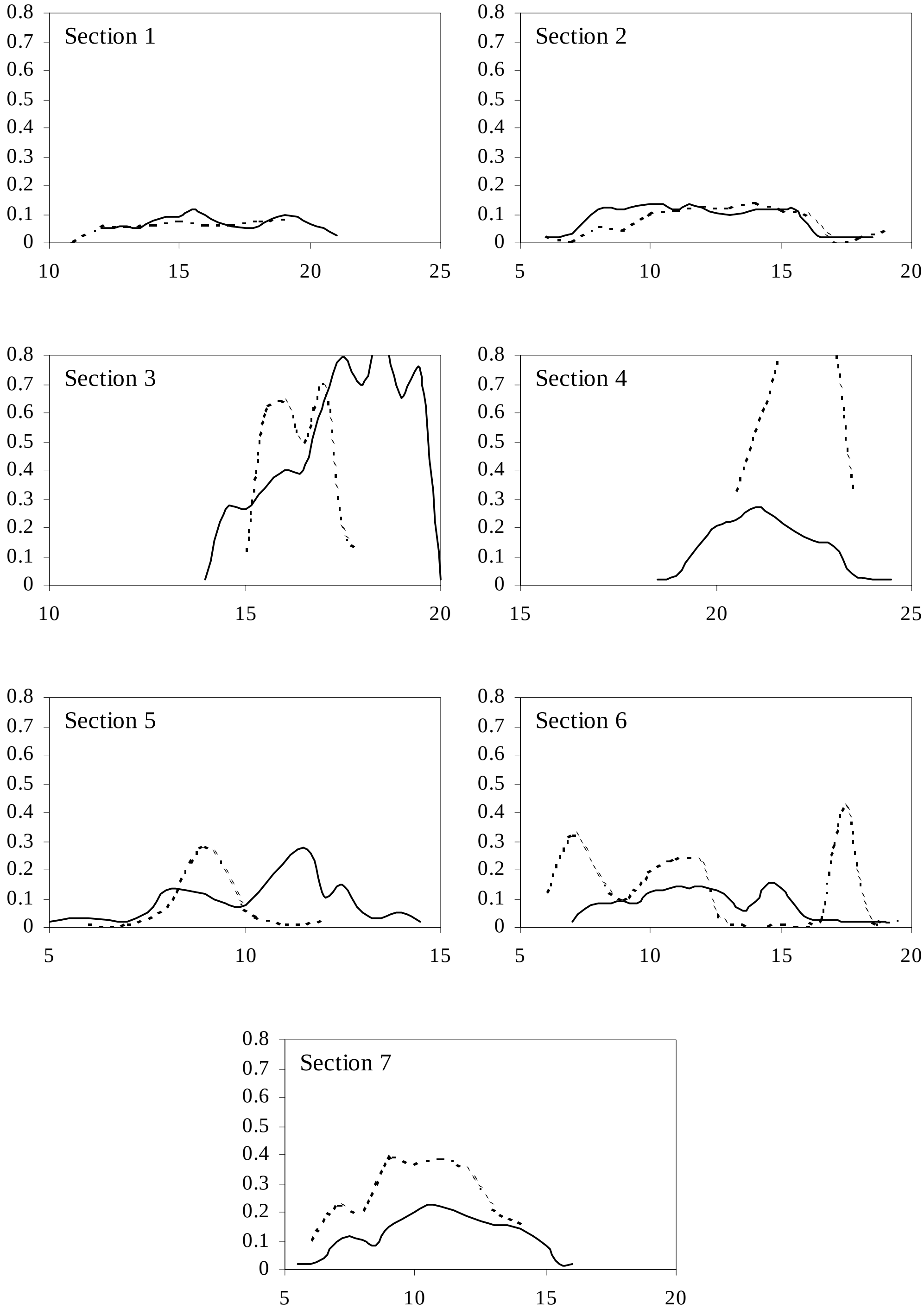

Figure 22: Cross-section velocity profiles in Broken River at 34 ML/d (the profile shown by a solid line is based on observations in April 1996 prior to rehabilitation works, the profile shown by a dashed line is modelled using data surveyed in May 1997 after rehabilitation works)

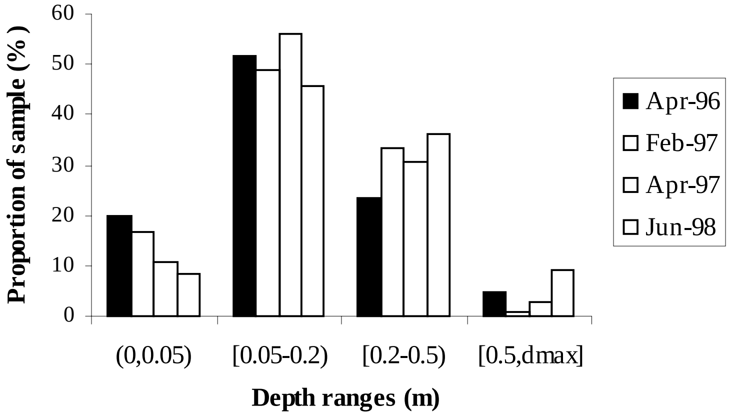

Figure 23: Depth distribution in Ryans Creek at 26 ML/d

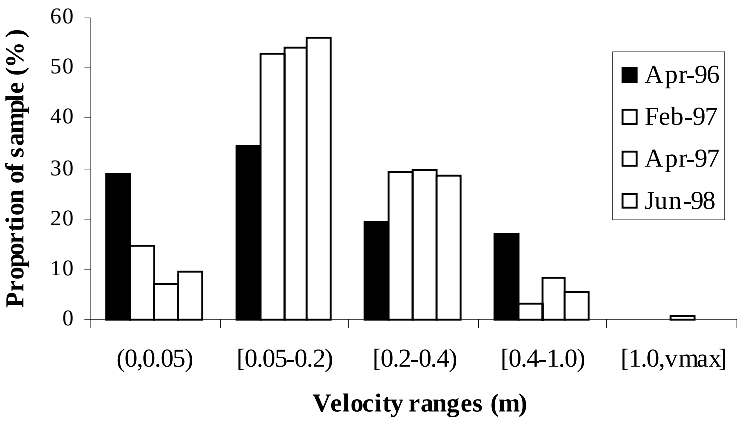

Figure 24: Velocity distribution in Ryans Creek at 26 ML/d

Changes in the depth distribution at Ryans Creek were relatively minor (Figure 23). There may have been a slight decrease in the area of shallower water and increases in moderate and deep water. There was a more substantial change in the velocity distribution at Ryans Creek, following rehabilitation works (Figure 24). The areas of very slow and fast water reduced following works and areas of slow and moderate flow increased.

