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

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Abstract

This study evaluates an experiment in river rehabilitation 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 five floods greater than the mean annual, and a further five events capable of mobilising the gravel bed. Five surveys of channel terrain 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 fish population in the reach 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, 40 $m^3/1000\ m^2$ more sediment than in the control. These values, it would appear, represent a new reach-scale dynamic equilibrium storage level over decadal timescales. Additional sediment storage amounts to 3.5 m^3/m^3 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%, respectively. Two indices of morphologic diversity were measured for each bed survey: the standard deviation of 3D residuals of change compared with the baseline survey ($SD_{i\Delta 3D}$); and the standard deviation of thalweg residuals from the line of best fit (SD_{iTR}). The $SD_{i\Delta 3D}$ 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_{iTR} index does not detect clear changes because of 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 after 4 years, analysis of individual structures show them to be high quality habitat for native fish compared to the rest of the reach and the upstream control.

These results highlight the challenges river managers face in achieving measurable improvements in the health of aquatic ecosystems in highly altered rivers. Managers must confront hysteresis in a biophysical and institutional sense when attempting to

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reverse the degradation of 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 the diversity of stream habitat expected by the community. The study also highlights problems with the strategy of attempting to meet multiple objectives within a reach scale rehabilitation project. 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.

Keywords: River rehabilitation; Large woody debris; Geomorphic recovery; Complex response; Meso-habitat; Micro-habitat; Freshwater fish

1. Introduction

1.1. Historical channel changes

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). A growing body of literature 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, 1997; Page and Carden, 1998; Nanson and Doyle, 1999; Brooks and Brierley, 2000; Brooks et al., 2003). In some cases the capacity to transport sediment 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) (Fig. 1), accompanied by deleterious effects on aquatic ecosystem health and resilience (Crook and Robertson, 1999; Boulton and Brock, 1999; Pusey and Arthington, 2003).

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) 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'), occurred. 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 desnagged and straightened (Brooks, 1999a; Rutherfurd, 2000; Brooks et al., 2003; Erskine and Webb, 2003), and consequently in-channel stream power tended to be maximised and led 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 programs in river engineering were implemented

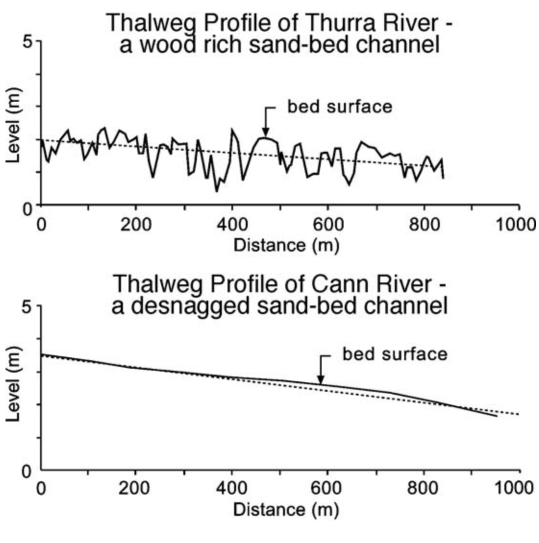


Fig. 1. Channel complexity associated with in-stream wood in an undisturbed river (top thalweg plot), contrasted with the thalweg from the adjacent Cann River catchment that has been cleared and desnagged (after Brooks et al., 2003).

throughout south eastern 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 (Rutherfurd, 2000). As an example, in the Hunter River (NSW) catchment (catchment area 22 000 km^2) during the 1970s, a work crew of 120 people engineered projects throughout this one catchment (Paul Collins, NSW Department of Natural Resources, personal communication, 2003).

1.2. Change towards ecologically based river management

In the last decade a fundamental shift in policy occurred 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 eight 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 paradigm for river management (sensu Hillman and Brierley, 2005), and given the capacity and resources that are now available for river rehabilitation works. This paper presents results from 5 years of post-implementation research on a relatively large experiment (within the current context) on reach-based rehabilitation in the Williams River, NSW, a northern tributary of the Hunter River (Fig. 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 four 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 evaluation 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.

2. Study area

A section of the Williams River at Munni was selected as the *test reach* (Fig. 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. The two reaches are similar with respect to regional-scale limitations of sediment-supply, gradient and channel capacity. Transport capacity is also comparable for the two reaches and 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 km^2 and 180 km^2, respectively (Fig. 2). The Munni test reach measured 1100 m in length (thalweg ~ 1500 m) with a baseline reach bed slope of 0.0019 and median clast size of 76 mm (n = 1800). The 500 m control reach (~ 600 m 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

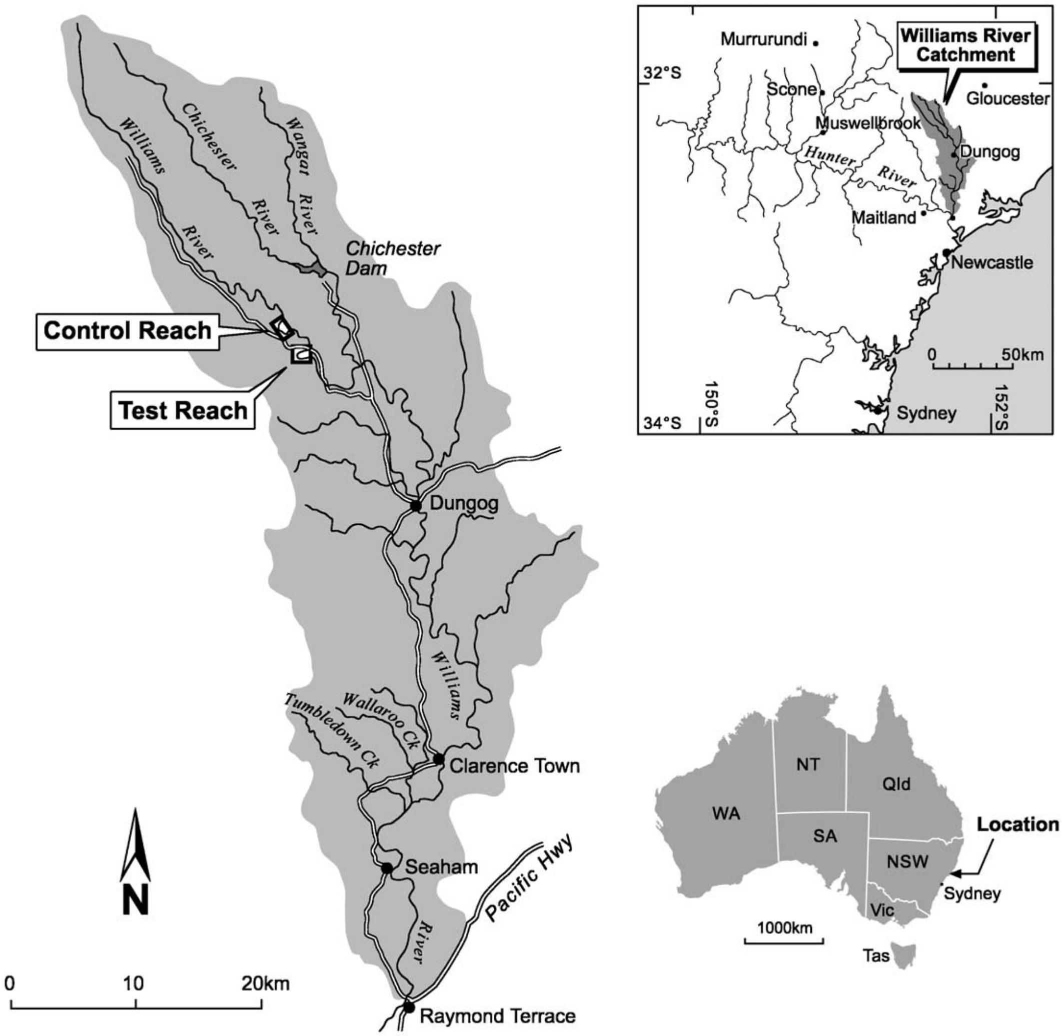


Fig. 2. Study area location map.

reach (catchment area 194 km^2). The mean annual flood (arithmetic mean of the annual flood series, 1931–1993) is 170 m^3 s^{-1}. Based on a cross-section defined by alluvial banks in the test reach, 'channel-full discharge' equals 800 m^3 s^{-1} — a flood with an average recurrence interval exceeding 100 years. Channel-full cross-sectional area ranges from 170 m^2 to 200 m^2 within both reaches. The large capacity is interpreted to stem from channel and riparian zone disturbance, particularly de-snagging, since European settlement (cf. Erskine and White, 1996; Brooks, 1999a,b; Brooks et al., 2003).

