Confronting hysteresis: wood based river rehabilitation in highly altered riverine landscapes of south-eastern Australia.

Andrew P Brooks¹, Timothy Howell¹², Tim B Abbe³ and Angela H. Arthington¹

¹Centre for Riverine Landscapes, Griffith University, Nathan Qld 4111 Australia. andrew.brooks@griffith.edu.au
²New South Wales Department of Primary Industries, Locked Bag 1, Nelson Bay 2315, Australia.
³Herrera Environmental Consultants Inc., 2200 Sixth Ave., Suite 1100, Seattle Washington, USA. 98121

Abstract
This study evaluates a river rehabilitation experiment which uses large wood to stimulate and emulate natural system processes in an effort to reverse channel degradation, excess sediment transport and habitat simplification that has resulted from two centuries of human induced disturbances, particularly desnagging. The experiment involved the reintroduction of 436 logs (350 t) within 20 engineered log jams (ELJs) over an 1100 m reach. Commencing in 1999, the experiment was set up as a standard BACI design, with a control reach 3 km upstream. In the 5 years since implementing the rehabilitation strategy, the study reach has experienced 5 floods greater than the mean annual, and a further 5 events capable of mobilising the gravel bed. Five channel terrain surveys have been completed since treatment implementation, and the changes to net sediment storage and morphologic diversity assessed in comparison to the control reach. Seven surveys of the reach fish population have also been undertaken during the project to measure the ecological response to the introduced wood. The experiment has demonstrated the effectiveness of ELJ technology in achieving engineering and geomorphic goals. To date, the treatment has halted further degradation of the river and increased sediment storage, with the test reach now storing, on average, 40m³/1000m² more than the control, and it would appear that this represents a new reach-scale dynamic equilibrium storage level. Additional sediment storage amounts to 3.5m³ per m³ of wood added. At the reach scale this additional storage represents a reduction of just 2% or less of the post-European expansion in channel capacity, suggesting far greater efforts are required than those employed here to reverse the cumulative effects of 180 years of channel erosion and simplification.
Pool and bar area in the test reach increased by around 5% and 3.5% respectively, while the corresponding values in the control were around 1.5% and 1%. Two indices of morphologic diversity were measured for each bed survey: the standard deviation of 3D residuals of change compared with the baseline survey (SD$_{\Delta 3D}$); and the standard deviation of thalweg residuals from the line of best fit (SD$_{TR}$). The SD$_{\Delta 3D}$ index shows both reaches increased in complexity through the study, with the treatment increasing more than the control (0.37 and 0.29 respectively). The SD$_{TR}$ index does not detect clear changes due to the low signal to noise ratio, however, it does suggest the test reach was more complex than the control at the outset. The observed increase in fish abundance after the first 12 months of monitoring, reported previously, is now far less distinct 4 years on – a pattern seemingly reflecting the relatively minor increases in critical pool habitat and habitat diversity over the same period. Although no significant differences were detectable in fish species richness or total abundance from the reach aggregate data, analysis of individual structures show them to be high quality native fish habitat compared to the rest of the reach and the upstream control.

These results highlight the challenges river managers face in achieving measurable improvements in aquatic ecosystem health in highly altered rivers. Managers must confront hysteresis in both a biophysical and institutional sense when attempting to reverse the degradation of these rivers. The scale of treatment implemented in this experiment was at the upper end of the spectrum of rehabilitation efforts currently being undertaken in Australia, suggesting that far greater resources and longer timescales are required to achieve the levels of improvement in stream habitat diversity expected by the community. The study also highlights problems with attempting to meet multiple objectives within a reach scale rehabilitation strategy. While this treatment successfully met some geomorphic study objectives, maximising the benefits for fish habitat would require a strategy focused primarily on the creation of complex woody habitat within deeper pools, particularly pools immediately below riffles.

Key Words: river rehabilitation; large woody debris; geomorphic recovery; complex response, meso-habitat; micro-habitat, freshwater fish
Introduction

Many rivers in south-eastern Australia have undergone a fundamental geomorphic and ecological transformation as a result of deforestation and channel clearing in the two centuries since Anglo-European settlement (Brierley, et. al., 1999, Rutherfurd, 2000, Prosser et. al., 2001). There is a growing body of literature that highlights a fundamental transformation in channel morphology, dimensions and sediment transfer dynamics within this region. The general trend within many rivers has been towards increased channel size as channels have incised and widened, and dramatically increased sediment transport capacity (Brooks and Brierley, 1997, Brierley and Murn, 1998, Page and Carden, 1998, Nanson and Doyle, 1999, Brooks and Brierley, 2000, Brooks et al., 2003). In some cases sediment transport capacity has increased by as much as three orders of magnitude (Brooks et al., 2003; Brooks and Brierley, 2004), with long -term sediment stores now acting as the dominant sediment sources to many rivers in south-eastern Australia (Wasson et. al., 1998, Prosser et. al., 2001, Olley and Wasson 2003, Wallbrink, 2004).

The erosion of channels and alluvial stores in the mid and upstream reaches results in the deposition of “sediment slugs” downstream (Bartley and Rutherfurd, 1999, 2005). In both scenarios – i.e. upstream channel erosion and downstream sedimentation - the result is often dramatic homogenisation of in-stream habitat (Brooks et al., 2003; Bartley and Rutherfurd, 1999, 2005) (Figure 1), accompanied by deleterious effects on aquatic ecosystem health and resilience (Crooks and Robertson, 1999; Boulton and Brock, 1999; Pusey and Arthington, 2003).

Figure 1 around here

The underlying mechanisms initiating these fundamental changes to channel morphology are often complex (Brooks and Brierley, 2000; Rutherfurd, 2000; Prosser et. al., 2001). Allowing for some generalisation, in the first century following colonisation (i.e. to the late C19th) there was usually a combination of riparian vegetation removal, in-channel grazing, altered hydrology due to catchment clearance, and to a lesser extent, removal of logs and woody debris (‘desnagging’). Certain rivers were also heavily impacted by alluvial gold mining operations (Knighton, 1989, 1991; Bird, 2000). In the second century following colonisation (i.e. the C20th), the initial disturbance mechanisms were often compounded by direct interventionist management, usually in the guise of flood mitigation or sand and gravel extraction (Erskine et.al., 1985; Erskine and White 1996;
Erskine and Green, 2000). Under these schemes channels were extensively de-snagged and straightened (Brooks 1999a; Rutherfurd, 2000; Brooks et al., 2003; Erskine and Webb, 2003), and consequently in-channel stream power tended to be maximised leading to increased erosion and sediment transfer; often necessitating the implementation of major erosion control works to stabilise the channels. From the 1950s continuing through to the early 1990s major river engineering works programs were implemented throughout SE Australia, particularly in the two most populous states - New South Wales (NSW) and Victoria - with large government funded work crews undertaking major erosion control and flood mitigation works on many rivers throughout these two states (Rutherfurd, 2000). As an example, in the Hunter River (NSW) catchment (catchment area 20 000 km²) during the 1970s, there was a work crew of 120 people working on river engineering projects throughout this one catchment (Paul Collins, NSW Dept. Natural Resources pers. comm. 2003).

In the last decade there has been a fundamental shift in policy away from government implemented river engineering programs primarily focused on flood mitigation and erosion control, towards community based river stewardship with an increasing ecological focus, but with only a fraction of the resources previously available to the engineers in government agencies. Furthermore, funding is now spread very thinly across myriad community groups around the country. To illustrate this point, in 2004 the last 8 member government funded river work crew operating in the Hunter Valley was effectively “privatised” and is now expected to operate as self-funded contractors doing work for the new quasi community/government Catchment Management Authorities or other government departments anywhere in the state. This is a far cry from the 120 person work crew of the 1960s and 1970s dedicated to one catchment.

This biophysical and institutional historical backdrop provides a critical context for assessing the environmental gains that can be realistically expected to flow from river rehabilitation projects implemented under the current ecologically based river management paradigm (sensu Hillman and Brierley, 2005), and given the capacity and resources that are now available for river rehabilitation works. In this paper we present some results, 5 years post-implementation, of a relatively large (within the current context) reach based rehabilitation experiment on the Williams River, NSW, a northern tributary of the Hunter River (see Figure 2). The project involved the reintroduction of
436 logs into an 1100 m reach of the Williams in September 2000 using a Before/After/Control/Impact (BACI) experimental design (Downes, et al., 2002), with a single control reach 3 km upstream. The rationale underpinning the rehabilitation strategy along with the rehabilitation project design and some early results are outlined in Brooks et al. (2004). In this paper we present the results from a further 4 years of monitoring. Assuming this type of rehabilitation represents “best practice” we then use these results to pose the question of whether the current approach to river management in Australia (and many other parts of the developed world) is anywhere near sufficient to meet the expectations of government and the community with regard to environmental outcomes of current management activities. This is particularly pertinent given the relatively small catchment area of the site where the experiment was conducted, the limited scale of the intervention, and the magnitude of geomorphic change that has typically ensued at this location. The results from this study have implications for the design and scale of works required in larger rivers.

Figure 2 around here

Study Area
A section of the Williams River at Munni was selected as the test reach (figure 2), based on a broad range of criteria including its past history of de-snagging, good anecdotal and archival data about the management history and channel changes, as well as good access and visibility for use as an educational facility for the local community (see Brooks et al., 2004). The test reach encompasses a full bedrock controlled meander, while the control reach 3.1 km upstream represents half of an equivalent meander. Both reaches are characterised by a discontinuous floodplain river style (Brierley et al., 2002; Brierley and Fryirs, 2005) typical of many coastal gravel-bed rivers in eastern Australia and have been subjected to a similar suit of disturbances. Thus, lessons learned here should have a wider significance for rehabilitation strategies elsewhere. Notwithstanding regional scale sediment supply limitation, the presence of active bank erosion and large mobile gravel bars within and immediately upstream of each reach, and that the two reaches have similar gradient and channel capacity, suggests and transport capacity is comparable for the two reaches and that local sediment supply was sufficient during the experimental period to induce morphological change.
The baseline attributes of the two study reaches include comparable channel dimensions, bed materials, riparian vegetation and flow characteristics. The two reaches drain upstream areas of 185 km² and 180 km² respectively (Figure 2). The Munni test reach measured 1100 m in length (thalweg ~1500m) with a baseline reach bed slope of 0.0019 and median clast size of 76 mm (n=1800). The 500 m control reach (~ 600m thalweg) had a baseline bed slope of 0.0019 and median clast size of 77 mm (n=400). Hydrological attributes of the study reaches were determined from the flow gauge at Tillegra Bridge—5.1 km downstream of the Munni test reach (catchment area 194 km²). The mean annual flood (arithmetic mean of the annual flood series, 1931-1993) is 170 m³sec⁻¹. Based on a cross-section defined by alluvial banks in the test reach, ‘channel-full discharge’ equals 800 m³sec⁻¹—a flood with an average recurrence interval exceeding 100 years. Channel-full cross-sectional area ranges from 170m² – 200m² within both reaches. The large capacity is interpreted to stem from channel and riparian zone disturbance since European settlement, particularly de-snagging (cf. Erskine and White 1996; Brooks 1999a,b; Brooks et al. 2003).