Increases in velocity occurred at cross-section 1, 1b, and 5b (Figure 25). Increases at cross-sections 1 and 1b appeared to be the result of shallower water resulting from deposition of sediments scoured from below upstream items of LWD. Velocities increased at cross-section 5b because of the increased gradient created by the riffle constructed at this section. There was a reduction in velocity at all other cross-sections except cross-section 2. A reduction in velocity at cross-sections 2b, 3 and 4 were probably the result of scour associated the "herring-bone" configuration of LWD items placed on a pre-existing riffle. Reductions in velocity at cross-sections 5, 6, 6b, 7, and 8 may have been the result of backwater effects upstream of the constructed riffles.

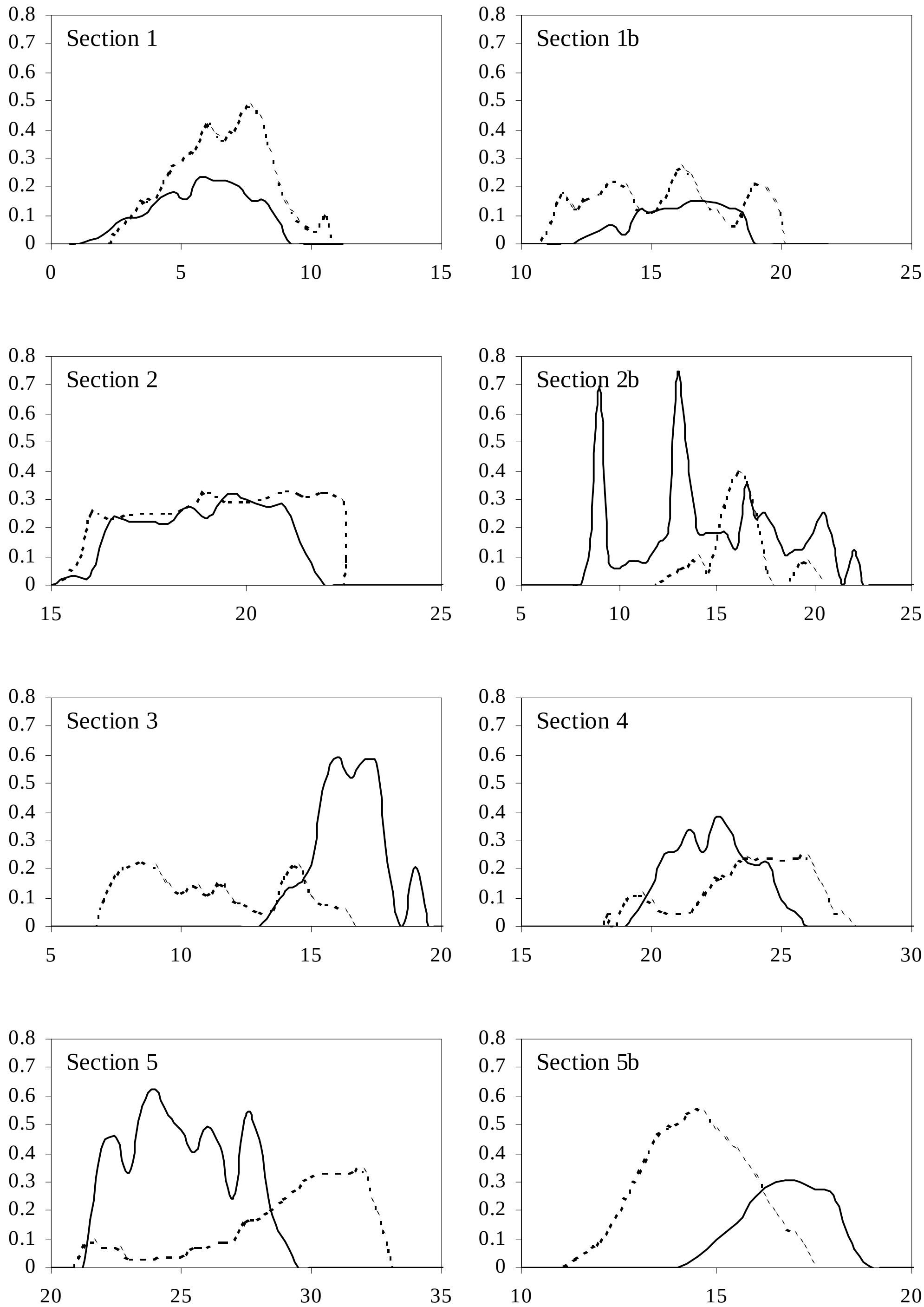

Figure 25 continued on next page /…

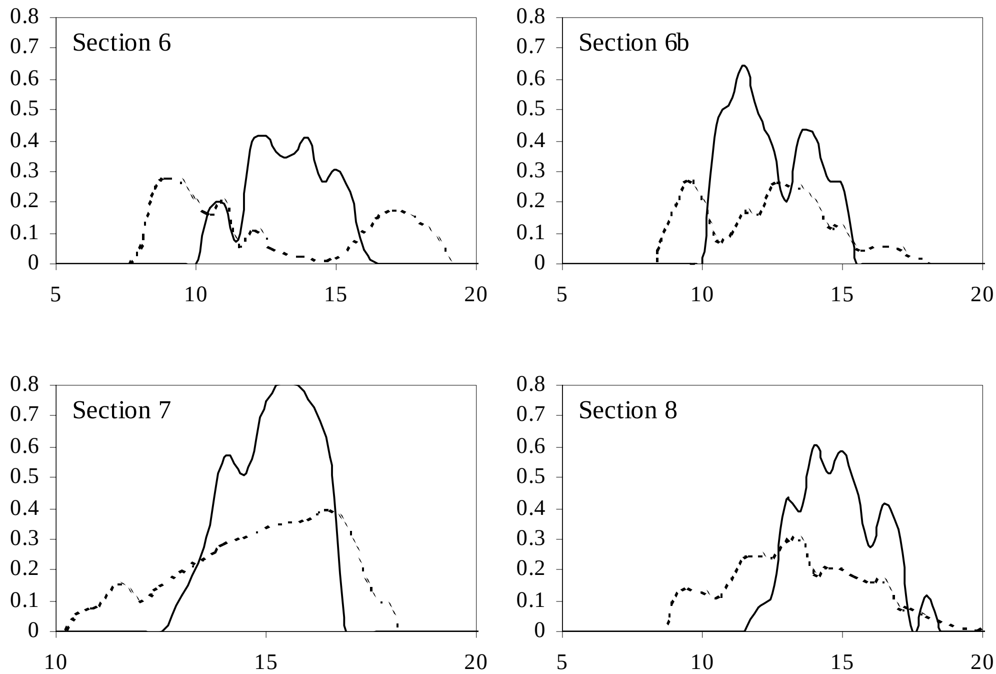

Figure 25: Cross-section velocity profiles in Ryans Creek at 26 ML/d (the profile shown by a solid line is based on observations in April 1996 prior to rehabilitation works, the profile shown by a dashed line is modelled using data surveyed in May 1997 after rehabilitation works)

6.2 Physical Habitat Diversity

It is widely claimed that increased physical or hydraulic diversity will result in greater species diversity in streams. Indeed the motivation for many rehabilitation designs is the enhancement of physical habitat diversity. However, it should be noted that very little evidence has been collected to support the claims of enhancement. Also, few definitions have been provided for physical habitat diversity in streams. Gorman and Karr (1978) and Schlosser (1982) have correlated fish community diversity with hydraulic diversity. These authors defined hydraulic diversity using the Shannon function applied to velocity and depth values. As it is has been shown to have some biological significance, this function was used in this study to evaluate changes in physical habitat conditions. However, it should be remembered that the relation between hydraulic diversity and species diversity remains untested in Australia. The Shannon function uses the observed proportion of samples occurring in different depth and velocity ranges defined according to Table 5. As there were four depth, and five velocity ranges, there was a total of 20 possible combinations of these ranges. A maximum value for the Shannon function would be calculated if there were equal proportions of the sample in each of these 20 hydraulic categories. If one or more categories had a greater number of samples than others, a lower value would result.

The Shannon function was calculated as