3. Strategy for reach rehabilitation

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, 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 (Fig. 3). Four types of

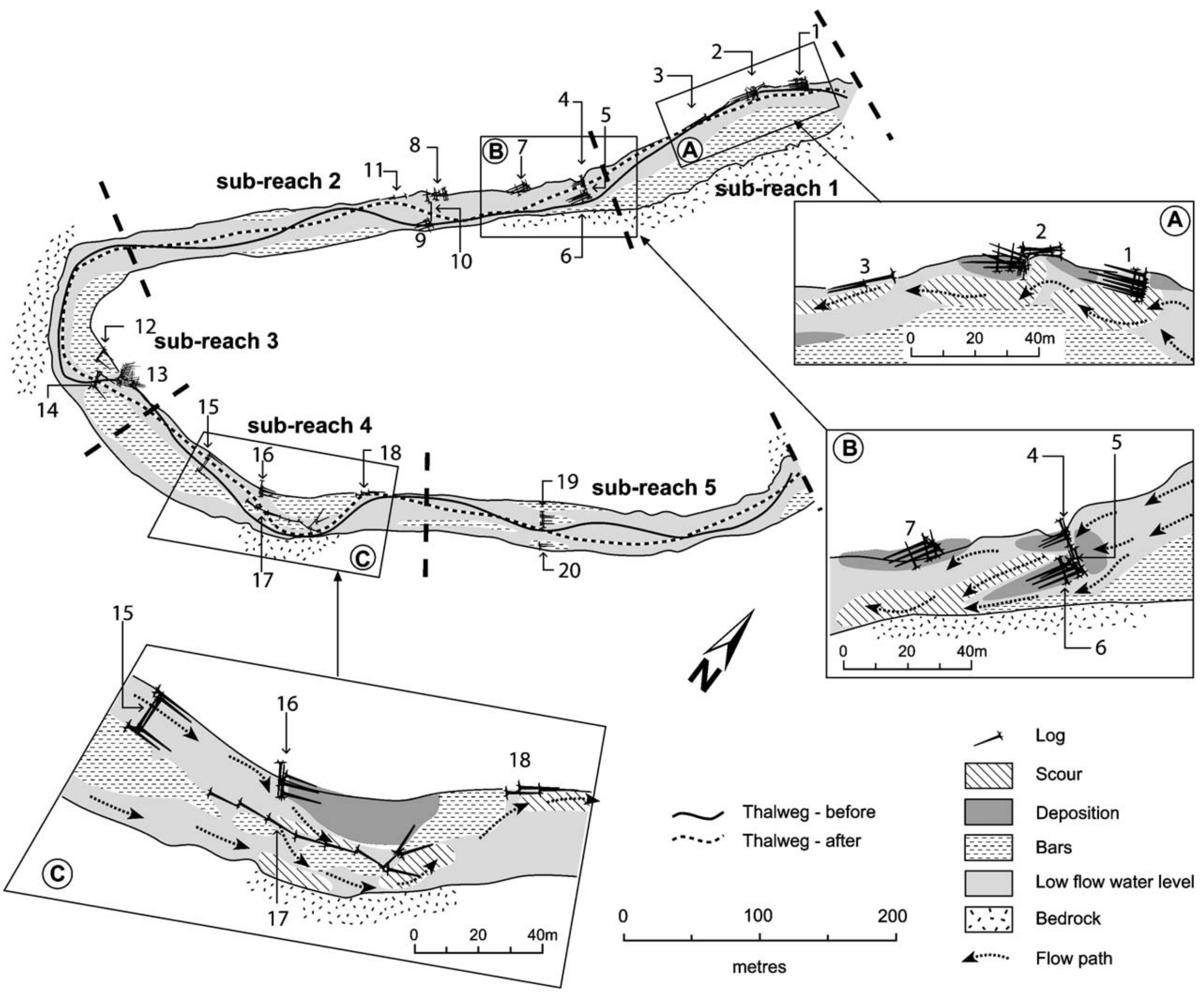


Fig. 3. Map of test reach showing the 20 structure and the five sub-reaches referred to in the text. Shaded areas in the blow out boxes presents a conceptual prediction of the scour and depositional areas expected near each structure (after Brooks et al., 2004).

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 Fig. 3. The volume of wood introduced to the test reach equates with an average reach loading of 0.0114 m^3/m^2 (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).

3.1. Objectives of rehabilitation strategy

When this rehabilitation experiment was proposed in 1998, river management in Australia was undergoing a radical transformation from the approach based on utilitarian engineering 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 new approaches were required that enhanced the natural biophysical processes within rivers, while at the same time meeting some 'traditional' engineering functions. 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

Table 1
Log jam descriptions and functions

Log structure type	Primary characteristics	Functional attributes
Deflector Jams (DFJs)	Large multiple log jamstructures built into eroding banks (typically 50 or more logs with root wads); suitable for banks subject to mass failure	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
Bar Apex Jams (BAJs)	Multiple log jam structures — typically 10–30 logs, built into the upstream apex of an existing bar or island	Bar stabilisation structures; inducement of bar/island deposition; complex habitat
Bank Revetment Structures (BRVTs)	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	Fluvial erosion control structures; ideal for re-creation of bank undercut habitat
Log Sill Structures (LSs)	Small stacked log accumulations (generally pyramidal in section) generally buried into bed perpendicular to flow — ideally with DFJ or BAJ abutments on either side	Bed control structures; inducement of step-pool type morphology; re-creation of hyporheic exchange functioning

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 to 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 sediment storage; (3) to test whether a reach-based wood

Table 2
Log structure identification codes and characteristics as per Fig. 3

Structure no.	Structure ID	No. of logs	Wood vol. (m^3)	Approx. Structure vol. (m^3)	Total surface area of wood (m^2)	Estimated surface area of wood in low flow channel (m^2)				
						@ srvy2	@ srvy3	@ srvy4	@ srvy5	@ srvy6
1	DFJ1	59	53.4	224	750	187	225	225	206	195
2	DFJ2	59	43.7	231	587	147	176	176	161	153
3	BRVT1	7	8.6	12	95	29	29	38	33	31
4	DFJ3	6	6.6	26	82	4	0	0	0	0
5	LS1	3	2.6	2.6	39	4	10	10	4	6
6	BAJ1	24	18.3	65	261	0	13	52	65	26
7	DFJ4	25	19.5	104	279	70	0	0	0	0
8	DFJ5	28	23.8	106	331	17	66	17	33	0
9	DFJ6	40	40.2	132	583	146	29	29	29	29
10	LS2	3	2.1	2.1	37	18	22	33	33	28
11	BRVT2	7	12.8	14	114	57	68	68	68	68
12	LS3	5	4.5	4.5	65	0	0	0	0	0
13	DFJ7	109	91.9	260	1284	96	0	0	0	0
14	LS4	5	6.2	6.2	73	18	29	0	0	0
15	LS5	6	4.9	4.9	79	20	12	0	0	0
16	DFJ8	11	9.6	19	129	0	0	0	13	6
17	LSC1	14	16.7	16.7	197	59	59	69	79	69
18	BRVT3	9	10.9	17	121	24	18	6	0	0
19	BAJ2	13	10.6	55	154	8	0	15	23	8
20	DFJ9	3	2.5	11	34	0	0	1.7	1.7	1.7
Total		436	389	1277	5294	903	756	740	750	621

Low flow wetted surface areas were estimated for the typical low flow condition of around 1 cumec.

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 the diversity and abundance, of fish species.

The study area included two species that were high value recreational fish, 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 the 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, and presumably 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.

Within the context of a reach-scale BACI experiment five 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.

