Third Australian Stream Management Conference.
Rutherfurd, I., Sheldon, F., Brierley, G. and Kenyon, C. (Editors)
Brisbane, 27-29 August, 2001

Putting the wood back into our rivers: An experiment in river rehabilitation

Andrew P. Brooks[1], Tim B. Abbe[2], John D. Jansen[1], Matt Taylor[1], Christopher J. Gippel[3]

SUMMARY: This paper presents an overview of a project established to assess the effectiveness of woody debris (WD) reintroduction as a river rehabilitation tool. An outline of an experiment is presented that aims to develop and assess the effectiveness of engineered log jams (ELJs) under Australian conditions, and to demonstrate the potential for using a range of ELJs to stabilise a previously de-snagged, high energy gravel-bed channel. Furthermore, the experiment will test the effectiveness of a reach based rehabilitation strategy to increase geomorphic variability and hence habitat diversity. While primarily focusing on the geomorphic and engineering aspects of the rehabilitation strategy, fish and freshwater mussel populations are also being monitored. The project is located within an 1100m reach of the Williams River, NSW. Twenty separate ELJ structures were constructed, incorporating a total of 430 logs placed without any artificial anchoring (e.g., no cabling or imported ballast). A geomorphic control reach was established 3.1 km upstream of the project reach. In the 6 months since the structures were built the study site has experienced 6 flows that have overtopped most structures, 3 of the flows were in excess of the mean annual flood, inundating 19 of the ELJs by 2 - 3 m, and one by 0.5 m. Early results indicate that with the exception of LS4 and LS5, all structures are performing as intended and that the geomorphic variability of the reach has substantially increased.

THE MAIN POINTS OF THIS PAPER

- In counterpoint to the river management mistakes of the past, we present the outline for a controlled experimental reintroduction of WD in a section of the Williams River, NSW, and assess the effectiveness of this strategy for river rehabilitation.
- WD reintroduction in the form of engineered log jams (ELJs) shows great promise as a river rehabilitation technique, and is cost comparable with rock and other 'hard-engineered' methods.
- The 20 constructed ELJs have incurred 6 overtopping flows in the 6 months since construction (including 3 flows > 200 m^3 sec^{-1}). All but 2 of the small log sill structures are performing as designed.
- A successful WD reintroduction programme requires good planning, and a considerable amount of empirical baseline data.
- WD is not a panacea for solving all river health problems and can create serious problems if improperly used and understood. It is one component of a comprehensive rehabilitation strategy.

1. Introduction

The practice of de-snagging, or removal of in-stream woody debris (WD), has been widespread in Australian rivers throughout the last 200 years. In many rivers almost the entire natural WD load has been removed (e.g. Gippel et al. 1992). The Australian experience reflects similar situations throughout the world, notably North America and Europe, where very few rivers retain WD loadings comparable with pre-agricultural forested conditions (eg Triska, 1984, Maser & Sedell, 1994, Brooks 1999a;b). The intended benefits of de-snagging are no longer relevant in most parts of the world and it is now widely recognised that de-snagging has adversely affected aquatic ecosystems and river stability (Keller & Swanson, 1979; Bilby, 1984; Shields & Nunnally, 1984; Harmon et al., 1986; Shields & Smith, 1992; Maser & Sedell, 1994). Research in Australian streams has confirmed international findings about the significance of wood as a control on channel hydraulics (Gippel et al. 1992, Shields & Gippel, 1995), channel morphology (e.g. Cohen, 1999; Brooks, 1999 a,b; Marsh et al, 1999), and biological responses (e.g. Koehn & O'Connor, 1990, O'Connor, 1992; Crook & Robertson, 1999; Treadwell, 1999). There is strong evidence to infer rivers subjected to de-snagging and riparian disturbance are now wider, deeper and straighter, have substantially higher rates of sediment flux, and bear little of their pre-disturbance morphological diversity (Brooks, 1999a, c; Buffington & Montgomery, 1999).

In Australia, issues associated with WD and riparian vegetation are now viewed as major river management concerns (see Lovett, 2000). There is currently a nationwide movement to rehabilitate channels (see Rutherfurd et al., 2000), and increasing WD loads is integral to rehabilitation strategies (see Lovett, 2000). This study is a new experimental approach to reintroduction of WD in a section of river in south-eastern Australia. The work aims to assess the performance of individual log structures, as well as their combined effects at the reach scale. The study is designed as a controlled, paired reach experiment, with a control reach upstream of the test reach. Two core comparisons will be undertaken: pre- and post-

[1]Department of Physical Geography, Macquarie University, NSW, Australia, 2109
[2]Phillip Williams and Associates, Consultants Seattle, WA USA/ University of Washington, Seattle
[3] Fluvial Systems Pty Ltd PO Box 4117 Melbourne University Retail, Parkville Vic 3010 Australia

placement in-stream responses *within the test reach*, and relative in-stream *between the test reach* and *control reach* over time.