$$H' = -\sum_{i=1}^{s} p_i \log_e p_i$$

where, s is the number of categories (s = 20) , and p_i is the proportion of the total sample belonging to each category (Krebs 1989). Krebs (1989) also suggests an adjustment to this function so that values vary between zero and one, with a value of one corresponding to maximum diversity, using

$$H'' = \frac{e^{H'}}{s}.$$

Values of H'' can vary from a theoretical minimum of 1/s to a maximum value of 1. Hydraulic diversity values, calculated for 125 river surveys in six different countries, are shown in Figure 26. Few values exceed 0.65. Most levels of hydraulic diversity are in the range 0.25 to 0.5. Values outside this range may be considered either high or low. This figure provided a pragmatic means of evaluating hydraulic diversity levels. A better approach to assessing hydraulic diversity would be to compare current conditions with those prior to disturbance of the channel. However there was insufficient historical data available to estimate the natural levels of diversity.

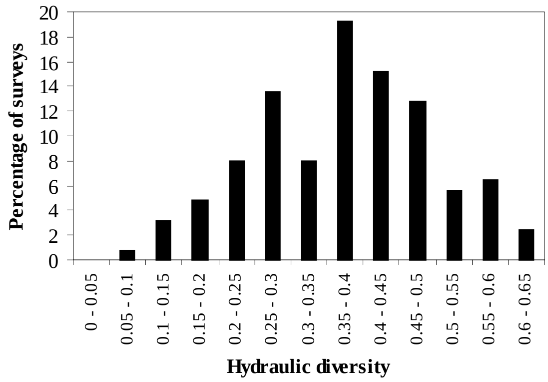

Figure 26: Frequency histogram of hydraulic diversity values (calculated using 125 surveys in rivers in UK, France, Norway, South Africa, New Zealand, and Australia)

The physical habitat diversity index for the Broken River rehabilitation reach was higher for surveys in 1997 and 1998 than prior to rehabilitation in 1996 (Figure 27). The diversity prior to rehabilitation was between 0.25 and 0.5 (decreasing with discharge). Since rehabilitation works were carried out the diversity increased to between 0.4 and 0.6. The diversity following rehabilitation was high in comparison to values calculated in other rivers (Figure 26). The increase in diversity was the result of hydraulic changes described in section 6.1. These changes resulted in more uniform depth and velocity distributions (Figure 20 and Figure 21). Surveys were conducted at Broken River reach in Februrary, April, and May of 1997. Discharges at the time of survey in February and April were higher than at the time of the May survey as a result of summer irrigation releases from Lake Nillahcootie. The hydraulic model has been used to estimate diversity indices for a range of flows based on a calibration at the May 1997 survey. Comparison of diversity indices predicted using the hydraulic model and diversity indices calculated using the April survey data were consistent (Figure 27). The model calibrated using the May data, underpredicted hydraulic diversity in February 1997. This may be due to model error or a result of channel change during the high irrigation flow period between these two surveys.