Reach Rehabilitation Strategy
Given the important role woody debris plays inducing geomorphic diversity and reducing bed load transport (sensu Montgomery et al., 1996, Buffington and Montgomery 1999, Brooks and Brierley, 2002) as well as improving ecological functioning (Crook and Robertson, 1999; Pusey and Arthington, 2003), the rehabilitation strategy was framed around the reintroduction of 436 logs within 20 “engineered log jams” (ELJs) across the study reach. The ELJ structures were modelled on naturally occurring log jams (Abbe and Montgomery, 1996; Abbe et al, 1997; Abbe et al., 2003a, b). The experiment was designed as a single treatment for the whole reach in which structures were designed to address site-specific objectives (e.g. bank stabilisation, riffle initiation, etc.) within a reach-scale framework. Logs used were primarily eucalypt species with root wads (totalling 350 t of wood), and were placed in 20 ELJs within the 1100 m test reach (figure 3). Four types of ELJ were designed for the test reach: deflector jams, bar apex jams, bank revetment structures and log-sill bed control structures. A summary description of the four structure types is given in Table 1, while Table 2 presents the summary attributes of each ELJ shown in Figure 3. The volume of wood introduced to the test reach equates with an average reach loading of 0.0114 m³/m² (i.e. of bed surface area), which falls within the guidelines outlined in Marsh et al. (1999) for the natural wood loads of
temperate rivers in this region. Full details of the different types of structures deployed are outlined in Brooks et al. (2004).

Objectives of Rehabilitation Strategy
When this rehabilitation experiment was proposed in 1998 river management in Australia was undergoing a radical transformation from the utilitarian engineering based approach that had prevailed since the end of the Second World War, with its focus on flood mitigation and water resources development, to a more ecologically focused approach (Hillman and Brierley, 2005). Under this new paradigm, the inherent ecological functions of rivers were permitted to be incorporated into the management equation, and as such new approaches were required that enhanced the natural biophysical processes within rivers, while at the same time meeting some ‘traditional’ engineering functions. It is fair to say that at this time not all were convinced of the wisdom of this new approach, particularly when it involved returning large numbers of logs to a section of river from which management authorities had spent the last 30 years removing logs. In this context, this experiment was as much about allaying people’s fears of having logs in rivers at all – let alone using them to meet particular engineering, geomorphic and ecological objectives. The conventional wisdom at the time was that logs caused floods, and that any attempt to reintroduce logs to a river would end in catastrophe, with logs being washed away in the first flood, causing log jams on downstream bridges, massive flooding and bridge failures.

In this context the study objectives were; 1) to demonstrate an approach for safely reintroducing logs to medium/high energy rivers, ensuring the structural stability of the reintroduced timber; 2) to test whether a reach-based rehabilitation strategy focused on the reintroduction of woody debris could help to stabilise the reach by reducing bank erosion and increasing reach sediment storage; 3) to test whether a reach-based wood reintroduction strategy could increase morphological diversity within the reach and thereby have a measurable affect on improving micro- and meso-habitat diversity for fish and hence fish species diversity and abundance.
The study area included two species that were high value recreational fish species, Australian bass (*Macquaria novemaculeata*) and eel-tailed catfish (*Tandanus tandanus*), both believed to be in decline over recent decades. Habitat simplification, and particularly desnagging, has been implicated as a primary factor leading to their decline. Also recorded in the study area were three fish species of some commercial value during their spawning phase - short-finned eel (*Anguilla australis*), long-finned eel (*Anguilla reinhardtii*) and sea mullet (*Mugil cephalus*). Little is known about the population dynamics of these species, however it is assumed that they too would have been under pressure from habitat simplification and loss, amongst other disturbances. As summarised in Table 3, most of these species have a strong preference for deep pool habitats (Pusey et al., 2004) and this habitat is thought to have diminished as a result of post-disturbance channel morphological response.

**Table 3 around here**

Within the context of a reach scale BACI experiment the following null hypotheses were posed regarding the expected responses to wood reintroduction: 1) that net sediment storage would be unchanged; 2) that pool habitat area would remain unchanged; 3) that morphological variability within both reaches will remain unchanged; 4) that fish species richness and abundance will show no significant variation between test and control reaches; 5) that fish assemblage composition will not vary significantly between these reaches.

**Methods**

**Reach Morphodynamics**

To enable quantitative analysis of geomorphic change induced within the experimental reach, a detailed topographic survey of the test and control reaches was conducted with a total station theodolite (c. 2000-3000 survey points per channel km) prior to ELJ construction, then at various intervals after construction following bed mobilising flows. The three-dimensional survey data was processed using *Surfer 7* (Golden Software, 1999) to generate contours and quantify depth classes. The contouring process involved superimposing a 1 x 1 m \(x-y\) grid, followed by application of a *Radial Base* smoothing function to fit an array of topographic contours across the channel zone at 0.2 m
intervals in the $\zeta$ dimension. The reach was re-surveyed at an equivalent resolution after major bed mobilising flows, in both the test and control reach. Survey 2 was an as-built (record) survey, and completed only in the test reach. Timing of the bed surveys is shown in Figure 4.

Figure 4 around here

Changes in the bed topography were quantified by comparing successive bed surveys with the baseline data. While only one baseline survey was completed in each reach, observations within the study reach over a 12 month period prior to the completion of the first survey indicated there were only very minor net changes associated with several large floods that occurred in early 2000.

From the survey data a number of morphological metrics were calculated to assess the effect of the ELJs on altering reach hydraulics and hence inducing bed scour, bar deposition and sediment storage (or retention) within the reach. Residuals of bed level changes for each survey compared with the baseline were determined at 0.2m depth slices and the areas of each depth class calculated. From this basic analysis a number of additional measures were derived. To reduce the effect of survey error on the results, residual data in the range +/- 0.2 m were excluded from the analysis. These data were shown to be fairly randomly spread throughout the reach and were assumed to be unduly influenced by measurement error.

**Net Reach Sediment Retention**

Volumetric changes for each depth class were determined from the product of depth class areas and their average depth. The net change in sediment deposited within, or lost from, the reach was calculated from the sum of all positive and negative residual volumes mapped within the reach. The reach volume data was then normalised to an equivalent bed surface area for the two reaches.

**Sediment Turnover**

Despite the relative proximity of the treatment and control reaches, the flashy nature of the flood regime and the low rates of sediment supply at the catchment scale mean that it is not safe to assume sediment transport continuity between the control and test reach.
during any one event. For this reason, a proxy measure of sediment turnover was
developed for the study to assess the relative change in sediment storage at each survey
in the two reaches, and to assess whether legitimate comparisons could be made of the
potential capacity for remoulding reach morphology, and habitat, during each period.
Sediment turnover was defined as the sum of all new deposition and scour between
consecutive surveys. In some respects it is a similar measure to sediment flux, however,
sediment turnover does not measure input and output from the reach. The sediment
turnover measure only provides a minimum measure of sediment remobilisation within the
reach during the interval between each survey, due to the fact that it only measures net
changes in bed morphology. The benefit of this measure is that it can be objectively
applied to provide a measure of the comparative flood effectiveness in the two reaches,
and hence whether the net response is more a function of inherent differences between
the reaches or the effect of the treatment. Sediment turnover is calculated from the sum
of the absolute values of the difference between the residuals of consecutive surveys with
respect to the baseline survey.

Reach Variability
A recent study by Bartley and Rutherfurd (2005) recommended a number of
morphometric indices by which reach morphology can be measured, all of which are
based on 2D cross sectional or longitudinal survey data. In this study we found that the
measures utilising 2D cross sectional or longitudinal profile data were highly sensitive to
variations in the resolution of the survey data, as well as the start and end points of the
survey. Given that there was significant spatial variability in the distribution of the major
changes and that the majority of changes where relatively subtle with respect to the
overall channel dimensions, we have opted to use a 3D bed morphological variability
index (denoted by $SD_{Δ3D}$), as well as the one of the 2D measures identified by Bartley
and Rutherfurd (2005) – the standard deviation of the residuals of the thalweg profile
(denoted by $SD_{TR}$).

2D Thalweg variability Index ($SD_{TR}$)
Thalwegs were extracted from each 3D survey using a semi-automated process within
ArcInfo. An iterative method was used, beginning with a line placed through the centre
of the data points as a first approximation of the thalweg. The entire length of the first
approximation line is converted into point data at 2m intervals and then a specified
radius around each point searched to find the lowest survey data point. The radius of the first iteration search must be large enough to reach the edge of the survey data points either side of the first approximation line. The low points found are converted into a second approximation thalweg line. The second approximation line is converted into point data at 2m intervals, and second iteration performed using a smaller radius. Similar iterations are repeated until a reasonable line is found. The process can capture anomalous points which are identified by an inspection of the plan map and longitudinal profile of the derive thalweg and removed. The Munni survey data thalwegs required four iterations at 30m 20m 10m and 5m. The Control survey data thalwegs required three iterations at 20m, 10m, and 5m. Once thalwegs were derived for each survey, these were plotted as a linear regression and the variability index calculated from the standard deviation of the residuals of thalweg point deviations from the line of best fit.

3D Bed Variability Change Index (SD_{3D}\Delta)
This index compares the standard deviation of the residuals of the full 3D bed data set for each survey with the baseline condition, survey 1. The residuals of each survey were calculated within _Surfer_ compared to a zero elevation surface, and these results used to calculate the residuals of the respective surveys with respect to survey 1. The output from this analysis forms the basis to the 3D residual plots in Figure 5. The index is then derived from the standard deviation of the residuals of change at each survey.