4. Methods

4.1. Reach morphodynamics and sediment implications

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 (ca. 2000–3000 survey points per channel kilometer) prior to ELJ construction, then at various intervals after construction following bed mobilising flows. The three-dimensional survey data were processed using *Surfer 7* (Golden Software, 1999) to generate contours and quantify

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

Fish species	Common name	Meso-habitat Preferences	References
Anguilla australis	Short finned eel	Runs characterised by moderate gradient, moderate depth and moderate mean water velocity	Pusey et al., 2004
Anguilla reinhardtii	Long finned eel	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.	Pusey et al., 2004
*Gambusia holbrooki**	Gambusia	Pools and backwaters characterised by low mean water velocity	Froese and Pauly, 2003
Gobiomorphus australis	Stripped gudgeon	Pools and runs characterised by low gradient, moderate depth and low mean water velocity	Pusey et al., 2004
Gobiomorphus coxii	Cox's gudgeon	Rapids, riffles and runs characterised by high gradient, moderate depth and moderate mean water velocity	Pusey et al., 2004, Richardson, 1984
Macquaria novemaculeata	Australian bass	Deep, slow-moving pools with abundant in-stream cover	Richardson, 1984
Mugil cephalus	Sea mullet	Highly mobile species found in a range of habitats and a variety of water depths	Pusey et al., 2004
Myxus petardi	Freshwater mullet	Deep pools characterised by low mean flow	Froese and Pauly, 2003
Philypnoden grandiceps	Flat head gudgeon	Pools and runs characterised by low gradient, moderate depth and low mean water velocity	Pusey et al., 2004
Philypnoden sp. 1	Dwarf flat head gudgeon	Pools and runs characterised by low gradient, moderate depth and low mean water velocity	Pusey et al., 2004
Potomolosa richmondia	Freshwater herring	Runs characterised by low gradient, moderate depth and moderate to high mean water velocity	Howell, unpublished data
Retropinna semoni	Australian smelt	High gradient riffles and runs characterised by shallow depth and high mean water velocity.	Pusey et al., 2004
Tandanus tandanus	Eel tailed catfish	Juvenile fish — shallow, moderately flowing runs; Adults — deeper runs and pools	Pusey et al., 2004

classes of depth. The contouring process involved superimposing a 1×1 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 *z* dimension. The reach was re-surveyed at an equivalent resolution after major bed mobilising flows, in 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 Fig. 4.

Changes in the bed topography were quantified by comparing successive bed surveys with the baseline data. Whereas 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 that only very minor net changes were 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 were calculated as vertical deviations from the 3D surface model and are interpreted as changes in bed elevation from the baseline at 0.2 m depth slices. To reduce the effect of survey error on the results, residual data between ±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.

4.1.1. Net retention of sediment in the reach and turnover of sediment

Volumetric changes for each class of depth were determined from the product of the surface area of each depth class and the 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 volume data for each reach were normalised to an equivalent bed surface area.

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 a continuity of sediment transport between the control and test reach during any one event. For this reason, a proxy measure of turnover of sediment 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 respect it is a similar measure to sediment flux, however, sediment turnover does not measure input and output from the reach. The measure of turnover of sediment only provides a *minimum* measure of sediment remobilisation within the reach during the interval between each survey, because t it only measures net changes in bed morphology. The benefit of this measure is that it can be objectively

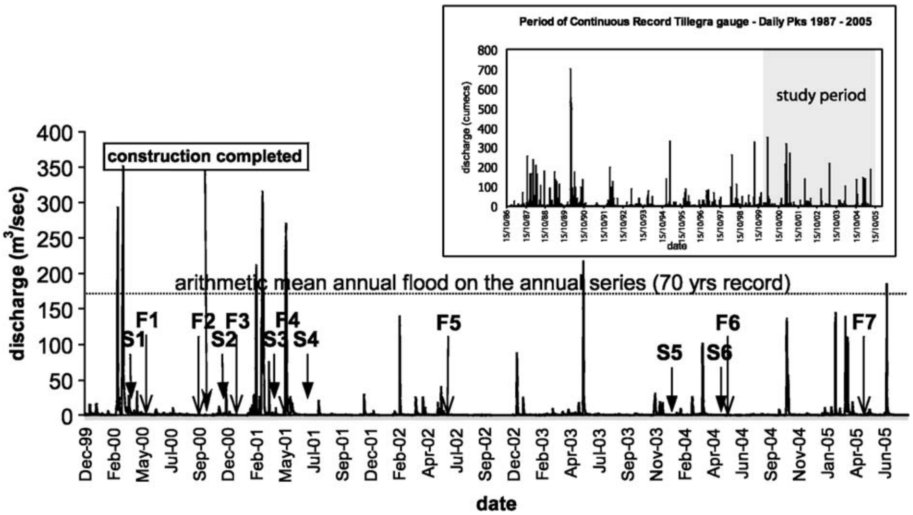


Fig. 4. Hydrograph (peak daily discharge) from the Tillegra gauge (Stn. 210011) 5.1 km downstream of the test reach. Also shown are the construction date, times of bed surveys (S1–S6), and the fish sampling dates (F1–F7). Inset shows the complete continuous stage record for Tillegra gauge. The shaded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

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. Turnover of sediment is calculated from the sum of the absolute values of the difference between the residuals of consecutive surveys with respect to the baseline survey.

4.1.2. Reach variability: indices of change in 2D thalweg variability and 3D bed 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. The measures utilising 2D cross-sectional or longitudinal profile data in this study were highly sensitive to variations in the resolution of the survey data, as well as the start and end points of the survey. Significant spatial variability exists in the distribution of the major changes and the majority of changes were relatively subtle with respect to the overall dimensions of the channel. A 3D bed morphological variability index (denoted by $SD_{i\Delta 3D}$) was selected for measuring bed variability. In addition, one of the 2D measures identified by Bartley and Rutherfurd (2005) was used: the standard deviation of the residuals of the thalweg profile (denoted by SD_{iTR}).

The *2D thalweg variability index* (SD_{iTR}) measures changes in the thalweg longitudinal profile for successive topographic surveys. 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 2 m 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 on 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 2 m 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 30 m, 20 m, 10 m and 5 m. The Control survey data thalwegs required three iterations at 20 m, 10 m, and 5 m. 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.

The *3D bed variability change index* ($SD_{i\Delta 3D}$) is the standard deviation of the residuals calculated by subtracting the baseline condition (survey 1) from the next topographic survey. The residuals of each survey with respect to the baseline were calculated within *Surfer* by subtracting the baseline 3D grid data from each successive 3D grid. The output from this analysis forms the basis to the 3D residual plots in Fig. 5. The index is then derived from the standard deviation of the residuals at each survey.

4.2. Changes to habitat and aquatic ecosystems

For the purposes of this study purely morphological methods were adopted for assessing habitat change.