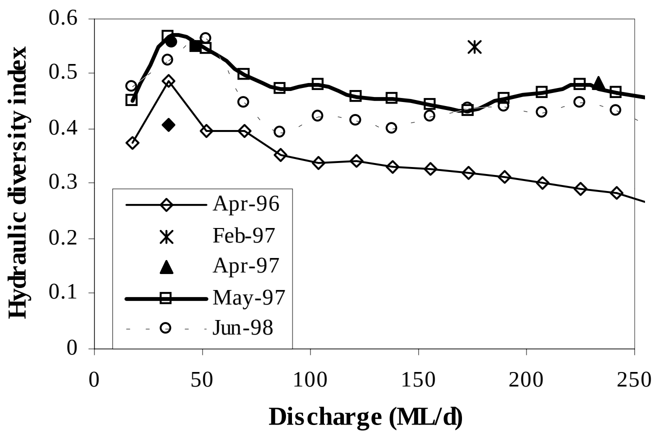

Figure 27: Hydraulic diversity at the Broken River reach (solid symbols indicate diversity calculated from observed rather than modelled data)

The statistical significance of changes in the adjusted Shannon diversity index (*H''*) were tested using a jackknife procedure described by Zahl (1977) (also described in Appendix I). This procedure was used to generate *n* replicates of the Shannon index, where *n* is the number of cross-sections. A two-tailed t-test, for paired data, was used to assess changes in the mean of these replicates between surveys. The level of statistical significance of changes in Shannon indices between April 1996 and June 1998 at the Broken River reach is shown in Figure 28. The 1998 works survey was selected for this test because discharges at the time of survey are relatively close to the discharge at the time of the April 1996 survey. Changes were significant (using p = 0.1 and a paired two-tailed t-test) between 120 ML/d and 200 ML/d. This range may correspond to the flows for which items of LWD and boulders had greatest hydraulic effect. At lower flows, water may have moved under and around flow obstructions without major distuurbance to the flow pattern. At higher flows, these structures would have been drowned. At intermediate flows, these structures would have had a relatively high blockage ratio and hence the greates hydraulic effect.

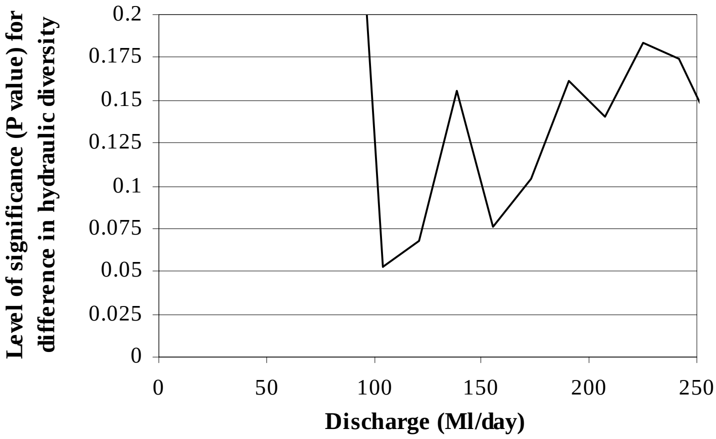

Figure 28: Statistical significance of changes in physical habitat diversity at Broken River between April 1996 and May 1997 [calculated using difference of means t-test for 12 paired replicates generated using the jackknife procedure described by Zahl (1977)]

Hydraulic diversity decreased following rehabilitation works in Ryans Creek (Figure 29). The reduction in physical diversity between surveys in April 1996 and February 1997 was statistically significant (p = 0.05, paired two-tailed t test) for discharges less than 70 ML/d (Figure 30). The February 1997 survey was used for this comparison because it was closest in discharge to the pre-works survey. Predictions of diversity index calibrated using the February 1997 and April 1997 surveys showed close agreement and predicted diversity values are consistent with those calculated from survey measurements. A reduction in physical habitat diversity resulted from structural works and subsequent channel changes. These factors have led to a reduction in the area of high velocity and still water, resulting in the dominance of intermediate and slow water velocities (Figure 24). Changes in hydraulic diversity at higher discharges may have been less significant because structural elements added to the channel were drowned out.

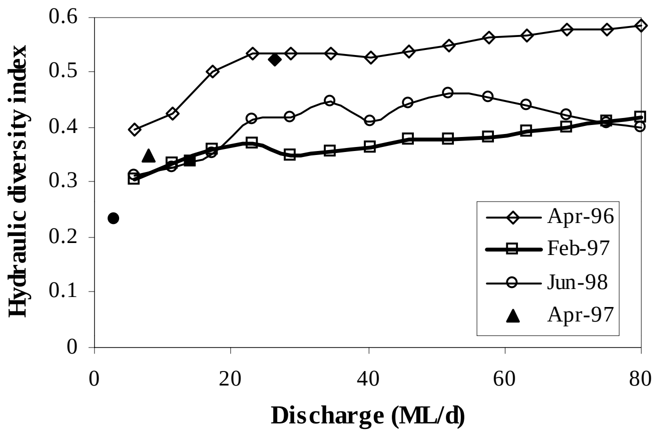

Figure 29: Hydraulic diversity at the Ryans Creek reach (solid symbols indicate diversity calculated from observed rather than modelled data)

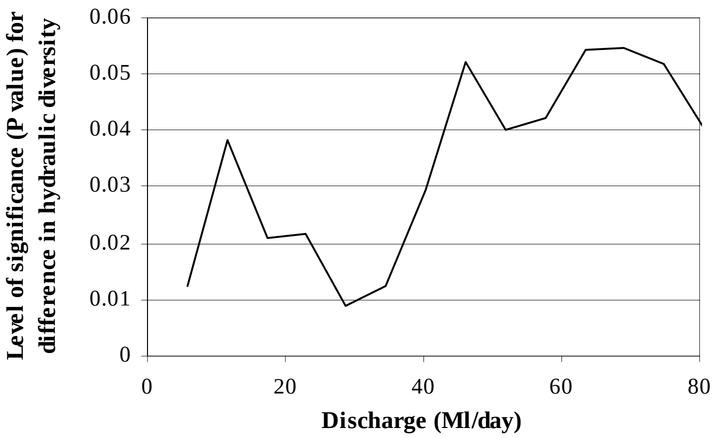

Figure 30: Statistical significance of changes in physical habitat diversity at Ryans Creek between April 1996 and February 1997 [calculated using difference of means t-test for 7 paired replicates generated using the jackknife procedure described by Zahl (1977)]

6.3 Pool Habitat

Shields et al. (1995) define pool habitat as areas of the channel with Froude number values (calculated using depth-averaged velocity) less than 0.15. Pool areas are considered to be an important rearing habitat for a number of native Australian fish species. Based on observations of a number of fish species in Armstrong Creek, Victoria, Koehn et al. (1994) define this habitat as areas with velocity less than 0.2 m/s and depth greater and 0.2 m. This latter habitat criterion is more restrictive than the Froude number criteria provided by Shields et al. (1995). Interestingly, at a depth of 0.2 m, the maximum velocity that still maintains a Froude number less than 0.15 is 0.21 m/s. Changes in pool habitat were assessed in this study with pool areas defined by a maximum Froude number of 0.15. The definition of Koehn et al. (1994) refers to the habitat for a particular life stage of a limited number of fish species based on observations in a single stream reach. It is unlikely that this habitat definition is transferable to other regions and results based on changes in this habitat will not be widely applicable. However, the biological significance of 0.15 as a threshold Froude number is supported by the depth-velocity criteria of Koehn et al. (1994).