Pool and Bar Habitat Area change
For the purposes of this study a purely morphological method was adopted for assessing habitat change, whereby it was assumed that new scour greater than 0.4 m is classified as new pool habitat, while new deposition greater than 0.4 m in depth was characterised as new bar habitat. Using this approach removes much of the subjectivity from the analysis, particularly the problems associated with flow stage at the time of survey, and allows for comparisons in the creation of “new habitats” between each survey. However, it is recognised that this measure is only a proxy for changes in the total distribution of pool and bar habitat within each reach, and does not represent changes in the absolute area of pools and bars.

Change in Wood Volume in contact with Low-flow Channel
The volume of wood in contact with the nominal low flow level was estimated for each structure through time, taking into account the fact that some structures became buried and were effectively incorporated into bars, while others had additional scour around and within them resulting in more wood becoming effective habitat within the low flow water column. It was assumed that this would provide a measure of the habitat quality formed by individual log structures (principally in terms of substrate and to a lesser extent complex cover – sensu Crook and Robertson, 1999).

Change in Fish Community Structure

Fish sampling was conducted using a boat-mounted electrofisher or a backpack electrofisher, where appropriate, depending on the types of habitat. Navigable habitat units (pools) were sampled by single pass electrofishing using FRV Polevolt, a 3.6 m aluminium punt equipped with a 2.5 kW Smith-Root electrofishing system operated at between 340 and 1000V DC, 3 to 15 A pulsed at 60 Hz and 70–90% duty cycle. Immobilized fish were removed from the water by dip net and transferred directly to a live well, identified to species level, measured for length (fork length for species with forked tails, total length for species with rounded tails), and returned to the water alive. Fish observed to be affected by the electrofisher but not caught were also recorded where positive identification could be made. Each habitat unit was sampled by conducting a 2 min electrofisher shot within the designated area. Habitats too shallow to navigate (runs and riffles) were sampled in a similar manner using a 400W Smith-Root Model 12 backpack electrofisher. Water quality and a comprehensive suite of habitat attributes covering substratum type, particle size, structural habitat, riparian and aquatic vegetation, channel characteristics and cover were recorded for each site on each sampling occasion.

Prior to wood introduction the fish assemblage was sampled twice, in autumn (April 2000) and spring (September 2000) (figure 4). In the year following wood introduction, sampling occurred in summer (December 2000) and autumn (April 2001), after which sampling was undertaken on a quasi-annual basis each autumn (figure 4). Differences in species richness and abundance between the test and control reaches were analysed using two-way ANalysis Of VAriance (two-way ANOVA) with the number of sampling times before and after wood introduction used as replicates. ANalysis Of SIMilarity (ANOSIM) (Clarke and Warwick, 2001) was used to analyse changes in fish composition,
with SIMilarity of PERcentages (SIMPER) (Clarke and Warwick, 2001) used to identify which fish species contributed to the changes in assemblage structure.

Results

Graphical representations of the net morphological changes at each survey compared with the baseline are shown in Figure 5. The November 2000 plot represents the changes purely associated with the construction process, and then each subsequent plot shows the net cumulative change with respect to the baseline survey (survey 1). These changes are best appreciated by referring to the hydrograph timeline shown in Figure 4, which shows graphically the timing and relative magnitude (in terms of peak stage) of floods responsible for the various changes. Table 4 provides further insight into the high and low flow periods occurring in each interval based on peak daily flow for the experimental period. From these data it can be seen that in the first 9 months post construction (to June 2001), the test reach experienced 10 flow days greater than 100 cumecs within three events. Flows from 2002 to survey 6 were of unusually low discharge, as was the case across much of south-eastern Australia, with only 4 additional flow days greater than 100 cumecs in three events. Flows through the study period were, however, found to be reasonably representative of the magnitude and variability of the period of record for Tillegra gauge (table 4). High magnitude flow days were slightly above the average through the study period, while the proportion of low and no flow days was slightly below average. It is also recognised that through the twentieth century there have been periods of higher and lower flood activity, known locally as flood and drought dominated regimes (Warner, 1987). However, a number of studies have shown that morphologic response to these regimes is conditioned by the nature of riparian and in-stream disturbances (Brooks and Brierley, 2000; Hubble, 2004), and as such the responses to in-stream disturbance or rehabilitation would tend to be amplified by these phases.

Figure 5 and Table 4 around here

From the contour plots of residuals of change shown in Figure 5 it is apparent that the majority of changes were experienced in the period between surveys 2 and 3, corresponding to periods of highest flow. It is also clear from the residuals of change at survey 3 that most scour and deposition was focused around the log structures. It should
be reiterated that the changes indicated in survey 2 are purely a function of the works undertaken at the time of construction. Note that a large pool that was excavated around the two bank jam structures (DFJ1 and 2) placed in the reach in anticipation of the scour that would occur here (as well as providing the ballast for the structures), has persisted through time in terms of its area, as well as deepening over time. Similarly, most of the changes initiated within the period between November 2000 and March 2001 have persisted and in some cases amplified through time. The tendency has been that changes associated with the smaller floods after survey 4 have had the effect of reworking and depositing material in the low flow channel – thereby smoothing and masking some of the larger changes initiated by the larger floods soon after construction. A conceptual model of expected responses associated with individual structures can be seen in Figure 3, where the shading shows the location and extent of predicted scour and deposition. The wood structure numbers, along with their type, identity and wood volume, can be found in Table 2. Table 5 provides a descriptive summary of the purpose of each structure as well as the observed response associated with each structure and the cumulative response of the structures at the sub-reach scale.

Control Reach Patterns of Change

In contrast to the test reach, the pattern of adjustment in bed morphology within the control reach over the last five years was far less complex. From Figure 5B it can be seen that the major changes occurred at the top and bottom of the reach, which in both locations were associated with bedrock constrictions. Within the major straight section of the reach, a lateral bar that was deposited by the flood in late February 2001 was completely removed in the next flood. This was the only major depositional feature recorded within the reach other than that associated with the point bar at the bedrock bend at the downstream end of the reach, and the riffle at the top of the reach (see figure 5B). Hence it is apparent that the only changes that were in any way persistent were associated with stable protrusions into the flow, which in this case are bedrock.

Reach Scale Trends

The major questions posed for this experiment were framed around measuring the response to the wood rehabilitation treatment at the whole of reach scale, rather than
changes associated with individual structures. Hence, the experiment was testing the cumulative effect of all site-specific changes outlined above. In the following section we outline the observed responses at the reach scale.

**Sediment Turnover**

A measure of the relative amount of geomorphic work done in each reach between consecutive surveys is shown in sediment turnover plots (figure 6). This graph shows that in general there was slightly more turnover in the test reach compared with the control, with the exception of the changes between survey 5 and 6. The general trend may partly be explained by the fact that the test reach was larger and more diverse than the control, thereby providing more opportunity for scour and deposition. However, the fact that these data are normalised suggests the treatment is likely to be partly responsible for the variance in minimum turnover between surveys. Despite this, these are minimum turnover values that suggest there are no fundamental differences in background turnover rates between the two reaches. It is interesting to note that the sediment turnover associated with the construction process (survey 1-2) is equivalent to that induced by a sizeable flood that occurred in the interval between survey 3 and 4.

*Figure 6 around here*

**Sediment Storage**

The sediment turnover data provides valuable context for the net sediment storage change data in Figure 7. These data show firstly, as one would expect given that no material other than the timber was imported to the site, that the net change at the time of construction was virtually zero. Following the first major bed-mobilising flows after construction, as represented by survey 3 (figure 7), an order of magnitude difference in the net sediment storage can be seen within the Test reach (60m$^3$/1000m$^2$) compared with the Control (6m$^3$/1000m$^2$). Between survey 3 and 4 both reaches recorded a net loss due to the occurrence of a more erosive flood (see Brooks et al., 2004), however, the test reach still had a substantial net gain compared with the baseline, while the control was in deficit. Between survey 4 and 5 the test reach experienced a further net loss of sediment, albeit still being substantially in credit compared to the baseline condition, while the control reach remained at about the same net condition as it has been at the previous survey. By the final survey, both reaches experienced net gains of
approximately the same volume per unit area. In summary, it would appear that both reaches followed a similar trend in terms of net gains and losses between each survey (and associated floods as indicated in table 4.). However, the fundamental difference between the two reaches was that rehabilitation treatment provided a mechanism for substantially increasing sediment storage around the larger log jams. It would appear that within the context of the prevailing regional sediment supply conditions, the maximum potential sediment storage capacity associated with the log structures was attained within the first flood, less than 6 months after the treatment was completed, at which point there was an order of magnitude difference in increased sediment storage between the test and control reaches. Subsequent floods have reworked some of this stored sediment to the point where storage in the test reach at the final survey was just 2.5 times more than in the control reach. Hence, the rehabilitation strategy resulted in a persistent net increase in sediment storage, albeit somewhat dissipated over time. The pattern of behaviour within the control reach suggests that reach sediment storage was in dynamic equilibrium around the level measured at the commencement of the project, while the test reach established a new reach-scale dynamic equilibrium in the vicinity of 40 m³/1000 m² more than the control reach. This is not to say that subsequent reach scale storage will not fluctuate considerably around this level, depending on the flood regime and background sediment supply. Furthermore, should background sediment supply increase, a new reach-scale dynamic equilibrium may be attained which might completely drown out any influence induced by the log structures. Nevertheless, under present (2005) sediment supply conditions, the log structures appeared to be imparting some sustained new sediment storage at the reach scale.

Figure 7 around here

**Scour and Deposition Range**

A greater appreciation of the nature of differences in scour and fill between the two reaches can be seen in the cut and fill depth distribution plots shown in Figure 8. These plots show that the range of scour (cut) and depositional depths (fill) in the test reach is double that in the control. When the distribution of scour and deposition is visualised in the residual plots in Figure 5, it is clear that this additional range in the cut and fill depths is almost entirely explained by the effects of the log structures. Furthermore, when the relative changes between surveys are compared between the two reaches, with the
exception of the 0.2 – 0.4m depth class, there appears to be less variation between individual depth classes. This suggests the sediment stored within the test reach in association with the structures has become resistant to change, and that a large portion of the fluctuations in sediment storage within the test reach occurs over a large area within a relatively shallow depth class range (i.e. +/- 0.4m). As can be seen in Figure 5, most of the cut and fill in this shallow depth range is not directly associated with the log structures.