4.2.1. Change in pool and bar habitat area

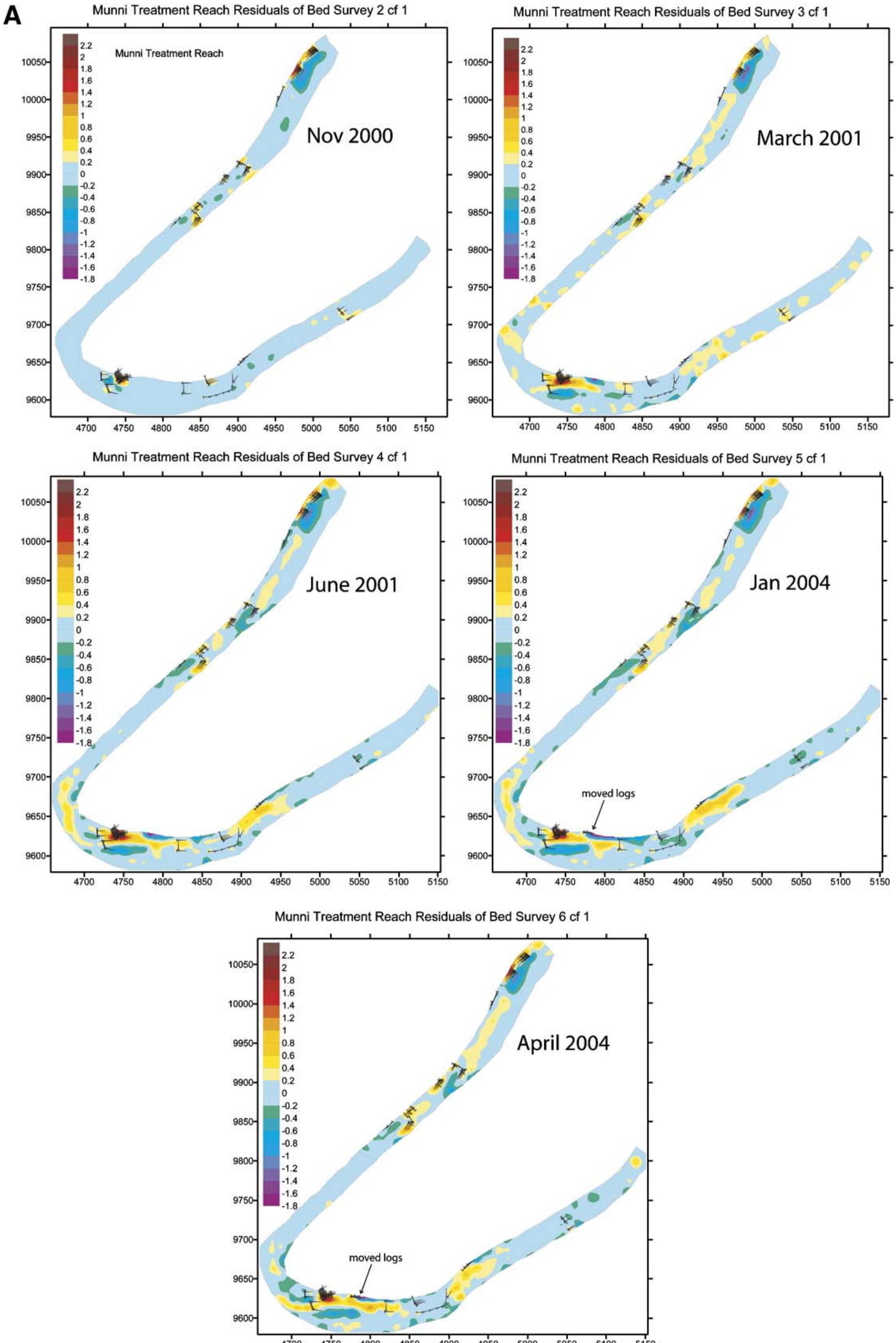
New scour greater than 0.4 m was assumed to be new pool habitat, while new deposition greater than 0.4 m in depth was classified as new bar habitat. This approach removes much of the subjectivity from the analysis, particularly the problems associated with flow stage at the time of survey, and allows comparisons between each survey to be used to identify the creation of "new habitats". This measure is only a proxy for changes in the total distribution of pool and bar habitat within each reach, however, and does not represent changes in the absolute area of pools and bars.

4.2.2. Change in the volume of wood in contact with low-flow channel

The volume of wood in contact with the nominal low flow level was estimated for each ELJ structure through time, taking into account 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 changes in volume would provide a measure of the habitat quality formed by individual log structures (principally in terms of wood substrate and to a lesser extent complex cover — sensu Crook and Robertson, 1999).

4.2.3. Change in fish community structure

Fish sampling was conducted using a boat-mounted electrofisher or a backpack-mounted electrofisher, where appropriate, depending on the types of habitat.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Munni Treatment Reach Residuals of Bed Survey 3 cf 1
March 2001
Munni Treatment Reach Residuals of Bed Survey 4 cf 1
June 2001
Munni Treatment Reach Residuals of Bed Survey 5 cf 1
Jan 2004
moved logs
Munni Treatment Reach Residuals of Bed Survey 6 cf 1
April 2004
moved logs
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
10050
10000
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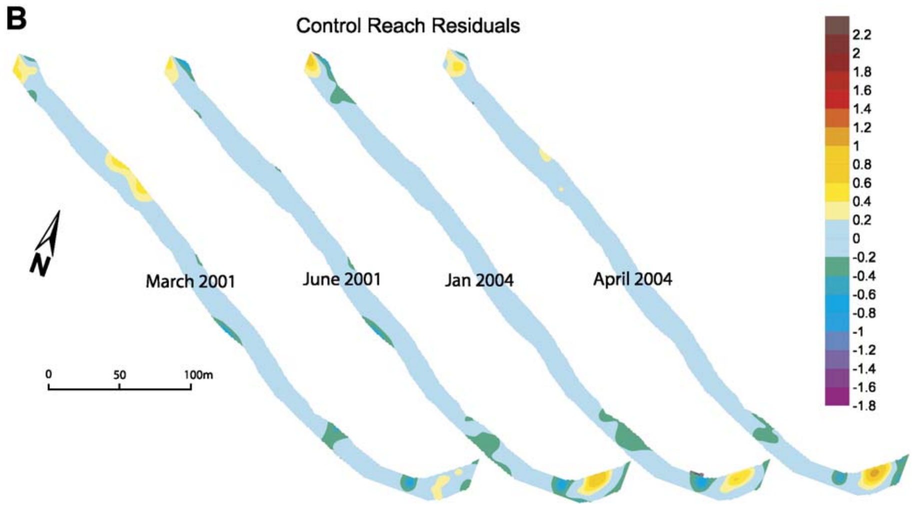

Fig. 5. Plots of the 3D residuals of bed elevation change in the test reach (A) and control reach (B) for each survey after construction with respect to the baseline survey. Reds and yellow shades represent deposition and blues and greens represent scour. Note the November 2000 survey (survey 2) was only completed for the test reach as this measures the effect of construction and no floods had occurred to induce any other change. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 1000 V DC, 3–15 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 400 W 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) (Fig. 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 (Fig. 4). Differences in species richness and abundance between the test and control reaches were analysed using two-way analysis of variance (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. Multi-dimensional scaling (MDS) (Clarke and Warwick, 2001) was used to illustrate changes in fish community assemblage over time.

5. Results

Graphical representations of the net morphological changes at each survey compared with the baseline are shown in Fig. 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 Fig. 4, which shows 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. These data show that in the first nine 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 four additional flow days greater than 100 cumecs in

Table 4
Flow spell analysis showing the key flow characteristics between the respective surveys

	Dates	Flow days> 170 cumecs	Flow days> 100 cumecs	Flow days> 50 cumecs	Flow days< 1 cumec	Flow days=0	Total days	%Days<1	
Flow statistics between consecutive bed surveys									
Test Bedsurv1	1/04/2000								Before
Test Bedsurv2	1/11/2000	0	0	0	113	0	214	53	Post-constr
Test Bedsurv3	20/03/2001	5	7	9	67	0	140	48	After
Test Bedsurv4	1/06/2001	3	3	5	33	0	72	46	
Test Bedsurv5	20/01/2004	1	2	5	754	25	964	78	
Test Bedsurv6	1/04/2004	0	2	2	33	0	70	47	
		9	**14**	**21**	**1000**	**25**	**1460**	**68.5**	**Total study**
		0.62	*0.96*	*1.44*	*68.5*	*1.71*	*100*		*% Total study*
CntrlBedsurv1	5/04/2000								Before
CntrlBedsurv3	24/03/2001	5	7	9	182	0	354	51	After
CntrlBedsurv4	5/06/2001	3	3	5	31	0	72	43	
CntrlBedsurv5	24/01/2004	1	2	5	756	25	964	78	
CntrlBedsurv6	5/04/2004	0	2	2	32	0	70	46	
		9	**14**	**21**	**1001**	**25**	**1460**	**68.6**	**Total study**
		0.62	0.96	1.44	68.6	1.71	100		% Total study
		33	***66***	***125***	***4332***	***270***	***6808***		***All record***
		0.48	*0.97*	*1.84*	*63.63*	*3.97*	*100*		*% Record*
Flow statistics between consecutive fish surveys									
Test FishSurv1	12/04/2000								Before
Test FishSurv2	11/09/2000	0	0	0	62	0	152	41	
Test FishSurv3	18/12/2000	0	0	0	73	0	98	74	After
Test FishSurv4	12/04/2000	5	7	10	57	0	115	50	
Test FishSurv5	12/06/2002	3	4	5	312	0	426	73	
Test FishSurv6	4/05/2004	1	3	6	527	25	692	76	
Test FishSurv7	12/04/2005	0	7	8	262	0	344	76	
		9	**21**	**29**	**1293**	**25**	**1827**	**71**	**Total study**
		0.49	*1.15*	*1.59*	*70.8*	*1.37*	*100*		*% Total study*
Cntrl Fish Surv1	13/04/2000								Before
Cntrl Fish Surv2	12/09/2000	0	0	0	63	0	152	41	
Cntrl Fish Surv3	19/12/2000	0	0	0	72	0	98	73	After
Cntrl Fish Surv4	13/04/2001	5	7	10	57	0	113	50	
Cntrl Fish Surv5	11/06/2002	3	4	5	312	0	426	73	
Cntrl Fish Surv6	3/05/2004	1	3	6	526	25	692	76	
Cntrl Fish Surv7	13/04/2005	0	7	8	263	0	346	76	
		9	**21**	**29**	**1293**	**25**	**1827**	**71**	**Total study**
		0.49	1.15	1.59	70.8	1.37	100		% Total study
		33	***66***	***125***	***4332***	***270***	***6808***		***All record***
		0.48	*0.97*	*1.84*	*63.63*	*3.97*	*100*		*% Record*

Flow thresholds were selected on the following basis: 170 cumecs is the arithmetic mean annual flood and (coincidentally) 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.