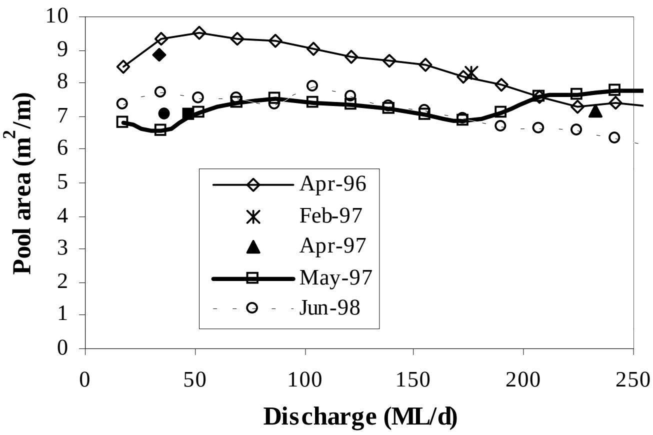

Figure 31: Pool area at the Broken River reach (solid symbols indicate pool area calculated from observed rather than modelled data)

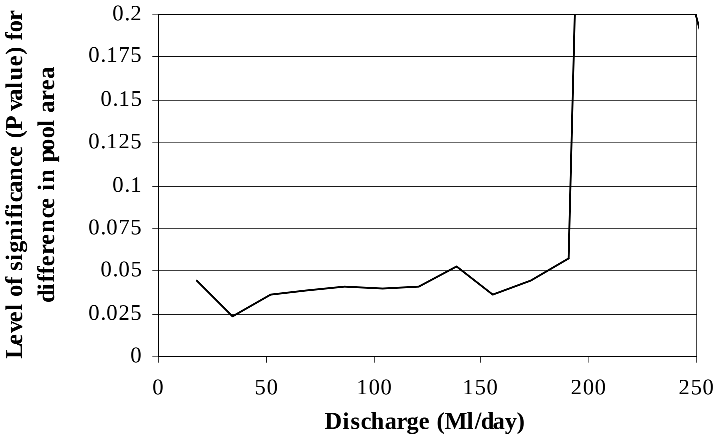

Figure 32: Statistical significance of changes in pool area at Broken River between April 1996 and May 1997 [calculated using difference of means t-test for 7 paired replicates generated using the jackknife procedure described by Zahl (1977)]

The pool area along the Broken River reach decreased following rehabilitation and remained relatively stable in the subsequent year (Figure 31). Using the jackknife procedure (described in Appendix I), the reduction was found to be significant (p = 0.05) for discharges less than 200 ML/d. However this analysis did not consider uncertainty associated with model error. Pool area predictions based on calibration using the May 1997 survey data differed from pool area determined from surveys in February 1997 and April 1997. This discrepancy may have been due to sediment movement during high, regulated summer flows between the February and May surveys. However, the model under-predicted pool areas in the case of the February survey and over-predicted pool areas in comparison to the April survey. If these differences were solely due to sediment movement, it would be expected that the model would have consistently under- or over-predicted pool areas. This would suggest that model error was at least partly responsible for these differences. If model uncertainty were to be considered, the significance of changes in pool area between years would be reduced. This effect would be small at discharges close to the calibration discharge. For this reason, the reduction in pool area is likely to be significant at low discharges regardless of model error. Unfortunately there were insufficient data available to fully account for model uncertainty in this analysis.

The area of pools in the Ryans Creek reach increased in the year following rehabilitation and remained unchanged in the subsequent year (Figure 33). This change was statistically significant (p=0.05) for discharges less than 25 ML/d. At higher discharges, no change in pool area was detected. This result was consistent with Figure 25, which showed a reduction in velocity at most cross-sections.

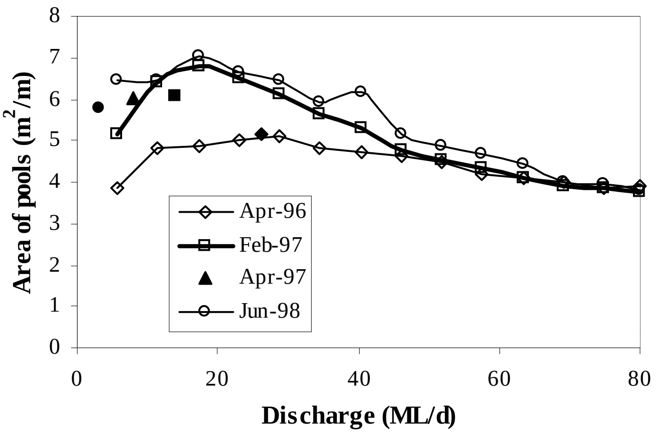

Figure 33: Pool area at the Ryans Creek reach (solid symbols indicate pool area calculated from observed rather than modelled data)