Reach Variability
Of the two morphologic diversity indices measured for each survey, the SD_{3D} (figure 9) showed that the test reach was consistently more complex than the control through all surveys, culminating at survey 6 with the test reach having three dimensional residual complexity index 22% higher than the control (0.37 cf 0.29 for the test and control reaches respectively). The thalweg variability index (SD_{TR}) shown in Figure 10 does suggest that the test reach variability has increased somewhat at survey 4 and 5, while the control variability declined over the same period. However, by survey 6, these data suggest that the situation was reversed albeit to a lesser extent. This graph also highlights the disparity in the inherent variability of the two reaches, suggesting the test reach was substantially more variable at the outset than the control. This higher baseline complexity is also reflected in the absolute values of three dimensional complexity, suggesting that the test reach was starting from a higher base complexity at the study outset.

Changes in Habitat Structure and Availability
In addressing the second and third hypotheses regarding habitat changes, there is a need to translate the reach scale sediment storage dynamics into measures that are likely to be meaningful to native fish species. The assumption was made at the project outset that reach geomorphic diversity had been reduced as a result of past river management works, and that pool habitat which was critical habitat for most of the target species (see table 3), had declined. A secondary assumption was that complex cover in the form of
structural woody habitat was also limiting within existing pools. Figure 11 shows the cumulative, net change in bar area through time in both reaches, while Figure 12 shows the respective change in the extent of pool area. These data show there was an increase in both pools and bars in the two reaches during the study period. However, the trend is both more pronounced and more consistent within the test reach. This reach showed a trend of bars increasing through time before reaching an apparent maximum representing transformation of 3.5% of the total bed surface area into new bar areas. The control reach on the other hand did not show a clear trend through time and only attained a maximum of around 2% new bar area by the time of survey 6.

Figures 11 – 12 around here

As might be expected, pool area in the test reach tended to increase in proportion to the increase in bar area, attaining a maximum of 6% of bed surface area transformed into new pool area at survey 5, and then decreasing in extent to around 4.5% by survey 6. Again the trend was less distinct in the control reach, where a maximum extent of around 2% of new pool area was attained by survey 4, which then declined markedly to less then 1% (compared to the baseline) by survey 6. This pattern can be seen as confirmation that the rehabilitation strategy has indeed performed as expected, given that it was predicated on initiating channel constriction as a means of inducing channel scour (along with direct scour associated with the log structures), and hence the creation of new pool habitat.

The other component of habitat change induced by the rehabilitation strategy was the increase in volume and surface area of wood within the wetted perimeter of the low flow channel (i.e. the portion of the channel where the wood could provide potential habitat under the prevailing low flow condition) (see table 4). Given that the rehabilitation strategy was primarily framed around the demonstration of stable log structure construction, and how these structures can be used to increase channel stability and sediment storage, a considerable proportion of the timber was buried at the outset, and was therefore not forming effective fish habitat within the low flow wetted perimeter. Given that the structures were modelled on natural formations found in undisturbed rivers, this was not an unnatural outcome, although, to many a fish biologist all this buried timber could be regarded as “wasted” potential habitat. In part, this dilemma is a
function of the fact that we were addressing multiple objectives within the study, and the inaccessibility of buried timber may partly explain the relatively poor response we measured in fish populations. Table 2 shows the surface area of wood contained within each structure along with the proportion exposed to the low flow wetted perimeter (i.e. the effective woody substrate for aquatic organisms) at each survey interval from construction onwards. These data show clearly that structures 1 and 2 have by far the greatest extent of effective wood substrate, and that by and large, this extent increased through time as the pool around and under the structures became scoured. Structures 6, 17 and 19 also showed marginal increases in the extent of effective substrate exposed through time, however, nearly all of the remaining structures experienced net losses in effective woody substrate exposed through time (i.e. due to burial). In total, there was a net decline of effective woody substrate within the low flow wetted perimeter through time from around 900 m² to 620 m², caused almost exclusively by burial of the logs, not the loss of timber from the study reach.

Fish Community Response
A total of 5618 fish was recorded over the seven sampling occasions, representing 13 species from 8 families (Table 6). In the control reach a total of 1082 fish were recorded encompassing nine species, while a total of twelve species and 4536 individuals were caught from the test reach. The most common species in both reaches were Australian smelt (Retropinna semoni), Cox’s gudgeon (Gobiomorphus coxii) and long-finned eels (Anguilla reinhardtii). One specimen of gambusia (Gambusia holbrooki) sampled in the test reach was the only exotic species recorded during the study period.

There was no significant effect of treatment on species richness five years after wood introduction (Figure 13) (two-way ANOVA, \( F = 1.96, \text{df} = 1,319, P = 0.16 \)), although there was considerable temporal variation in number of species recorded between sampling occasions (two-way ANOVA, \( F = 8.19, \text{df} = 1,319, P < 0.005 \)).

Five years after wood introduction there was no significant difference in fish abundance between the test and control reaches (two-way ANOVA, \( F = 0.44, \text{df} = 1,319, P = 0.51 \), log 10 transformed), although the seasonal timing of sampling had a significant effect on abundance (two-way ANOVA, \( F = 4.00, \text{df} = 1,319, P < 0.05, \text{log 10 transformed} \) (figure 14).
The species composition of the fish assemblage in the control reach did not differ significantly from that of the test reach (ANOSIM $P = 0.99$) prior to wood reintroduction, nor did composition in the control reach differ after wood introduction (ANOSIM $P = 0.9$). Five years following the rehabilitation treatment there was also no significant difference in fish assemblage structure between the control and test reaches (ANOSIM $P = 0.23$) or in the before/after test reach data (ANOSIM $P = 0.24$). An ordination of fish assemblage structure (based on multi-dimensional scaling) illustrates that fish assemblages in both reaches moved in the same direction and displayed similar variability between sampling occasions (figure 15), with the temporal variability almost certainly related to the seasonality of sampling.

Before rehabilitation, fish assemblages in the control and test reaches had a dissimilarity of 83% (SIMPER). The majority of this difference was induced by just four species. The test reach had a greater abundance of Australian smelt (44.5%) and long-finned eels (11%) compared to the control reach, and a lower abundance of Cox’s gudgeon (11%) and Australian bass (11.4%). After rehabilitation there was still 72% (SIMPER) dissimilarity between the reaches, with the same four species driving the patterns. Australian smelt (33%) and Cox’s gudgeon (18%) were more abundant in the test reach compared to the control, while Australian bass numbers increased in both reaches, although the increase was greater in the control reach.

The main changes in the fish assemblage in both the control and test reaches over time were the increased abundance of Australian smelt and Australian bass, and a slight decrease in long-finned eels. Cox’s gudgeon increased in the test reach but decreased slightly in the control. The topographic survey data showed that riffle area increased within the test reach during the study, particularly in sub-reaches 2 and 3. This habitat increase may explain the increase in abundance of Cox’s gudgeon through the study period.

To provide more detailed insight into the relationship between habitat change and fish numbers, a sub-set of the data was analysed in an attempt to tease out any site specific responses. Deflector Jams 1 and 2 (DFJ1 and DFJ2) (Figure 3, inset A) located at the...
upstream end of the test reach showed a notable increase in fish abundance following wood introduction. The Australian smelt, which were highly variable in abundance throughout both reaches, were excluded from the analysis as it was assumed that their mobile schooling habits could disproportionately affect results. Fish abundance around DFJ1 increased from only one individual fish before rehabilitation to 6.4 ± 2.0 per electrofishing shot following rehabilitation (Fig 16). At structure DFJ2 fish abundance increased from 4.0 ± 2.0 per electrofishing shot before rehabilitation to 12.4 ± 3.3 fish per shot after rehabilitation respectively (Fig 16). This change can be compared to reach averages of 4.3 ± 0.58 and 5.4 ± 0.68 for the test and control reaches respectively before rehabilitation and 6.0 ± 0.43 and 5.6 ± 0.65 for the test and control reaches respectively following rehabilitation. The low capture rate during sampling time 5 is most likely related to the winter conditions. Further to this, in a depletion survey carried out at DFJ2 (which entailed electrofishing until no further fish were caught) a total of 27 Australian bass, 3 eel-tailed catfish, 4 long-finned eels and 2 Cox’s gudgeon were extracted. Indeed, more Australian bass were caught from this one structure than were caught on average (i.e. 24 ±14) from the whole test reach during a single survey period.

Structure Performance and Changed Perceptions

Of the three primary objectives outlined for this experimental demonstration site, the first was framed primarily around altering perceptions towards the idea of putting wood back in streams, rather than taking it out, while the other two objectives were couched in terms of quantifying the response to the treatment and providing a more objective measure of the success or failure of the project. Most of the results and analysis have focused on evaluating the second and third objective, the morphological and ecological responses to the treatment. From a broader community perspective, one of the greatest perceived successes of the project to date was the least quantified; the fact that the structures remained in place, and the most visible structures appeared to be doing the primary job they were designed to do – erosion control. In effect, this was the sixth unstated hypothesis we were testing, which could be assessed by a simple measure of whether the structures remained or moved. On the whole we can state that most structures did perform largely as expected from an engineering and geomorphic perspective (see Table 5), although the response induced by some of the structures (notably structure 13) was greater than anticipated. Two of the log sill structures “failed” through undermining (structure 9) or outflanking (structure 14), effectively causing them
to cease functioning as bed controls, while structure 15 was buried. This is not to say
that the habitat potential of these structures was lost altogether, given that they were still
contributing woody substrate and cover to the reach (sensu Crook and Robertson, 1999).
A number of logs were also removed from individual structures (approx 20 in total
during the project; < 1 %), however, with the exception of three structural pieces on
structures 8 and 16, all of the logs that moved were cosmetic rack logs at the front of
deflector jam structures, and none of these logs moved beyond the test reach.