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. Through the twentieth century periods of higher and lower flood activity occurred, known locally as flood and drought dominated regimes (Warner, 1987). A number of studies have shown, however, that morphologic response to these regimes is conditioned by the nature of riparian and in-stream disturbances (Brooks and Brierley, 2000; Hubble, 2004), and the responses to in-stream disturbance or rehabilitation tend to be amplified by these phases.

From the contour plots of residuals of change, shown in Fig. 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. The residuals of change at survey 3 show that most scour and deposition was focused around the log structures. The changes indicated in survey 2 are purely a function of the works undertaken at the time of construction. A large pool, 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 maintained its area and has deepened 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 for changes associated with the smaller floods after survey 4 to rework and deposit 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 Fig. 3, where the shading shows the location and extent of predicted scour and deposition. The numbers of the wood structure, along with the 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.

5.1.1. 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 5 years was far less complex. Fig. 5B reveals 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 Fig. 5B). Hence, the only changes that were in any way persistent were associated with stable protrusions into the flow, which in this case are bedrock.

5.1.2. 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 tested the cumulative effect of all site-specific changes outlined above. In the following section we outline the observed responses at the reach scale.

5.1.3. Sediment turnover

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

5.1.4. Sediment storage

The data for sediment turnover provide valuable context for the data of net change in sediment storage shown in Fig. 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 flows that mobilised the bed after construction, as represented by survey 3 (Fig. 7), an order of magnitude difference in the net storage of sediment can be seen within the test reach (60 m^3/1000 m^2) compared with the control (6 m^3/1000 m^2). Between surveys 3 and 4 both reaches recorded a net loss because of 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 surveys 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, both reaches followed a similar trend in terms of net gains and losses between each survey (and associated floods as indicated in Table 4.). The fundamental difference between the two reaches,

Table 5
Summary characteristics of individual structure design objectives, the site specific performance and the cumulative effects of the structures at the sub-reach scale

Sub-reach	Structure no.	Structure type	Intended purpose of structure	Site specific response to structure	Structure condition @ survey 6	Sub-reach cumulative response
SR1	1	DFJ	Bank erosion control; deflection of thalweg from bank toe; scour pool formation and maintenance; provision of complex cover within pool d/s of riffle.	No further bank erosion evident during study period; scour pool maintained and enhanced (i.e. > than excavated – pool now ~1–1.5 deep × 4 × 15 m)	A	Bar and riffle aggraded u/s of structures 1 and 2 following major floods in 2001 although some re-incision into riffle evident through 2003–2004 — bringing riffle crest back to 1999 level; good deep water habitat created and maintained around structures 1 and 2 throughout survey period; some aggradation in-channel at lower end of SR1, u/s of structures 4–6
	2	DFJ	As per 1	As per 1	A	
	3	BRVT	Erosion control of low bank on inset bench; maintenance of ~1 m deep run along bank; provision of bank overhang habitat	Minor erosion evident along top of log revetment; minor additional bed scour (~30 cm) adjacent to root wad (<2 m wide); effective bank overhang maintained	A	
SR2	4	DFJ	Channel constriction; roughness element to help induce deposition of riffle; abutment for LS1	Some scour around structure, but still performing primary functions	B	The sequence of alternating bank jam structures and cross spanning log-sills were intended to narrow the channel by inducing bar deposition, 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
	5	LS	Bed control (increasing riffle crest height). Low flow hydraulic jump for inducing small d/s pool	Functioning as designed	A	
	6	BAJ	As per 4 + inducement of mid-channel bar deposition; initiator of flow separation to help induce scour pool at d/s end of structure	Functioning as designed — although some small logs removed from structure	B	
	7	DFJ	Channel constriction; channel storage inducement	Substantial deposition around and within structure such that low flow channel no longer in contact with structure. Structure almost completely buried	A	
	8	DFJ	As per 7 + abutment for structure 10	Several non-structural logs lost; aggradation induced around structure has constricted the low flow channel	B	
	9	DFJ	As per 9 + bank erosion control and deflection of thalweg from bank toe	Bank erosion in this vicinity appears to have slowed — with the exception of the bank 20 m d/s of structure where a large tree was undermined and recruited to the channel. This log was incorporated into the structure	A	
	10	LS	Bed control, and inducement of a new riffle (in conjunction with 8 and 9)	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	C	
	11	BRVT	Revetment of low bank and maintenance of farm water extraction point	Functioning as designed	A	
SR3	12	LS	Bed control through chute	Functioned as designed before partial structure failure in 2005	B	At the study outset, there was a short steep riffle located immediately d/s of the large bend pool, at

	13	DFJ	Bank erosion control; scour inducement; complex habitat formation	Pre-existing bank erosion halted; Structure induced >2 m deposition, largely burying the whole structure, and shifting the channel laterally by ∼20 m; 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 50 m d/s and induced new wood recruitment	A	the bottom of which was a 3 m 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.
	14	LS	Bed control to help stabilise riffle crest at downstream end of main bend pool	Structure failed when outflanked and buried as the channel shifted laterally	D	
SR4	15	LS	Inducement of longitudinal bed complexity	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	C	The primary goal here was to enhance complexity by inducing channel contraction and maximising the extent of the existing bedrock forced pool. The intention was to induce additional accretion on the point bar through the location of a deflector jam at the head of the point bar, thereby contract the channel and increasing flow depth/unit discharge and hence scour within the pool. The strategy had mixed success, with the initial bar deposition reworked downstream in subsequent events, where it had little effect on the channel capacity adjacent to the pool. The resulting pattern of bar aggradation may indeed have locally reduced the energy gradient through the pool.
	16	DFJ	Inducement of bar aggradation, and hence constriction of flow against bedrock outer bank, and hence maximisation of scour in pre-existing bedrock forced pool	Some logs lost from structure but despite this substantial deposition induced on point bar complex immediately downstream	B	
	17	LSC	Local habitat; bed control on u/s side of pool and to prevent material being reworked into the pool during smaller events	Structure largely performing as intended, but partially buried due to deposition induced by str 16	B	
	18	BRVT	Erosion control of low bank on inset bench; maintenance; provision of bank overhang habitat	Bank erosion largely halted, however, substantial d/s extension of the point bar complex has buried the u/s half of the structure	A	
SR5	19	BAJ	Bar/island stabilisation, riffle maintenance	Structure has maintained the location and function of a willow induced bar, and helped maintain the riffle	A	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.
	20	DFJ	Hydraulic roughness	As per 19	A	

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.

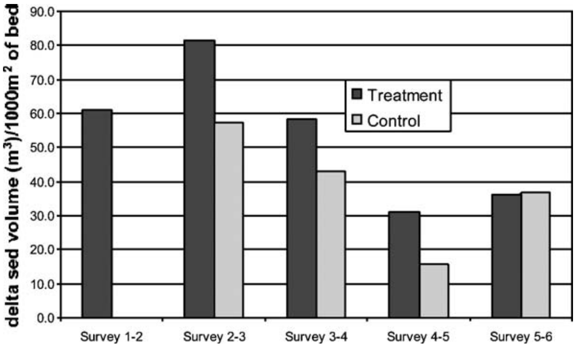

Fig. 6. Graph showing minimum turnover of sediment between consecutive surveys as a measure of the relative geomorphic effectiveness of flows in each reach.

however, was that rehabilitation treatment provided a mechanism for substantially increasing sediment storage around the larger log jams. Within the context of the prevailing regional conditions of sediment supply, the maximum potential storage capacity of sediment associated with the log structures was apparently attained within the first flood, less than 6 months after the treatment was completed, at which point an order of magnitude difference in increased sediment storage existed 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 response within the control reach suggests that sediment storage in the reach was in dynamic equilibrium around the level measured at the commencement of the project (over decadal timescales), while the test reach established a new reach-scale dynamic equilibrium in the vicinity of 40 m^3/1000 m^2 more than the control reach. Subsequent reach scale storage may 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.