2. Project Aims

1. Design a reach-based strategy to improve channel stability, increase habitat diversity and productivity, using WD.
2. Assess the performance of WD structures under SE Australian conditions, suitable for both habitat rehabilitation and as an alternative to traditional engineering methods of channel stabilisation.
3. Establish a demonstration site to educate the local community—together with regional, state and national management agencies—about the critical role of WD in our rivers.

The above aims include: quantification of geomorphic and hydraulic changes induced in the test reach associated with the WD structure emplacement; establishment of design procedures for constructing WD structures under local conditions; and evaluation of the effects of channel morphology on reach ecology after structure emplacement, focusing on populations of fish and freshwater mussels.

3. STUDY AREA

A section of the Williams River at Munni was selected as the *test reach* (**Figure 1**), based on a broad range of criteria including its past history of de-snagging, good anecdotal and archival data on the management history and channel changes, and good access and visibility for the community. The *control reach*, 3.1 km upstream, is geomorphically similar to the test reach at Munni. Most importantly, the two study sites are characterised by a *discontinuous floodplain* river style (Brierley & Fryirs, 2000) typical of many coastal gravel-bed rivers in eastern Australia. Thus, lessons learned here have a wider significance for rehabilitation strategies elsewhere.

The two study reaches feature comparable channel dimensions, bed materials and flow characteristics. The Munni test reach measures 1100 m in length with a reach bed slope of 0.0025 and median clast size of 76 mm (n=1800). The 550 m control reach has a bed slope of 0.0017 and median clast size of 77 mm (n=450). The two reaches drain upstream areas of 190 km^2 and 180 km^2 respectively (**Figure 1**). Hydrological attributes of the study reaches determined from the flow gauge at Tillegra Bridge—5.1 km downstream of the Munni Test reach. The mean annual flood (arithmetic mean of the annual flood series, 1931-1993) is 170 m^3/s, with an average recurrence interval of about 2 years. Based on a cross-section defined by alluvial banks in the test reach, 'bankfull discharge' is modelled at 800 m^3/s—a flood with a recurrence exceeding 100 years. The large capacity is interpreted to stem from channel and riparian zone disturbance since European settlement, particularly de-snagging (cf. Erskine & White 1996; Brooks 1999a,b).

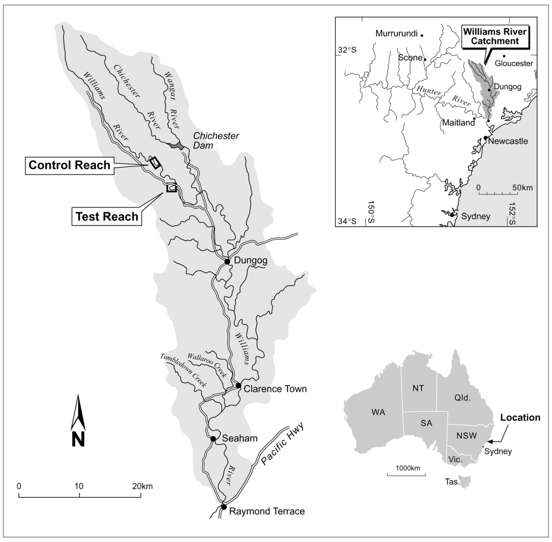

Figure 1: *Study site location map*

4. REHABILITATION STRATEGY

The rehabilitation strategy is designed to address specific reach and sub-reach scale 'problems' or deficiencies within the designated river reach. Hence, the strategy outlined here is tailor-made for this particular river reach, with due regard to the river style setting (Brierley & Fryirs, 2000), and catchment-scale management and channel stability issues. It is not intended that the specific strategy devised for this reach will be appropriate elsewhere. Of primary importance are the general principles governing the decision making process upon which this strategy is based.

Three key geomorphic 'problems' were identified in the study reaches: 1) bed homogenisation (i.e. the flattening of riffles and infilling of pools); 2) excessive bed mobility (i.e. high sediment flux); 3) local bank erosion, particularly in the areas downstream of bedrock-forced pools, where gravel-bars accrete and deflect the channel thalweg laterally.

A range of ecological implications is hypothesised to stem from each of these geomorphic 'problems'. (1): the loss of gross habitat and habitat diversity, including some niche habitats; (2) given the high bed shear stresses and bed material mobility, this probably no longer offers viable habitat for many benthic species; (3) increased bank erosion raises sediment supply to the river (both fine and coarse fractions) increasing turbidity during flood flows, and further exacerbating 'problems' (1) and (2). In more general terms there is now a lack of direct habitat associated with WD.