While we did not set out to quantify altered perceptions regarding large wood in rivers
(sensu Piegay et al., 2005), there has been a demonstrable change in community attitudes
towards using ELJs as a rehabilitation measure. Evidence for this can be found in the
fact that local farmers upon seeing the “success” of these structures following the first
few floods, lobbied the local authorities to have similar structures built elsewhere to
address similar problems. The “success” they were referring to was the simple fact that
the main structures did not wash away in what was generally regarded as a major flood,
and that the active erosion was perceived to have been halted. Furthermore, the
expected flooding issue was not considered to be significant (or even noticeable) by the
local landholders. Measured flood stage during the largest flood observed post-treatment
did in fact suggest there was up to a 10% increase in peak instantaneous stage compared
with a similar magnitude flood observed before the treatment. This is, however, likely to
lie within the measurement error for the gauging station rating curve.

These early “successes” have subsequently been communicated beyond this study region,
and the regional Catchment Management Authority no longer regards the technique as
experimental. A number of similar projects have now been completed in the same
region as part of on-going river management works. On the basis of this, largely
anecdotal, evidence, it would seem that the project has successfully addressed the first
objective, and has correspondingly shifted community perceptions to the point where
timber reintroduction to rivers is now actively promoted by the same organisation that
was removing logs (“desnagging”) less than a decade ago.

DISCUSSION: Implications for long term river rehabilitation

Sediment Storage
In light of this newfound enthusiasm for wood reintroduction, can the enthusiasm be
justified from the quantitative evidence of beneficial change? The treatment appears to
have been highly effective at not just halting the further decline of sediment storage within the reach, but increasing sediment storage. The test reach now stores, on average, around 40 m$^3$/1000 m$^2$ more than the control. Thus there is strong evidence to suggest that that sediment storage has increased in the wood treated reach compared with the control (hypothesis 1). This result tends to confirm evidence from channel evolution studies which suggests that high wood loadings are a prerequisite for sediment retention and hence the aggradation and evolution of some alluvial channels (sensu Montgomery et. al., 1996; Brooks et al., 2002). However, when this degree of change induced by the rehabilitation treatment is placed within the context of historical increases in channel cross-sectional area at the reach-scale, the extent of this additional storage appears rather small. While we do not know the exact magnitude of this channel expansion at this location during the historical period, the channel width increase evident since the first aerial photographs were taken of this reach in the 1940s suggests that a 50% increase in cross sectional area would be a very conservative estimate, particularly considering that the average return interval of the morphological bank full flood is now in the order of the 1:100 years. That major channel expansion occurred within the historical period is also backed up by oral evidence from the landholder whose family lived on this property for three generations (E Smith pers. comm., 2000).

At present the reach channel volume (at morphological bankfull) is approximately 187,000 m$^3$. Hence, if we assume conservatively that the pre-disturbance channel was approximately two thirds of this volume (124,600 m$^3$), then the average additional storage induced by the treatment across the reach (1,360 m$^3$) represents 2.2% of the sediment storage lost in the channel expansion phase. If we assume that the pre-disturbance channel condition represents the long term (thousands of years) equilibrium channel condition in which sediment transport capacity is in dynamic equilibrium with the sediment supply rate mediated by the pre-existing riparian vegetation and wood loading (sensu Brooks and Brierley, 2002), then the transport capacity of the current channel configuration is now well in excess of that which can be sustained by the long term sediment yield (i.e. it is supply limited). Hence, it is not surprising that a new mediated sediment storage capacity appears to have been attained very quickly, following the addition of the log structures. Furthermore, the observation that the additional sediment storage capacity in the test reach appears to have reached close to its storage capacity within the first flood, would tend to support the assertion that even though the
catchment may be supply limited, there is still ample sediment transport occurring due to
the high reach-scale transport capacity. Thus, if the goal of a long term river
rehabilitation strategy was to reduce channel capacity such that the reach sediment
transport capacity was brought down to somewhere near the long term sustainable yield
(leaving aside changing sediment supply issues at the catchment scale), a similar
magnitude of additional storage would need to be created in the reach every 5 years for
200 years. This is not to suggest this is necessarily a desirable management goal, rather it
highlights the substantial hysteresis associated with attempting to recover lost sediment
storage in sediment supply limited systems.

Habitat Change
The magnitude of new pool and bar area induced by the reach scale treatment outlined
here can notionally be represented by the difference between the test and control
reaches, which respectively equates to around 3.5% and 2.5% of pool and bar area as a
proportion of the total reach bed area. These results suggest that we can reject the
hypothesis that the log jam treatment has not created additional pool habitat, however it
is difficult to say whether this is a significant result or not. Given that the scale and cost
of the intervention undertaken here is probably at the upper end of the spectrum of
interventions likely to be undertaken in this region (approx. AUD $130/linear m
channel) the observed changes are fairly minor, and might partly explain the limited
response in the reach scale fish population. The magnitude of the increase in effective
structural woody habitat (sensu Gerhke and Brooks, 2003) shown in Table 2 is also fairly
low given the total volume of wood introduced to the reach. At the completion of
construction only 17% of the total wood surface area was within the low flow wetted
perimeter, declining to 11.7% after 4 years. From a fish habitat perspective the effective
wood surface area within the water column, coupled with the complexity of the habitat,
would appear to be the critical functions of wood for fish (Kennard, 1995; Crook and
Robertson, 1999; Pusey and Arthington, 2003). However, from a structural engineering
point of view a significant degree of timber burial is crucial for structure stability. This
represents a potential problem for the overall reach rehabilitation strategy that is a
function of attempting to address multiple objectives across the reach; something that is
generally accepted as being desirable (Rutherfurd, et al., 2001). In this case, the sediment
retention objectives of the project may well be in direct conflict with the habitat
objectives, given that maximum sediment storage is achieved when the timber structures are buried.

**Reach Complexity**

Of the two measures used to assess reach complexity, the standard deviation of residuals of 3D change appears to be the most reliable index for measuring a reach scale channel response to this type of intervention. This index effectively filters the background noise and hence provides a better means of measuring the response. The thalweg variability index is useful for assessing gross reach variability, however, as a monitoring tool in an experiment such as this, it is quite sensitive to start and end location and to the correct selection of the thalweg path (which despite being defined using an automated algorithm in Arc-GIS, inevitably has a degree of error depending on the location of the survey points).

The thalweg data do suggest that the test reach has a higher degree of baseline variability than the control, which may indicate that habitat complexity was not a limiting variable at the project outset and partly explain the lack of significant response in the fish population data. Hence, it would be wise to determine the reach variability index as one of the site selection criteria in future experiments of this nature. Ironically, had we selected a more degraded reach to conduct the treatment, something which we intentionally did not do in an attempt to avoid the “raising the titanic scenario” (sensu Rutherfurd et al., 2001), we may well have observed a more significant morphological and ecological response.

**Fish Response**

Fish assemblages in the control and test reaches were similar to those previously sampled in the Williams River near and above the town of Dungog (Gehrke and Harris, 2001; Howell and Creese, 2005, Howell and Creese, in press; Howell, 2005 unpublished data). In addition to the species recorded here, other studies have recorded empire gudgeon (*Hypseleotris compressa*) and bullrout (*Notesthes robusta*) but have failed to collect short-finned eels and gambusia (*Gambusia holbrooki*).

An increase in fish species richness and abundance was noted by Brooks et al. (2004) in the two surveys of the test reach after rehabilitation. This earlier analysis of the first 12
months response post construction (to June 2001) showed that the increased abundance was driven primarily by Australian smelt and Cox’s gudgeon, and that there appeared to be an association with increased habitat complexity induced by the rehabilitation strategy (Brooks et. al., 2004). Four years on, the results are far more equivocal, with no significant increase in species richness or abundance in the test reach now evident compared to the control. There are a number of possible explanations for this pattern of response, and most likely it is a combination of several factors.

First, the sampling regime suffered in that it was somewhat irregular due to competing commitments of the sampling crew. There is clearly a seasonal signal within the fish assemblage data, and hence the observed significant effect of time could be strongly influenced by the timing of surveys. The fact that the sampling regime shifted from semi seasonal to quasi-annual from 2001 is also likely to have had an effect on the observed trends. A second factor that could have caused the fish response to diminish with time is the effect of the flow regime throughout the study period. The hydrograph shown in Figure 4 indicates there was a run of large floods in the first 12 months after the completion of the treatment, and since then there have been extended periods of low or no flow. Indeed, we know that the river ceased to flow for 25 days between fish surveys 5 and 6. Under conditions of no flow we would expect that the pool refugia created by the structures would have increased the resilience of the population within the test reach (Boulton and Brock, 1999, Downes, et al., 2002; Arthington et al., 2005), and therefore we might expect this to be reflected in the data. The available data show no such effect.

A third factor may be that the treatment has altered predator/prey relationships, tipping the balance in favour of predatory species such as Australian Bass and long-finned eels, which have then reduced the abundance of small prey species. Indeed, the high proportion of predatory species extracted from DFJ2 during the depletion survey suggests that the structures provide ideal habitat for the main predatory species in this river.

A fourth possible explanation for the lack of an observed response in the test reach is that the sampling strategy employed was too insensitive to detect the response (i.e. observer error), given that it was attempting to replicate the sampling strategy employed prior to structure emplacement. As such the sampling regime was not geared to
sampling within and around the actual log structures, but was instead focused on open water habitat in pools, runs and riffles, and may well have completely missed any population or assemblage response to the treatment.

A fifth explanation is that given the treatment was addressing multiple objectives, which were predominantly reach scale geomorphic and engineering effects, that there was insufficient modification of the reach habitat at the appropriate meso- or micro-habitat scale to induce any measurable consequences for fish. The observed changes to habitat at the reach scale, which were essentially 3.5% by area of new pool habitat and around 600 m² of woody substrate surface area, may not have been sufficient to elicit a detectable response in a BACI design. The relatively small changes in the reach scale 3D bed variability index would tend to support this assertion.

A sixth explanation is that the spatial extent of the treated reach was insufficient to have any significant influence on fish populations at the system scale, possibly allowing higher order controls on population dynamics to override the effects of any improvements in habitat structure and availability at the reach scale. Indeed movement of fish among reaches in the Williams River is likely, considering the migratory behaviour of most of the species recorded (Gehrke et al., 2002, Pusey et al., 2004). Spatial autocorrelation can also make it difficult to distinguish between long-term changes in fish production in the rehabilitated area, and increased attraction of fish from nearby habitats into the modified area (e.g. Riley and Fausch, 1995). The lack of replication and lower sampling effort in the control reach, along with the irregularity of sample timing, also make it difficult to interpret population trends in terms of treatment effects alone.