5.1.5. The range of scour and deposition

A greater appreciation of the nature of differences in scour and fill between the two reaches can be seen in the distribution of depths in the cut and fill plots shown in Fig. 8. These plots show that the range of scour (cut) and depositional depths (fill) in the test reach is double that in the control. The distribution of scour and deposition in the residual plots (Fig. 5) show 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 0.2–0.4 m depth class, the test reach apparently has less variation between individual classes of depths. 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 class range of depth (i.e. ±0.4 m). As can be seen in Fig. 5, most of the cut and fill in this shallow range of depths is not directly associated with the log structures.

5.1.6. Reach variability

Of the two morphologic diversity indices measured for each survey, the $SD_{i\Delta 3D}$ (Fig. 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 and 0.29 for the test and control reaches, respectively). The thalweg variability index (SD_{iTR}), shown in Fig. 10, does suggest that the variability in the test reach has increased somewhat at surveyS 4 and 5, while the control variability declined over the same period. By survey 6, however, 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, and suggests the test reach was substantially more variable at the outset than the control. This

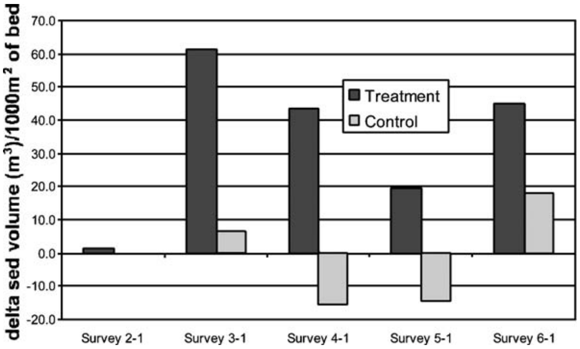

Fig. 7. Graph showing net change in sediment storage within each reach as compared with the baseline condition at each survey interval.

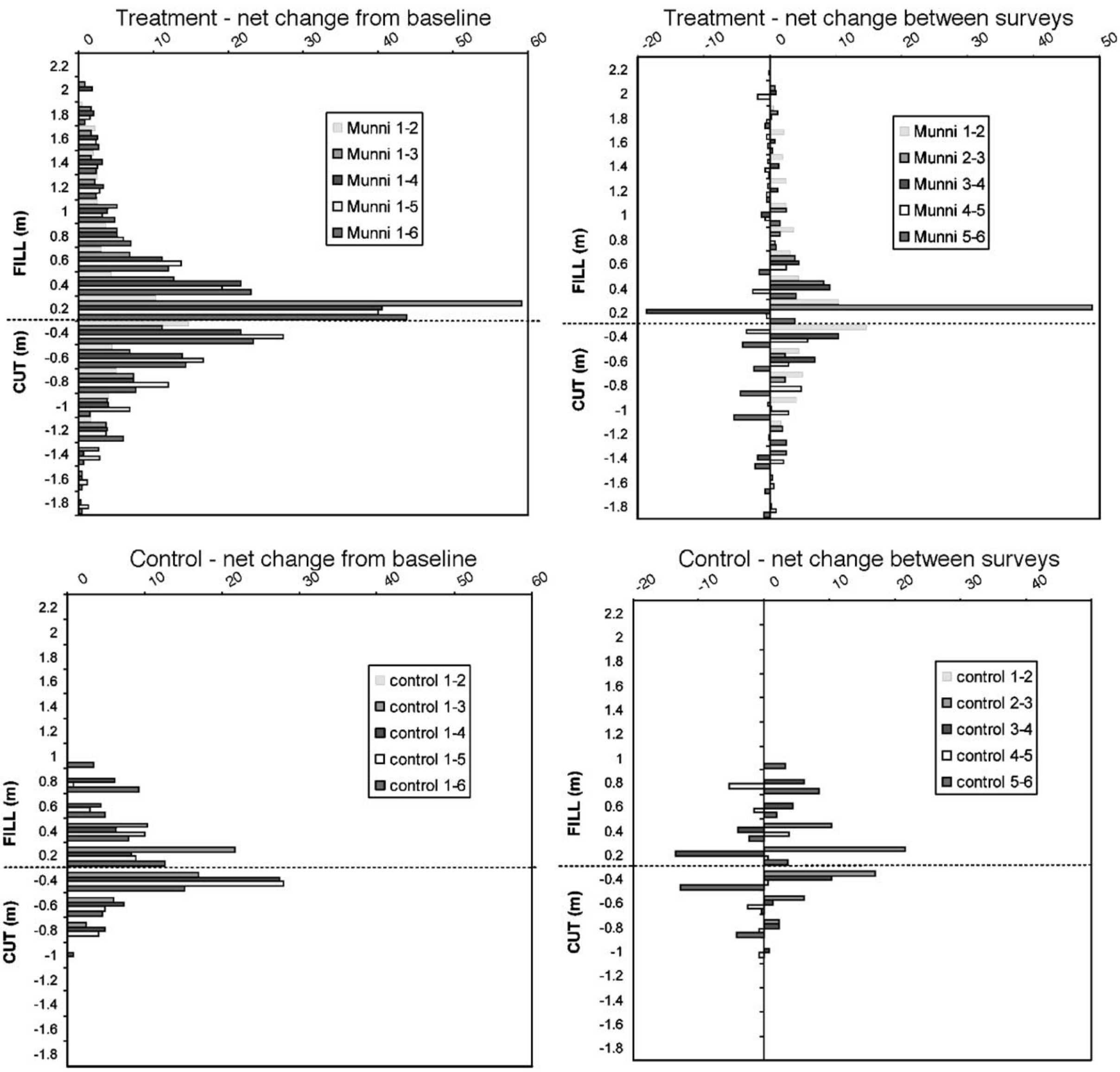

Fig. 8. Graphs showing the relative extent of scour (cut) and deposition (fill) in different classes of depth for the two reaches on the left hand plots. The ±0.2 m class of depth has been excluded as this is largely considered to represent noise over the majority of the reach in which relatively little change was observed. The range of scour and deposition depths in the test reach is 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. With the exception of the +0.2 m class of depth, the relative change (*X* axis range) is less in the test reach than the control, implying greater resistance to change occurs in this reach.

higher complexity of the baseline is also reflected in the absolute values of three dimensional complexity, and suggested that the test reach was starting from a higher degree of base level complexity.

5.2. Changes in habitat structure and availability

In addressing the second and third hypotheses regarding habitat changes, the reach-scale sediment-storage dynamics need to be translated into measures that are likely to be meaningful to native fish species. The assumption was made at the project outset that the geomorphic diversity of the reach 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 (Table 3), had declined. A secondary assumption was that complex cover in the form of structural woody habitat was also limiting within existing pools. Fig. 11

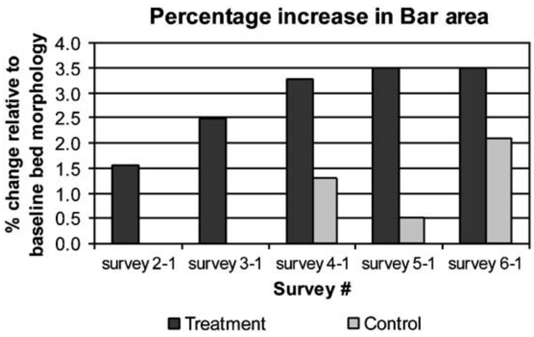

Fig. 9. Graph showing the relative changes in bar area (new deposition > 0.4 m) within the study reaches through time.

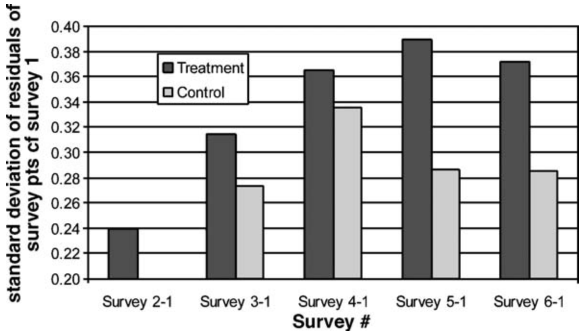

Fig. 11. Graphs showing the relative change in 3D morphological complexity between the two reaches through the study period, as measured by the standard deviation of the 3D residuals with respect to the baseline survey.

shows the cumulative, net change in bar area through time in both reaches, while Fig. 12 shows the respective change in the extent of pool area. These data show an increase in both pools and bars in the two reaches during the study period. The trend, however, is 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.