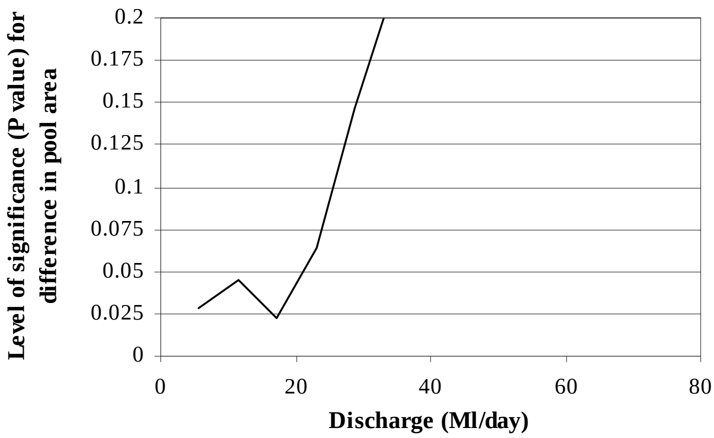

Figure 34: Statistical significance of changes in pool area at Ryans Creek between April 1996 and February 1997 [calculated using difference of means t-test for 7 paired replicates generated using the jackknife procedure described by Zahl (1977)]

6.4 Discussion

Physical habitat diversity defined by the Shannon index increased over a range of low to moderate flows in the Broken River reach following the introduction of LWD and boulders into the channel. This increase in diversity was consistent with the results of earlier studies (V.A. Poulin and Associates, 1991; Shields, 1992) despite the use of different methods for assessing diversity. The area of pool habitat at low flows decreased over the same period. This change was opposite to that observed in other studies of the physical effect of LWD and instream structures. An increase in velocity seems to have been caused by shallower water associated sedimentation around LWD and boulders. Such sedimentation would have resulted in the transformation of pool areas to faster water. One might expect that backwater effects from the LWD items would have offset this effect. However, it is possible that at low flows, LWD items that did not extend to the channel bed have little hydraulic effect. The effect of LWD is likely to be greatest at intermediate flows when they create a major channel blockage. Once overtopped, increases in discharge would result in a reduced blockage ratio created by the LWD and a reduction in the hydraulic effect. This could explain why hydraulic diversity, at higher discharges, was unaffected by the introduction if LWD in the Broken River reach. Before rehabilitation, physical habitat diversity was low to average (Figure 26) and following rehabilitation works, physical habitat diversity was average to high.

The physical habitat diversity of the Ryans Creek reach decreased following rehabilitation and at low flows, pool areas increased. An increase in pool area was consistent with other studies of the effect of instream structures and LWD on instream habitat. However, no earlier studies report a reduction in habitat diversity following the re-introduction of LWD. The construction of riffles that were steeper than the pre-existing riffles may have been responsible for a reduction in riffle area and an increase in pool area. In addition, a channel was scoured through a long riffle (70 m below transect 1) following the placement of a “herring-bone” configuration of LWD items on the riffle. The effect of these changes was to increase the area of lower velocity regions and reduce the physical habitat diversity along the reach. Although reduced from pre-rehabilitation levels, the physical diversity of the reach was average to high when compared to surveys conducted in a range of other rivers (Figure 26). Prior to rehabilitation works, the physical habitat diversity of the Ryans Creek was very high in comparison to these other surveys.

7 CHANGES IN THE DIVERSITY OF FISH AND INVERTEBRATE FAUNA

7.1 Diversity of Fish and Macroinvertebrate Fauna

This report presents the results of physical evaluations of the stream rehabilitation works. A companion report by the Marine and Freshwater Resources Institute (Snobs Creek) provides the results of biological monitoring and evaluations of the works. As only 2 years of monitoring were carried out following rehabilitation works, it is unlikely that changes in the aquatic community had reached an equilibrium state on completion of the project. Another limitation to biological monitoring in this reach-scale rehabilitation trial is that the river upstream and downstream of the site remains in its original state. Changes in fish fauna may be the result of movement into or out of the rehabilitated reach. The longitudinal extent of rehabilitation works are likely to be particularly significant for migratory species or species with an extended home range. For this reason the response of fish and other fauna to larger scale projects may differ from responses observed in this project.

Despite these limitations, biological monitoring was considered to provide an indication of the likely trends in aquatic communities following rehabilitation works (Brown et al. under review). Brown et al. (under review) provide a summary of the results of fish and macroinvertebrate monitoring at the Broken River and Ryans Creek reaches. The only significant change in the diversity of fauna detected by this study was an increase in the diversity of fish fauna at the Broken River, relative to changes at control reaches. Macroinvertebrate species diversity at this reach was not significantly affected by the rehabilitation works. At the Ryans Creek reach, changes in the diversity of fish and macroinvertebrate fauna were not significantly different to control reaches.

These biological results are reproduced in this report to aid the interpretation of physical changes at the two reaches. However, changes in biological diversity are not the only method of assessing biological impacts of the rehabilitation works. Changes in individual species populations and age classes may also reveal significant effects of the rehabilitation works. A comprehensive report of biological changes at these and another two reaches is being prepared by the Marine and Freshwater Resources Institute (Snobs Creek). Readers are referred to this report for a description and explanation of trends in fish and invertebrate fauna at these reaches.

7.2 Comparison of Biological and Physical Response

Changes in hydraulic diversity based on the bi-variate distribution of depth-averaged velocity and depth is more likely to have affected the diversity of fish fauna than macro-invertebrate fauna. Fine-scale and near-bed measurements are probably required to characterise physical habitat conditions for the benthic macroinvertebrate community. There is some discussion in the ecological literature of the relation between habitat diversity and biological diversity and it is widely hypothesised that greater physical habitat diversity in streams will lead to a more diverse fauna. This theoretical relation assumes that physical habitat availability is a key factor regulating the biological community rather than factors such as food supply, patterns of disturbance, fish stocking, or angling. Results at the Broken River reach were consistent with this hypothesis with increases in both physical habitat and fish fauna diversity following rehabilitation works. At the Ryans Creek reach, habitat diversity decreased whilst the diversity of fish fauna was not significantly affected by the rehabilitation works. This suggests that physical habitat availability was not a key factor regulating fish fauna diversity at Ryans Creek. This is not unexpected given that the physical habitat diversity prior to rehabilitation works was higher than that observed in many other streams. Whilst these observations do not provide a scientific test of ecological theory they are consistent with the hypothesis that low physical habitat diversity results in a low diversity of fish fauna. However, this relationship may not apply to streams with a high physical habitat diversity.