While the results of the fish surveys were not statistically significant after five years at the assemblage scale, the site specific results from structures 1 and 2 provide some important insights into how rehabilitation projects such as this operative and how they might be improved. The fish survey results from these two structures tend to be consistent with the known habitat preferences of the key target species in this region (Pusey et al., 2004), but also suggest that the reach scale sampling strategy may have been under recording the numbers of some species. While it was anticipated that deep scour pools with large amounts of complex woody structures would provide excellent habitat for Australian bass, the presence of long-finned eels and Cox’s gudgeon suggests that there is flexibility
in individual species habitat preferences, and as such river rehabilitation treatments should be designed with a view to the habitat requirements of the fish assemblage rather than single species or a few species of social or recreational significance.

Studies of the efficacy of rehabilitation efforts are often somewhat constrained by logistical and practical issues to fully satisfy concerns about experimental design and statistical examination of field data (Downes et al., 2002). Other potentially confounding factors in this study are the effect of fish stocking by recreational fishers, preferential fishing pressure in the treatment reach, and the removal of a small in-stream barrier downstream of the study reach in 2003. A multiple lines and levels of evidence approach (Downes et al., 2002) is likely to be the most effective means of accounting for the effects of some of these confounding variables, and testing the effectiveness of adding structural woody habitat to a river system (Howell et al., 2005). This study has demonstrated that wood-based rehabilitation strategies can certainly have a positive influence on river channel stability, habitat availability and complexity and the composition of fish assemblages as well as population levels of individual species. However, the cost-benefit ratio needs to be carefully considered in future projects when one considers the scale of response outlined here. The study has also highlighted a range of issues regarding the appropriate spatial and temporal scale of both the treatment and monitoring of its effects. Future studies should focus on maximising effective wood loads without compromising the engineering and geomorphic attributes of wood structures. A more robust sampling design may be required, including several reference reaches (where possible) and increased spatial and temporal replication of fish surveys. However, the cost of more intensive survey is a real concern which may make such an approach prohibitive. To maximise the benefit of rehabilitation for fish large amounts of wood are required to permanently change meso-habitat scale features such as pool-riffle sequences to a sufficient degree to improve fish populations and adjust the composition of assemblages. In large-scale rehabilitation strategies there is also a need to design structures specifically to meet fish habitat preferences at the micro-scale. However, it is extremely risky attempting to focus purely on the reconstruction of a specific type and scale of habitat within a dynamic river system. The complex interplay between flow, sediment supply, sediment calibre and reach hydraulics makes it difficult to precisely predict the resultant array of habitat units. Consequently, the ideal approach is to emulate the features of complex natural systems as effectively as possible and spread the
risk of failure versus success by addressing rehabilitation of habitat structure and availability at a range of scales within a river reach.

CONCLUSION
This study has demonstrated that effective river rehabilitation that produces lasting and fundamental changes in river integrity and biodiversity is going to be a long, hard and expensive road, if we are serious about it. In south-eastern Australia the condition and health of many fluvial systems has been undergoing a consistent incremental decline for around 200 years. In some cases major geomorphic and ecological thresholds have been crossed (Brooks et al, 2003) that cannot be reversed readily or cheaply. Where they can be reversed they often involve large hysteresis effects, with recovery times sometimes being orders of magnitude greater than time taken to degrade the system (Brooks and Brierley, 2004). The outcomes of the Williams Rivers study suggest that interventionist rehabilitation efforts can begin to halt the process of channel degradation that has been underway for 200 years, but the level of intervention carried out here must be regarded as the minimum. Furthermore, this level of intervention (coupled with a range of riparian rehabilitation measures) will be required throughout the majority of the channel network if real progress is to be made towards reducing channel capacity, lowering stream power, reducing sediment transport capacity, and improving habitat quality and quantity. In addition to the biophysical hysteresis currently confronting river managers, it would also appear they also confront large institutional hysteresis, with the resource levels now far less than those previously used to engineer many of the current problems.

The low background rates of sediment supply in many southeast Australian rivers mean that the issue of excess sediment transport capacity is a major problem for long-term river dynamics. In the post-European period as channels enlarged and in-channel stream power increased, sediment transport capacity increased to levels well above those that could be supplied by background rates. Consequently, much of the sediment load in these rivers is now supplied from long-term alluvial storages, and stabilising the supply from these sources has been the focus of much river engineering effort over the last 40 years. Unless the issue of the imbalance between sediment transport capacity and supply is addressed, sediment depletion and ongoing channel instability will continue in perpetuity. The rehabilitation techniques developed in this study are part of the solution, albeit required on a substantially larger scale. At present the level of intervention
undertaken in this experiment is at the upper end of the spectrum of resources and effort expended on reach-scale river rehabilitation in south-eastern Australia, and yet the results outlined here suggest that even with this degree of intervention we are having a minimal effect, at least during the temporal extent of the study. The implication of this is that given the current resource levels being directed towards river rehabilitation, we must question whether we are having any real effect on the physical and ecological functioning of these systems in the short-term (5 years). This is not to say that the situation is hopeless, as the level of resources required to achieve the, not insubstantial, gains made in this project are not unduly excessive for an advanced OECD economy. It is a question of priorities, and of understanding that given the magnitude of changes to rivers, reversing 200 years of degradation is a long-term project that will require significant resources extending well beyond the typical 3–4 year political cycle.

Considering that the catchment area for the Williams study reach is only relatively small, scaling this type of rehabilitation strategy up to larger rivers within the current resourcing model will be fraught with logistical and resource problems. A whole of reach approach is unlikely to be feasible in higher order main stem channels, except at strategic locations where key infrastructure may be threatened, or where critical ecological assets require preservation or reconstruction. Over the majority of the riverscape, the preferred option would be to target the reestablishment of site-specific biophysical process linkages, such as hyporheic functioning (sensu Boulton et al., 2003; Wolfenden et al., 2004), and augmentation of targeted fish habitat (sensu Howell et al., 2005). This study has shown that simply creating small increases in pool and riffle area within a single reach is probably inadequate to achieve lasting gains in fish habitat sufficient to restore original historical fish assemblage structure and populations levels. The striking results obtained at structures 1 and 2 (DFJ1 and DFJ2), where deep pools with complex cover were created, highlight the potential for introduced wood structures to create high quality habitat for some fish species. However, further experimentation with a range of structures is needed to understand species specific preferences and responses if rehabilitation is to improve habitat for entire fish assemblages within a given reach.

Acknowledgements
This manuscript is dedicated to the memory of the late Edwin Smith on whose property these works were undertaken. Special thanks also to Naida Smith for her ongoing
support of this work. This project would never have proceeded without the support of Allan Raine from NSW DNR and Sharon Vernon from the then HCMT. Special thanks to Rod Gleeson for the survey work, the Dungog Work Crew and Rob Argent for their efforts implementing the rehabilitation works. Thanks to Brian Woodward, Matt Taylor and John Jansen for data collection and analysis; to Dean Oliver for drafting many of the figures and to John Spencer for the thalweg analysis. The project has benefited from the efforts of numerous field assistants over the years. Initial fish survey work was undertaken by Peter Gehrke, with assistance from Simon Hartley, Andrew Bruce, Tony Fowler, Debrah Ballagh, Michael Rodgers, Ian Wooden and Tom Rayner with fish sampling and data processing. Thanks also to Scott Babakaiffe and Chris Gippel for their input into the development of the study design; and two anonymous reviewers for their constructive comments. This research was funded by LWA grant no GRU27 and ARC Linkage Grant LP0346918 along with support from NSW Fisheries and Griffith University’s Centre for Riverine Landscapes.

References


FIGURE CAPTIONS

Figure 1. (after Brooks et al., 2003). Channel complexity associated with in-stream wood in an undisturbed river (top thalweg plot), contrasted with the thalweg from the adjacent Cann River catchment that has been cleared and desnagged.

Figure 2. Study area location map

Figure 3 (after Brooks et al., 2004) Map of test reach showing the 20 structure and the 5 sub-reaches referred to in the text. Shaded areas in the blow out boxes presents a conceptual prediction of the scour and depositional areas expected near each structure.

Figure 4. Hydrograph (peak daily discharge) from the Tillegra gauge (stn. 210011) 5.1 km downstream of the test reach. Also shown are the construction date, times of bed surveys (S1 – S6), and the fish sampling dates (F1 – F7). Inset shows the complete continuous stage record for Tillegra gauge. The shaded bar on the inset hydrograph represents the study period shown in the main figure.

Figure 5. Plots of the 3D residuals of bed elevation change in the test reach (5A) and control reach (5B) for each survey after construction with respect to the baseline survey. Reds and yellow shades represent deposition and blues and greens represent scour. Note the November 2000 survey (survey 2) was only completed for the test reach as this measures the effect of construction and no floods had occurred to induce any other change.

Figure 6. Graph showing minimum sediment turnover between consecutive surveys as a measure of the relative geomorphic effectiveness of flows in each reach.

Figure 7. Graph showing net change in sediment storage within each reach as compared with the baseline condition at each survey interval.

Figure 8. Graphs showing the relative extent of scour (cut) and deposition (fill) in different depth classes for the two reaches on the left hand plots. Note the depth classes of +/- 0.2m have been excluded as this is largely considered to represent noise over the
The majority of the reach in which there was relatively little change. Note the range of scour and deposition depths in the test reach are approximately double those in the control. The plots on the right show the change in extent of scour and deposition within various depth classes between consecutive surveys. Note that with the exception of the +0.2m depth class, the relative change (X axis range) is less in the test reach than the control, implying there is greater resistance to change in this reach.

**Figure 9.** Graph showing the relative changes in bar area (new deposition > 0.4m) within the study reaches through time.

**Figure 10.** Graph showing the relative changes in pool area (new scour < 0.4m) within the study reaches through time.

**Figure 11.** Graphs showing the relative change in 3D morphological complexity between the two reaches through the study period, as measured by the standard deviation of the 3D residuals with respect to the baseline survey.

**Figure 12.** Graphs showing the relative change in 2D thalweg complexity between the two reaches through the study period, as measured by the standard deviation of the 2D residuals from the line of best fit.

**Figure 13.** Changes in species richness, estimated as the mean number of fish species per electrofishing shot, before (samples 1 and 2) and after (samples 3 - 7) placing structural woody habitat in the test reach of the Williams River.