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 strategy of rehabilitation 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.

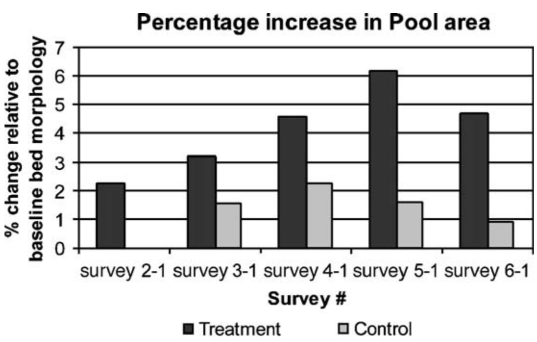

Fig. 10. Graph showing the relative changes in pool area (new scour < 0.4 m) within the study reaches through time.

The other component of habitat change, induced by the program of rehabilitation, 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) (Table 4). Given that the strategy of rehabilitation was primarily framed around the demonstration of the construction of stable log structure, 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 fish biologists all this buried timber could be regarded as “wasted” potential habitat. In part, this dilemma is a function of addressing multiple objectives within the study, and the inaccessibility of buried timber may partly explain the relatively poor response that 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 this extent increased through time as the pool around and under the structures became scoured. Structures 6, 17 and 19

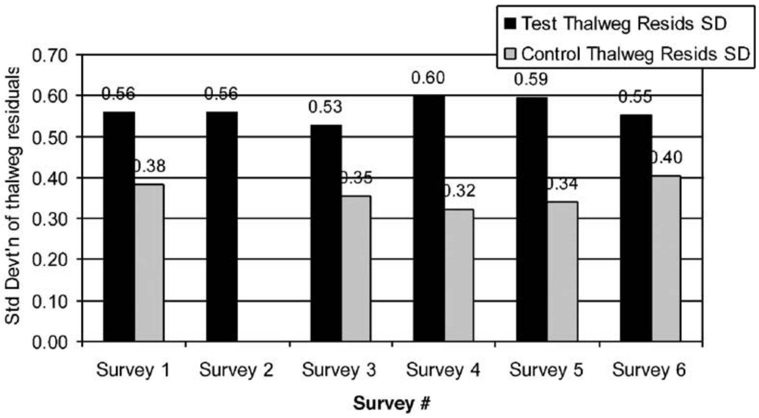

Fig. 12. Graphs showing the relative change in 2D thalweg complexity between the two reaches through the study period, as measured by the standard deviation of the 2D residuals from the line of best fit.

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, a net decline of effective woody substrate occurred within the low flow wetted perimeter through time from around 900 m^2 to 620 m^2, caused almost exclusively by burial of the logs, not the loss of timber from the study reach.

5.2.1. Fish community response

A total of 5618 fish from 13 species within eight families was collected over the seven sampling occasions (Table 6). In the control reach a total of 1082 fish from nine species was recorded, while a total of twelve species and 4536 individuals was collected 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 (*A. reinhardtii*). The only alien species recorded during the study period was a single specimen of *Gambusia holbrooki* from the test reach. No significant effect of treatment on species richness was observed 5 years after wood introduction (Fig. 13) (two-way ANOVA, $F=1.96$, $df=1{,}319$, $P=0.16$), although considerable temporal variation was observed in the number of species recorded between sampling occasions (two-way ANOVA, $F=8.19$, $df=6{,}319$, $P<0.005$). Five years after wood introduction, no significant difference in fish abundance was observed between the test and control reaches (two-way ANOVA, $F=0.44$, $df=1{,}319$,

Table 6
Fish species and numbers caught during the study

Species	Control							Total	Treatment							Total	Grand Total
Sampling occasion	1	2	3	4	5	6	7		1	2	3	4	5	6	7		
Electrofishing shots	11	11	11	11	11	11	11	77	30	30	37	37	36	38	39	247	648
Anguilla australis	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	2	2
Anguilla reinhardtii	41	22	25	27	3	18	20	156	86	68	91	90	46	84	61	526	682
Gambusia holbrooki	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1
Gobiomorphus australis	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1
Gobiomorphus coxii	24	16	36	34	4	3	21	138	28	41	218	152	6	13	42	500	638
Macquaria novemaculeata	8	3	19	45	4	6	8	93	8	3	30	32	26	44	22	165	258
Mugil cephalus	0	0	7	0	0	3	0	10	0	2	1	6	0	10	0	19	29
Myxus petardi	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	2	2
Philypnoden grandiceps	0	0	0	0	2	6	0	8	0	0	2	0	4	6	4	16	24
Philypnoden sp. 1	0	0	1	0	0	5	0	6	0	0	3	4	2	15	21	45	51
Potomolosa richmondia	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1
Retropinna semoni	145	28	18	39	229	148	49	656	396	80	432	523	546	927	249	3153	3809
Tandanus tandanus	4	1	1	5	0	1	2	14	12	6	5	23	14	39	7	106	120
Grand total	222	70	107	151	242	190	100	1082	531	201	782	833	644	1139	406	4536	5618

Exotic species denoted by *.

$P=0.51$, log 10 transformed), although the seasonal timing of sampling had a significant effect on abundance (two-way ANOVA, $F=4.00$, $df=6,319$, $P<0.05$, log 10 transformed) (Fig. 14).

Fish assemblage structure, based on the presence/absence of individual species, did not differ significantly between test and control reaches prior to wood introduction (ANOSIM $P=0.99$), nor did it differ significantly after wood introduction ($P=0.90$). Essentially the same species were present in the control and test reaches prior to and immediately after wood introduction in the test reach. Indeed, the same suite of species were present in control and test reaches 5 years after wood introduction ($P=0.23$) and no difference in assemblage composition could be detected ($P=0.24$) in the test reach after wood introduction. Ordination (MDS) revealed that temporal changes in assemblage composition were common to test and control reaches (i.e. they followed similar trajectories in ordination space through time) (Fig. 15) in response to some seasonal aspect of the riverine environment.

Before rehabilitation, fish assemblages in the control and test reaches had a dissimilarity of 17% (SIMPER) whilst after rehabilitation only 28% (SIMPER) dissimilarity was evident between the reaches. The main changes in the fish assemblage in 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.

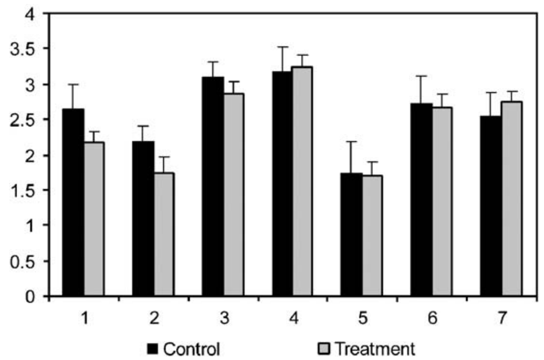

Fig. 13. Changes in species richness, estimated as the mean number of fish species per electrofishing shot, before (samples 1 and 2) and after (samples 3–7) placing structural woody habitat in the test reach of the Williams River.

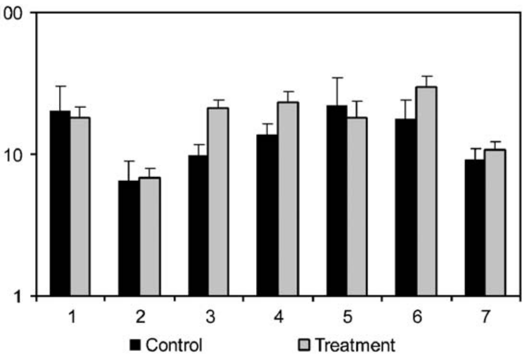

Fig. 14. Changes in fish abundance, estimated as the mean number of individuals per electrofishing shot, before (samples 1 and 2) and after (samples 3–7) the wood reintroduction treatment.

To provide more detailed insight into the relationship between habitat change and numbers of fish, a subset of the data was analysed in an attempt to tease out any site-specific responses. Deflector Jams 1 and 2 (DFJ1 and DFJ2) (Fig. 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 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 rate of capture 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.