8 CONCLUSIONS

8.1 Evaluation of Rehabilitation Works

This study tested the hypotheses that (i) works would increase habitat diversity and (ii) that increased habitat diversity would result in increased biological diversity. Results at the Broken River reach were consistent with these hypotheses with increases in both physical habitat and fish fauna diversity following rehabilitation works. At the Ryans Creek reach, habitat diversity decreased whilst the diversity of fish fauna was not significantly affected by the rehabilitation works. This suggests that physical habitat availability was not a key factor regulating fish fauna diversity at Ryans Creek. This is not unexpected given that the physical habitat diversity prior to rehabilitation works was higher than that observed in many other streams. Whilst these observations do not provide a scientific test of ecological theory they are consistent with the hypothesis that low physical habitat diversity results in a low diversity of fish fauna. However, changes in physical habitat diversity may not always influence biological diversity, particularly if physical habitat diversity is high. The introduction of instream structures does not always increase the diversity of physical habitats. An increase in habitat diversity is more likely to result if structures are designed to enhance the natural processes of pool and riffle formation. Rehabilitation works did not reduce the discharge capacity of either channel.

8.2 Physical Changes at the Project Reaches

Broken River Reach

Large woody debris and boulders were used in combination with bank protection works to rehabilitate a reach of Broken River in April 1996. In general, the size of bed features and bank-full geometry were unaffected by rehabilitation of the Broken River reach, although local deposition and scour did occur. The rehabilitation works have enhanced the diversity of physical habitat conditions along the reach and reduced the area of pools. While enhancing hydraulic diversity, rehabilitation works have not significantly reduced the discharge capacity of the channel. This was not unexpected given that the scale of the works was small in comparison to the size of the channel. The increase in hydraulic diversity appeared to be related to increases in areas of shallow, fast flowing and torrential water and decreases in deeper water and areas with moderate velocities. This change is likely to have been the result of deposition at introduced items of LWD. The area of pool habitat decreased following rehabilitation works.

Ryans Creek Reach

Large woody debris, boulders and two artificial riffles were installed in a reach of Ryans Creek in April 1996 for the purpose of stream rehabilitation. Monitoring prior to, and two years after, rehabilitation works indicated scour and deposition associated with large woody debris placed in the channel increased the frequency of bed oscillations, reduced the length of pools and riffles, and reduced the longitudinal channel variability. Although flow resistance increased following the works, an increase in channel dimensions meant there was no net reduction in channel capacity following the rehabilitation works. A reduction in hydraulic diversity appeared to have resulted from the disruption of the pool-riffle bedform established prior to rehabilitation. An increase in the area of pools at low flows was the result of bed scour at a riffle, and backwater affects at the artificial riffles.

8.3 Use of Rehabilitation Methods

Large Woody Debris

The hydraulic effect of LWD varies with stage. At low discharge a significant portion of flow may pass under LWD items and the hydraulic effect may be small, particularly if LWD is raised above the channel bed. The hydraulic effect of LWD items is likely to be greatest at intermediate discharges when blockage ratios are a maximum. At these intermediate discharges, energy is dissipated at LWD items through turbulence and upstream backwater effects enhance the availability of pool habitats. At higher discharges LWD items may be overtopped, and their hydraulic effect diminished. Items placed in constricted sections and riffles are likely to result in greater flow blockage than in pools and larger sections. When placing LWD within a channel it is useful to consider the blockage created by the LWD at different discharges from low to bank-full.

From information available in the literature and this study, it appears that in the absence of systematic morphological change, the introduction of LWD enhances physical habitat diversity. However, if there is a systematic morphological change following LWD introduction, physical habitat diversity can decrease. To minimise morphological changes following introduction of LWD, it is recommended that the blockage created by LWD at higher discharges is relatively small and LWD is not introduced at riffles or flow constrictions. Regardless of these precautions, local morphological changes may still occur. In this study, logs spanning the channel resulted in deep scour pools at and downstream of the LWD item. In some situations, LWD placed as a deflector oriented in the downstream direction resulted in scour of the bed adjacent to the deflector. Field observations suggested that flows over-topping such configurations resulted in scour downstream of the LWD and adjacent to the bank. Deflecting LWD items raised well above the channel bed and located in pools did not appear to have a major impact on bed topography.

LWD can be introduced without a reduction in flow capacity while still contributing to enhanced physical habitat diversity. Introduced LWD which creates a substantial flow blockage at bank-full discharges will result in an increased flow resistance. However, channel enlargement following the introduction of LWD may offset the effect of enhanced flow resistance on flow capacity of the channel. The assumption of a rigid boundary (i.e. no channel change) used by existing models predicting the effect of altered LWD loading on channel capacity, is unlikely to be valid in situations of high LWD loading.

Boulders

Bed sediment accumulated at boulders following their introduction in both Broken River and Ryans Creek. This is not unexpected given that they are likely to decrease flow velocities close to the channel bed at higher flows and promote depositions of transported sediments. As a result of this, boulders may become partially buried. Depositions of fine sediments may limit environmental benefits of boulders. Some international experts have advised that rehabilitation works should mimic natural channel characteristics. This is justified on the basis that natural features are more likely to be sustainable and create a natural range of physical habitats at a range of spatial scales. Given this recommendation, the use of boulders in lowland and cobble-bed streams should be avoided.

Artificial Riffles

If the downstream gradient of artificial riffles is steeper than pre-existing riffle features, then their construction will lead to a reduction in faster flowing riffle habitats and an increase in pool habitats. This may result in a reduction in physical habitat diversity if riffle habitats are scarce in the pre-rehabilitation channel. For this reason, it is recommended that downstream gradients of riffles are the same as those that occur naturally. Deposition may occur upstream of isolated riffles resulting in accumulation of fine material. A series of riffles is required to ensure that fine sediments are flushed out of pools during high flow events. Where possible, artificial riffles should be constructed so as to compliment pre-existing pool-riffle development.