**Figure 14.** Changes in fish abundance, estimated as the mean number of individuals per electrofishing shot, before (samples 1 and 2) and after (samples 3 - 7) the wood reintroduction treatment.

**Figure 15.** Multi-dimensional scaling ordination showing trajectories and variability of fish assemblages in the control reach (solid symbols) and the test reach (hollow symbols) in respect to time of sampling from April 2000 to April 2005.
Figure 16. Species and average abundance of fish recorded from structures 1 and 2 (DFJ1 and DFJ 2), over time periods 1 (May 2000) to 7 (April, 2005)
TABLE CAPTIONS

Table 1. Log jam descriptions and functions.

Table 2. Log structure identification codes and characteristics as per Figure 3. Low flow wetted surface areas were estimated for the typical low flow condition of around 1 cumec.

Table 3. Primary meso-habitat preferences of all fish species recorded during the study.

Table 4. Flow spell analysis showing the key flow characteristics between the respective surveys. Flow thresholds were selected on the following basis: 170 Cumecs is the arithmetic mean annual flood and (coincidently) the flow that will enable mobilisation of the d50; 100 cumecs is the flow when all log structures are inundated and which will cause minor bed mobilisation; 50 cumecs is a flow likely to facilitate movement of aquatic fauna; 1 cumec represents the upper limit of the typical low flow discharge.

Table 5. Summary characteristics of individual structure design objectives, their site specific performance and the cumulative effects of the structures at the sub-reach scale. Structure condition codes refer to the condition of the structure at bed survey 6 and incorporate an assessment of the extent to which the structure is still performing the primary function for which it was designed. A) Fully functioning – structure in similar overall state to the “as built” condition; B) Structure partially modified but still largely performing as designed; C) Structure significantly modified- only partially performing design function; D) structure removed

Table 6. Fish species and numbers caught during the study.
<table>
<thead>
<tr>
<th>Log Structure Type</th>
<th>Primary Characteristics</th>
<th>Functional Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflector Jams (DFJs)</td>
<td>Large Multiple log jam structures built into eroding banks (typically 50 or more logs with root wads); suitable for banks subject to mass failure.</td>
<td>Bank erosion control structures; redirection of thalweg towards channel center (away from eroding bank toe); pool scour inducement – adjacent to upstream stream-ward edge of structure; complex habitat within structure itself.</td>
</tr>
<tr>
<td>Bar Apex Jams (BAJs)</td>
<td>Multiple log jam structures - typically 10 – 30 logs, built into the upstream apex of an existing bar or island</td>
<td>Bar stabilisation structures; inducement of bar/island deposition; complex habitat</td>
</tr>
<tr>
<td>Bank Revetment Structures (BRVTs)</td>
<td>Small structures consisting of several stacked logs (+/- root wads) parallel to flow at bank toe; generally only for low banks not subject to mass failure</td>
<td>Fluvial erosion control structures; ideal for recreation of bank undercut habitat</td>
</tr>
<tr>
<td>Log Sill Structures (LSs)</td>
<td>Small stacked log accumulations (generally pyramidal in section) generally buried into bed perpendicular to flow – ideally with DFJ or BAJ abutments on either side.</td>
<td>Bed control structures; inducement of step-pool type morphology; re-creation of hyporheic exchange functioning</td>
</tr>
</tbody>
</table>

Table 1
<table>
<thead>
<tr>
<th>Structure ID</th>
<th>No. logs</th>
<th>Wood vol. (m³)</th>
<th>Approx. Structure Vol. (m³)</th>
<th>total surface area of wood (m²)</th>
<th>@ srvy2</th>
<th>@ srvy3</th>
<th>@ srvy4</th>
<th>@ srvy5</th>
<th>@ srvy6</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFJ1</td>
<td>59</td>
<td>53.4</td>
<td>224</td>
<td>750</td>
<td>187</td>
<td>225</td>
<td>225</td>
<td>206</td>
<td>195</td>
</tr>
<tr>
<td>DFJ2</td>
<td>59</td>
<td>43.7</td>
<td>231</td>
<td>587</td>
<td>147</td>
<td>176</td>
<td>176</td>
<td>161</td>
<td>153</td>
</tr>
<tr>
<td>BRVT1</td>
<td>7</td>
<td>8.6</td>
<td>12</td>
<td>95</td>
<td>29</td>
<td>29</td>
<td>38</td>
<td>33</td>
<td>31</td>
</tr>
<tr>
<td>DFJ3</td>
<td>6</td>
<td>6.6</td>
<td>26</td>
<td>82</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LS1</td>
<td>3</td>
<td>2.6</td>
<td>2.6</td>
<td>39</td>
<td>4</td>
<td>10</td>
<td>10</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>BAJ1</td>
<td>24</td>
<td>18.3</td>
<td>65</td>
<td>261</td>
<td>0</td>
<td>13</td>
<td>52</td>
<td>65</td>
<td>26</td>
</tr>
<tr>
<td>DFJ4</td>
<td>25</td>
<td>19.5</td>
<td>104</td>
<td>279</td>
<td>70</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DFJ5</td>
<td>28</td>
<td>23.8</td>
<td>106</td>
<td>331</td>
<td>17</td>
<td>66</td>
<td>17</td>
<td>33</td>
<td>0</td>
</tr>
<tr>
<td>DFJ6</td>
<td>40</td>
<td>40.2</td>
<td>132</td>
<td>583</td>
<td>146</td>
<td>29</td>
<td>29</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>LS2</td>
<td>3</td>
<td>2.1</td>
<td>2.1</td>
<td>37</td>
<td>18</td>
<td>22</td>
<td>33</td>
<td>33</td>
<td>28</td>
</tr>
<tr>
<td>BRVT2</td>
<td>7</td>
<td>12.8</td>
<td>14</td>
<td>114</td>
<td>57</td>
<td>68</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>LS3</td>
<td>5</td>
<td>4.5</td>
<td>4.5</td>
<td>65</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DFJ7</td>
<td>109</td>
<td>91.9</td>
<td>260</td>
<td>1284</td>
<td>96</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LS4</td>
<td>5</td>
<td>6.2</td>
<td>6.2</td>
<td>73</td>
<td>18</td>
<td>29</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LS5</td>
<td>6</td>
<td>4.9</td>
<td>4.9</td>
<td>79</td>
<td>20</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DFJ8</td>
<td>11</td>
<td>9.6</td>
<td>19</td>
<td>129</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>6</td>
</tr>
<tr>
<td>LSC1</td>
<td>14</td>
<td>16.7</td>
<td>16.7</td>
<td>197</td>
<td>59</td>
<td>59</td>
<td>69</td>
<td>79</td>
<td>69</td>
</tr>
<tr>
<td>BRVT3</td>
<td>9</td>
<td>10.9</td>
<td>17</td>
<td>121</td>
<td>24</td>
<td>18</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BAJ2</td>
<td>13</td>
<td>10.6</td>
<td>55</td>
<td>154</td>
<td>8</td>
<td>0</td>
<td>15</td>
<td>23</td>
<td>8</td>
</tr>
<tr>
<td>DFJ9</td>
<td>3</td>
<td>2.5</td>
<td>11</td>
<td>34</td>
<td>0</td>
<td>0</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table 2
<table>
<thead>
<tr>
<th>Fish species</th>
<th>Common name</th>
<th>Meso-habitat Preferences</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anguilla australis</td>
<td>Short finned eel</td>
<td>Runs characterised by moderate gradient, moderate depth and moderate mean water velocity</td>
<td>Pusey et al. 2004</td>
</tr>
<tr>
<td>Anguilla reinhardtii</td>
<td>Long finned eel</td>
<td>Largest individuals - deep, slow-moving pools, Juveniles and adults - main channel rapids and runs characterised by high gradients, relatively shallow depths and high water velocities.</td>
<td>Pusey et al. 2004</td>
</tr>
<tr>
<td>Gambusia holbrooki</td>
<td>Gambusia</td>
<td>Pools and backwaters characterised by low mean water velocity</td>
<td>Froese and Pauly 2003</td>
</tr>
<tr>
<td>Gobiomorphus australis</td>
<td>Stripped gudgeon</td>
<td>Pools and runs characterised by low gradient, moderate depth and low mean water velocity</td>
<td>Pusey et al. 2004</td>
</tr>
<tr>
<td>Gobiomorphus coxii</td>
<td>Cox's gudgeon</td>
<td>Rapids, riffles and runs characterised by high gradient, moderate depth and moderate mean water velocity</td>
<td>Pusey et al. 2004, Richardson 1984</td>
</tr>
<tr>
<td>Macquaria novemaculeata</td>
<td>Australian bass</td>
<td>Deep, slow-moving pools with abundant in-stream cover</td>
<td>Richardson 1984</td>
</tr>
<tr>
<td>Mugil cephalus</td>
<td>Sea mullet</td>
<td>Highly mobile species found in a range of habitats and a variety of water depths</td>
<td>Pusey et al. 2004</td>
</tr>
<tr>
<td>Myxus petardi</td>
<td>Freshwater mullet</td>
<td>Deep pools characterised by low mean flow</td>
<td>Froese and Pauly 2003</td>
</tr>
<tr>
<td>Philypnoden grandiceps</td>
<td>Flat head gudgeon</td>
<td>Pools and runs characterised by low gradient, moderate depth and low mean water velocity</td>
<td>Pusey et al. 2004</td>
</tr>
<tr>
<td>oPhilypnoden Sp.1</td>
<td>Dwarf flat head gudgeon</td>
<td>Pools and runs characterised by low gradient, moderate depth and low mean water velocity</td>
<td>Pusey et al. 2004</td>
</tr>
<tr>
<td>Potomolosa richmondi</td>
<td>Freshwater herring</td>
<td>Runs characterised by low gradient, moderate depth and moderate to high mean water velocity</td>
<td>Howell unpublished data 2005</td>
</tr>
<tr>
<td>Retropinna semoni</td>
<td>Australian smelt</td>
<td>High gradient riffles and runs characterised by shallow depth and high mean water velocity.</td>
<td>Pusey et al. 2004</td>
</tr>
<tr>
<td>Tandanus tandanus</td>
<td>Eel tailed catfish</td>
<td>Juvenile fish - shallow, moderately flowing runs, Adults - deeper runs and pools</td>
<td>Pusey et al. 2004</td>
</tr>
</tbody>
</table>