5.3. Structure performance and changed perceptions

Of the three primary objectives outlined for this experimental demonstration site, the first was framed

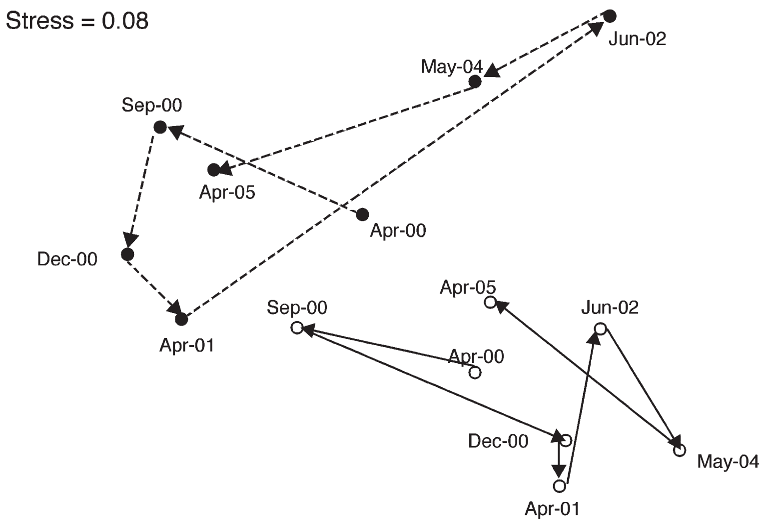

Fig. 15. Multi-dimensional scaling ordination showing trajectories and variability of fish assemblages in the control reach (solid symbols) and the test reach (hollow symbols) in respect to time of sampling from April 2000 to April 2005.

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, however, 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

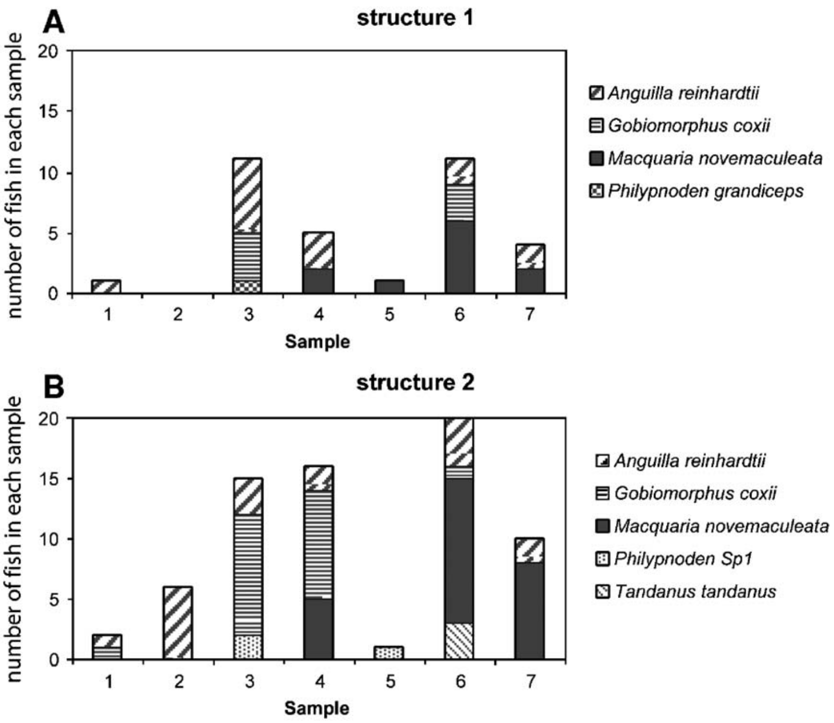

Fig. 16. Species and average abundance of fish recorded from structures 1 and 2 (DFJ1 and DFJ 2), over time periods 1 (May 2000) to 7 (April 2005).

structures appeared to be doing the primary job they were designed to do — erosion control. In effect, this was the sixth unstated hypothesis tested, which could be assessed by a simple measure of whether the structures remained or moved. On the whole, most structures performed largely as expected from an engineering and geomorphic perspective (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. The habitat potential of these structures was not 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%). With the exception of three structural pieces on structures 8 and 16, however, 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.

Altered perceptions regarding large wood in rivers (sensu Piegay et al., 2005) were not quantified, although a demonstrable change was observed in community attitudes towards using ELJs as a rehabilitation measure. Evidence for this change in perceptions can be found in 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 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 suggest that up to a 10% increase occurred in peak instantaneous stage compared with a similar magnitude flood observed before the treatment. This increase 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, the project appears to have 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.

6. Discussion: implications for long term river rehabilitation

6.1. 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 halting the further decline of sediment storage within the reach, and increasing sediment storage. The test reach now stores, on average, around 40 m^3/1000 m^2 more than the control. Thus, strong evidence suggests 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., 2003). 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, however, 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 a 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, personal communication, 2000).

At present the volume of the test reach channel (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 (1360 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 rate of sediment supply 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 almost attained its storage capacity within the first flood, would tend to support the assertion that even though the catchment may be supply limited, ample sediment transport still occurs because of the high reach-scale transport capacity. Thus, if the goal of a long term strategy for river rehabilitation 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.

6.2. 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 area of the reach bed. These results suggest that the hypothesis that the log jam treatment has not created additional pool habitat can be rejected, but whether or not this is a significant result is difficult to determine. 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 fish population at the reach scale. The magnitude of the increase in effective structural woody habitat (sensu Gehrke 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 area of wood surface was within the low flow wetted perimeter, declining to 11.7% after 4 years. From the perspective of fish habitat the effective surface area of the wood 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). From a structural engineering point of view, however, a significant degree of timber burial is crucial for structure stability. This represents a potential problem for the overall strategy of reach rehabilitation 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 objectives of sediment retention 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.

6.3. 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 channel response to this type of intervention at the reach scale. 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 variability in the reach. As a monitoring tool in an experiment such as this, however, the method is quite sensitive to start and end location and to the correct selection of the thalweg path. (Despite being defined using an automated algorithm in Arc-GIS, thalweg variability 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. A more degraded reach could have been selected to conduct the treatment, but such a selection process was avoided as it could have resulted in the “raising the titanic scenario” (sensu Rutherfurd et al., 2001).

6.4. 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, in press; Howell, unpublished data). In addition to the species observed 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 the richness and abundance of fish species was noted by Brooks et al. (2004) in the first 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 an association was apparent 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.

6.4.1. Explanations for lack of species changes

A number of explanations are possible for the observed pattern of response, and most likely it is a combination of several factors. First, the sampling regime was somewhat irregular because of competing commitments of the sampling crew. A seasonal signal clearly exists within the fish assemblage data, and, hence, the observed significant effect of time could be strongly influenced by the timing of surveys. Shifting the sampling regime 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 Fig. 4 indicates a run of large floods occurred in the first 12 months after the completion of the treatment, and since then extended periods of low or no flow occurred. Indeed, the river ceased to flow for 25 days between fish surveys 5 and 6. Under conditions of no flow the pool refugia created by the structures would be expected to 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 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 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, that were predominantly reach-scale geomorphic and engineering effects, so modification of the reach habitat at the appropriate meso-or micro-habitat scale was insufficient 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 m^2 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 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.

6.4.2. Future experiments

Whereas 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 operate and how they might be improved. The results of the fish survey 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 suggests that the sampling strategy at the reach scale 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 flexibility in individual species habitat preferences exists, 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 strategies of wood-based rehabilitation 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. The cost–benefit ratio, however, 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 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. The cost of a more intensive survey, however, 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 strategies of rehabilitation a need exists to design structures specifically to meet fish habitat preferences at the micro-scale. Attempting to focus purely on the reconstruction of a specific type and scale of habitat within a dynamic river system, however, is extremely risky. 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.

7. 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 operation, if we are serious about it. In south-eastern Australia the condition and health of many fluvial systems has been undergoing 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 efforts at rehabilitation 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, apparently 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. Yet, the results outlined here suggest that even this high degree of intervention has a minimal effect, at least during the temporal extent of the study. The implication of this limited effect is that, given the current low resource levels being directed towards river rehabilitation, whether or not any real effect on the physical and ecological functioning of these systems in the short-term (5 years), must be questioned. The situation is not hopeless, because the level of resources required to achieve the modest morphological changes made in this project are not unduly excessive for an advanced OECD economy. It is a question of priorities and of understanding. 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 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 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. Further experimentation with a range of structures, however, is needed to understand specific preferences and responses of individual species if rehabilitation is to improve habitat for entire fish assemblages within a given reach.

Acknowledgements

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