8.4 Physical Habitat Diversity as a Design Goal

Physical variability or habitat diversity is a practical goal for the design of instream rehabilitation works. However, it should be used with caution, and its selection requires some justification. Problems associated with this approach are:

- the scale and type of measurements used to calculate habitat diversity are likely to influence results,
- the method of calculation may influence results,
- habitat diversity that exceeds natural levels may not be desirable, and
- biological diversity may be influenced by factors other than physical habitat diversity, particularly in streams where physical habitat diversity is high.

It is recommended that the physical habitat conditions of a comparable channel in a relatively natural state is an appropriate design goal and that consideration should be given to characteristics at a range of spatial scales. If physical habitat diversity is to be used, then a desired level should be selected based on comparisons with other streams and the cause of reduced physical diversity should be established prior to the design of works.

APPENDIX I: STATISTICAL METHODS

With the exception of Jackknifing, the following descriptions are taken from Snedecor and Cochran (1989). The description of the Jackknifing is adapted from Zahl (1977).

Comparison of the Means of Paired Samples

If a particular sample of a population is observed on two occasions then the observations are said to be *paired*. This is often the case with stream monitoring, when measurements are taken at the same location on two or more occasions. The aim of pairing is to make comparisons between samples more accurate by having members of any pair as alike as possible apart from the treatment. To compare the difference in means of paired data the difference D_i of individual pairs is calculated (where i = 1 to n, and n is the number of pairs). Using the mean ($\overline{D}$) and standard deviation (s_D) of the differences it is possible to calculate the t statistic using

$$t = \frac{\overline{D} - \mu_D}{s_D}$$

where μ_D is the mean difference for the entire population of pairs. Assuming the individual differences (D_i) are independent and normally distributed, the t statistic follows the Student t distribution with (n-1) degrees of freedom. The t distribution can be used to test the null hypothesis that $\mu_D = 0$. Most statistics texts provide a table of critical values for the t distribution for various levels of significance.

Equality of Variances

Consider two samples with standard deviations s_1 and s_2. The F statistic is calculated using

$$F = \frac{s_1^2}{s_2^2}$$

If the populations are normally distributed and have equal variances, F has a standard distribution. Tables of values for F are provided in many statistical texts for different significance level. The F statistic can be used to test the null hypothesis that the two populations have the same variance.

Analysis of Frequencies with Two-way Classifications

Different methods are required to detect statistically significant changes in the distribution of discrete variables between surveys. An example of a problem of this type is detection of change in substrate composition between two surveys, where substrate is classified into *m* different types. In this case, we may want to test the null hypothesis that there is no change in substrate composition between surveys. The surveys provide the number of sample observations p_i and q_i of each substrate type (where i = 1 to m, and p and q refer to the two surveys). If the composition is unchanged then the expected values of p_i and q_i are given by

$$P_i = \frac{(p_i + q_i)\sum_{i=1}^{m} p_i}{\sum_{i=1}^{m} p_i + \sum_{i=1}^{m} q_i} \quad \text{and} \quad Q_i = \frac{(p_i + q_i)\sum_{i=1}^{m} q_i}{\sum_{i=1}^{m} p_i + \sum_{i=1}^{m} q_i}$$

The χ^2 statistic can be calculated as

$$\chi^2 = \sum_{i=1}^{m} \frac{(p_i - P_i)^2}{P_i} + \sum_{i=1}^{m} \frac{(q_i - Q_i)^2}{Q_i}$$

and has (m-1) degrees of freedom.

A larger value of χ^2 indicates a greater difference in the two sample distributions. Critical values of χ^2 for rejecting the null hypothesis are provided in most statistic texts. This test assumes that individual observations are independent. This is not strictly true where several observations are made at each cross-section. To overcome this problem it is suggested that substrate composition should be randomly sampled throughout the reach rather than at cross-sections.

Jackknifing

If a particular measure is calculated based on two different sample populations then comparisons of changes in that variable must consider the possibility that observed changes are the result of sample variability rather than a change in the overall population. For simple statistics, like the mean and standard deviation, there are well-defined methods for doing this, (e.g. the tests described above). For more obscure statistics like indices of diversity, there is often no such test. The technique of Jackknifing offers a relatively simple method for detecting significant changes. The technique assumes that each observation is independent. However, a number of observations at a stream cross-section are not independent. To overcome this problem it is suggested that observations at each cross-section be aggregated and the jackknifing procedure be based on a sample size of *n* where *n* = the number of cross-sections. If the same cross-sections are sampled in each survey, then two surveys provide paired samples (i.e. one pair for each cross-section).

Before applying this method to an index of hydraulic diversity, consider a simpler situation where some parameter *G* describes the distribution of a particular variable *X*. Let us also assume that this parameter can be estimated from a sample x_i where *i* = 1 to *n* by the function $g^0 = g(x_i, i = 1 \text{ to } n)$. Imagine that we used our single sample of *n* measurements to create n different samples of (*n*-1) measurements by leaving out one measurement in turn from each sample. It would then be possible to calculate *n* values of *g* based on each of these new samples. Lets refer to these values as g_i, where *i* = 1 to *n*. Clearly these values will not be independent. The jackknifing procedure specifies that new values, or pseudo values, are calculated using

$$g_i' = ng^0 - (n-1)g_i$$

The jackknife estimate of G is given by

$$g_J = \frac{1}{n}\sum_{i=1}^{n} g_i'$$

Under certain assumption, the pseudo values can be considered to be independent and normally distributed. If these assumptions are valid, changes in *G* can be assessed using standard difference of means tests.

Now consider the application of Jackknifing to calculating habitat diversity (e.g. the procedure described in section 6.2 of this report). Lets define the $L_{i,j}$ as the width of the i^{th} cross-section that is in the j^{th} hydraulic category (20 hydraulic categories are defined in section 6.2, based on velocity and depth). In this case *G* is the adjusted Shannon index (defined as *H''* in section 6.2) and *n* is the number of cross-section. The *n* values of g_i, are calculated from *n* samples of $L_{i,j}$, each excluding a different cross-section. The jackknife estimate is then calculated using the equations given above. Because the same cross-sections are used in each survey, it is assumed that pseudo values based on sub-sets of the data that excludes the same cross-section can be treated as paired samples. As a result, changes in the Jackknife estimate of habitat diversity can be tested using the t-test for paired samples (described above).

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