Table 3
Flow statistics between consecutive bed surveys

<table>
<thead>
<tr>
<th>Dates</th>
<th>flow days&gt;170 cumecs</th>
<th>flow days&gt;100 cumecs</th>
<th>flow days&gt;50 cumecs</th>
<th>flow days&lt;1 cumec</th>
<th>flow days = 0 DAYS</th>
<th>TOTAL DAYS %DAYS&lt;1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Bedsurv1 1/04/2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Bedsurv2 1/11/2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Bedsurv3 20/03/2001</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Bedsurv4 1/06/2001</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Bedsurv5 20/01/2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Bedsurv6 1/04/2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Flow statistics between consecutive fish surveys

<table>
<thead>
<tr>
<th>Dates</th>
<th>flow days&gt;170 cumecs</th>
<th>flow days&gt;100 cumecs</th>
<th>flow days&gt;50 cumecs</th>
<th>flow days&lt;1 cumec</th>
<th>flow days = 0 DAYS</th>
<th>TOTAL DAYS %DAYS&lt;1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test FishSurv1 12/04/2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test FishSurv2 11/09/2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test FishSurv3 18/12/2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test FishSurv4 12/04/2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test FishSurv5 12/06/2002</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test FishSurv6 4/05/2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test FishSurv7 12/04/2005</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4
<table>
<thead>
<tr>
<th>Sub-reach</th>
<th>Structure #</th>
<th>Structure type</th>
<th>Intended purpose of structure</th>
<th>Site specific response to structure</th>
<th>Structure condition @ survey 6</th>
<th>Sub-reach cumulative response</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR1</td>
<td>1</td>
<td>DFJ</td>
<td>Bank erosion control; deflection of thalweg from bank toe; scour pool formation and maintenance; provision of complex cover within pool d/s of riffle.</td>
<td>No further bank erosion evident during study period; scour pool maintained and enhanced (i.e. &gt; than excavated – pool now ~ 1 – 1.5 deep x 4 x 15m);</td>
<td>A</td>
<td>Bar &amp; riffle aggraded u/s of structures 1 &amp; 2 following major floods in 2001 although some re-incision into riffle evident through 2003-04 – bringing riffle crest back to 1999 level; good deep water habitat created and maintained around structures 1 &amp; 2 throughout survey period; some aggradation in-channel at lower end of SR1, u/s of structures 4-6.</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>DFJ</td>
<td>Erosion control of low bank on inset bench; maintenance of ~1m deep run along bank; provision of bank overhang habitat</td>
<td>Minor erosion evident along top of log revetment; minor additional bed scour (~30cm) adjacent to root wad (&lt;2m wide); effective bank overhang maintained</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>BRVT</td>
<td></td>
<td></td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>DFJ</td>
<td>Channel constriction; roughness element to help induce deposition of riffle; abutment for LS1</td>
<td>Some scour around structure, but still performing primary functions</td>
<td>B</td>
<td>The sequence of alternating bank jam structures and cross spanning log-sills were intended to narrow the channel by inducing bank erosion, and create greater pool scour through a combination of flow constriction and flow separation – particularly around structure 6. In large part this has occurred. From survey 3 onwards deposition is evident within and upstream of the riffle on which structures 4 – 6 are located, and scour is evident immediately downstream – particularly in surveys (4-6). Deposition occurred below the scour in the vicinity of structures 8-10 - in effect creating a new pool riffle sequence. Substantial channel contraction and sediment storage has been induced by structures 6-9. Due to deposition on most structures, little wood remains in contact with the low-flow channel - hence providing limited direct aquatic habitat</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>LS</td>
<td>Bed control (increasing riffle crest height). Low flow hydraulic jump for inducing small d/pool.</td>
<td>Functioning as designed</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>BAJ</td>
<td>As per 4 + induction of mid-channel bar deposition; initiator of flow separation to help induce scour pool at d/s end of structure</td>
<td>Functioning as designed – although some small logs removed from structure</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>DFJ</td>
<td>Channel constriction; channel storage inducement</td>
<td>Substantial deposition around and within structure such that low flow channel no longer in contact with structure. Structure almost completely buried</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>DFJ</td>
<td>As per 7 + abutment for structure 10</td>
<td>Several non-structural logs lost; aggradation induced around structure has constricted the low flow channel</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>DFJ</td>
<td>As per 9 + bank erosion control &amp; deflection of thalweg from bank toe</td>
<td>Bank erosion in this vicinity appears to have slowed – with the exception of the bank 20m d/s of structure where a large tree was undermined and recruited to the channel. This log was incorporated into the structure</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>LS</td>
<td>Bed control, and induction of a new riffle (in conjunction with 8 &amp; 9).</td>
<td>Initially functioned well as bed control but subsequently failed through scour beneath logs. Now inducing a small scour hole beneath the X spanning logs – which is forming useful fish habitat – but not bed control</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>BRVT</td>
<td>Revetment of low bank and maintenance of farm water extraction point</td>
<td>Functioning as designed</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>SR3</td>
<td>12</td>
<td>LS</td>
<td>Bed control through chute</td>
<td>Functioned as designed before partial structure failure in 2005</td>
<td>B</td>
<td>At the study outset, there was a short steep riffle located immediately d/s of the large bend pool, at the bottom of which was a 3m high eroding bank - followed by a long glide down to the site where structure 16 is located. The original bank erosion has been halted and the riffle has been transformed to a much longer lower slope riffle with a series of small step pools. The new wood recruited by the d/s bank erosion was relocated to the bank toe, so as not to confound the outcomes of the experiment.</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>DFJ</td>
<td>Bank erosion control; scour induction; complex habitat formation</td>
<td>Pre-existing bank erosion halted; Structure induced &gt; 2m deposition, largely burying the whole structure, and shifting the channel laterally by ~ 20m; new scour shown in Fig 5 is the result of erosion into the vegetated mid-channel island rather than pool scour; increased radius of bend curvature caused new bank erosion 50m d/s and induced new wood recruitment.</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>LS</td>
<td>Bed control to help stabilise riffle crest at downstream end of main bend pool.</td>
<td>Structure failed when outflanked and buried as the channel shifted laterally</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>Sub-reach #</td>
<td>Structure type</td>
<td>Intended purpose of structure</td>
<td>Site specific response to structure</td>
<td>Structure condition @ survey 6</td>
<td>Sub-reach cumulative response</td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>----------------</td>
<td>------------------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------</td>
<td>--------------------------------</td>
<td>--------------------------------</td>
<td></td>
</tr>
<tr>
<td>SR4</td>
<td>15 LS</td>
<td>Inducement of longitudinal bed complexity</td>
<td>Structure buried as bed level aggraded in this segment – probably from sediment scoured immediately upstream, and as a result of the small backwater induced by str 16.</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16 DFJ</td>
<td>Inducement of bar aggradation, and hence constriction of flow against bedrock outer bank, and hence maximisation of scour in pre-existing bedrock forced pool</td>
<td>Some logs lost from structure but despite this substantial deposition induced on point bar complex immediately downstream</td>
<td>B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>17 LSC</td>
<td>Local habitat; bed control on u/s side of pool and to prevent material being reworked into the pool during smaller events.</td>
<td>Structure largely performing as intended, but partially buried due to deposition induced by str 16.</td>
<td>B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>18 BRVT</td>
<td>Erosion control of low bank on inset bench; maintenance; provision of bank overhang habitat</td>
<td>Bank erosion largely halted, however, substantial d/s extension of the point bar complex has buried the u/s half of the structure</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR5</td>
<td>19 BAJ</td>
<td>Bar/island stabilisation, riffle maintenance</td>
<td>Structure has maintained the location and function of a willow induced bar, and helped maintain the riffle</td>
<td>A</td>
<td>The bar/riffle complex within which these structures are located provides the hydraulic control for the pool at the top of SR5. This feature only appeared at this location in 1999 in association with the willows that had colonised the bed in this vicinity. The primary purpose of the structures at this site was to provide a more permanent structural control for this riffle with a view to maintaining the riffle at this location and thereby the pool habitat upstream. The strategy appears to have been successful, albeit that there has been reworking of sediment accreted in the floods immediately post-construction.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20 DFJ</td>
<td>Hydraulic roughness</td>
<td>As per 19</td>
<td>A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5
<table>
<thead>
<tr>
<th>Species</th>
<th>Control</th>
<th>Total</th>
<th>Treatment</th>
<th>Total</th>
<th>Grand Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling occasion</td>
<td>1 2 3 4 5 6 7</td>
<td>1 2 3 4 5 6 7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrofishing shots</td>
<td>11 11 11 11 11 11 11</td>
<td>77 30 37 36 38 39 247</td>
<td>648</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anguilla australis</td>
<td>0 0 0 0 0 0 0</td>
<td>0 0 0 0 0 0 0 1 0 0 0 0 0 1 0 2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anguilla reinhardtii</td>
<td>41 22 25 27 3 18 20</td>
<td>156 86 68 91 90 46 84 61</td>
<td>526 682</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gambusia holbrooki</td>
<td>0 0 0 0 0 0 0</td>
<td>0 0 0 0 0 0 0 1 0 0 0 0 1 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gobiomorphus australis</td>
<td>0 0 0 1 0 0 0</td>
<td>1 0 0 0 0 0 0 0 0 0 0 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gobiomorphus coxii</td>
<td>24 16 36 34 4 3</td>
<td>21 138 28 41 218 152 6 13</td>
<td>42 500 638</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Macquaria novemaculeata</td>
<td>8 3 19 45 4 6 8 93 8 3 30 32 28 44 22 165 258</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mugil cephalus</td>
<td>0 0 7 0 0 3 0 10 0 2 1 6 0 10 0 19 29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Myxus petardi</td>
<td>0 0 0 0 0 0 0 0 0 0 1 0 0 0 1 0 0 0 2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Philypnoden grandiceps</td>
<td>0 0 0 0 2 6 0 8 0 0 2 0 4 6 4 16 24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Philypnoden Sp.1</td>
<td>0 0 1 0 0 5 0 6 0 0 3 4 2 15 21 45 51</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potomolosa richmonida</td>
<td>0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Retropinna semoni</td>
<td>145 28 18 39 229 148 49 656 396 80 432 523 546 927 249 3153 3809</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tandanus tandanus</td>
<td>4 1 1 5 0 1 2</td>
<td>14 12 6 5 23 14 39 7 106 120</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 6**