4.1 WD rehabilitation principles to be applied at the reach scale:

- The strategy should be designed to work with the river not against it—i.e. structures should be built to enhance and stabilise incipient or transient geomorphic units, within a framework that accounts for catchment setting and catchment scale disturbance processes.
- A WD rehabilitation strategy should be implemented in conjunction with efforts to optimise the ecological integrity of the riparian vegetation corridor.
- Hydraulic roughness (and thus energy dissipation) should be maximised within the channel, through increased WD roughness, increased form roughness, and increased in-stream vegetation.
- When combating bank erosion, in addition to bank revetment, flow should also be deflected away, thereby treating the causal mechanism driving erosion.
- Induce channel contraction to facilitate pool scour.
- Where possible, pool scour should be maximised by deflecting flow towards resistant banks (particularly bedrock or well-vegetated areas).
- Whenever flow is deflected, provide counter-measures of reinforcement in the zones receiving the deflected flow to prevent the initiation of new erosion.

5. LOG STRUCTURES

WD structures developed in this rehabilitation strategy are hybrids of ELJs developed by Tim Abbe (e.g. Abbe et al, 1997, 1998, *submitted*; Abbe, 2000). ELJs are modelled on naturally occurring log jams. Field observations indicate that such features can remain stable for thousands of years in natural settings (Abbe, 2000). Under natural conditions, the stability of the logjams is a function of the burial of the key log root wads into the river bed, the interlocking of accreted logs within the structure, ballast associated with subsequent sediment deposition, and vegetation, which tends to colonise the whole structure. The engineered version, therefore, uses the same principles for structural stability. Of critical importance to the built structures is the utilisation of logs with intact root wads.

In the Williams River test reach, about 430, primarily eucalypt logs with root wads (or about 350t of wood), were placed in 20 ELJs within the 1100 m reach. Structural stability analysis followed a combination of the approaches adopted by D'Aoust & Millar (1999), Abbe et al. (1997), Abbe (2000) and Shields et al. (2000). Four types of ELJ were designed for the test reach (**Figure 2**): deflector jams, bar apex jams, bank revetment structures and log-sill bed control structures. Full design guidelines and stability analysis for each ELJ type will be presented elsewhere. Following is a general description of each type with an outline of their primary purpose.

5.1 Deflector jams (DFJs 1–8)

Bank-attached, multi-layered, impermeable log jams with gravel back-fill for ballast, and rack logs on the upstream side of the structures to help decrease permeability. Basal key logs are buried to a depth greater than the predicted scour depth for the design flow. The magnitude of the log jams varies depending on the specific location, however, where the primary role is bank erosion protection, they should extend to at least half bankfull height (Abbe et al. 1997; *submitted*)

Purpose

1. Alternative bank erosion protection to traditional rock revetment.. Generally, when performing this function they are located on concave eroding banks—actively deflecting the channel thalweg away from the bank, thereby reducing the force driving the erosion. They also induce toe-revetment. The length of bank protected from erosion through thalweg deflection is a function of the extent of jam protrusion into the flow. Depending on the angle of incident of flow, the length of bank protection is 3-5 times the width of flow obstruction.(e.g. Klingeman et al. 1984; Miller et al. 1984; Drury 1999).
2. Mechanism for inducing channel contraction by modifying the channel cross section. This contractionary function is enhanced by sedimentation on and around the structure, which further constricts the cross section.
3. Mechanism for re-directing flow such that pool scour and thus energy dissipation are maximised.

5.2 Bar apex jams (BAJ1– 2)

Mid-channel, multi-layered, impermeable log jams with ballast provided by gravel back-fill and additional ballast provided by any existing bar vegetation. These log jams are built on or around existing mid-channel bars. ELJ dimensions depend on the size of the bar, or the desired endpoint feature.

Purpose

1. Direct mid-channel roughness elements.
2. Bar stabilisation and accretion, thereby inducing secondary form roughness elements. When located in association with existing riffles, riffle crest height can be increased due to backwater effects.
3. In general, these are habitat enhancement structures that offer the direct benefits of wood in the channel, together with provision of greater diversity of in-stream habitat units.

5.3 Bank revetment structures (BRVT1– 3)

Staggered and/or layered log structures in which the logs lie parallel to the flow along low banks or inset benches. Logs should cover the majority of the bank face exposed to flow. Of course, the extent of bank protection depends on the height of the log jam. Basal logs are keyed into the bed.

Purpose

1. Bank erosion protection via buttressing of the bank toe and physical protection of the bank face. Protruding root wads deflect some flow and therefore foster some additional boundary roughness.
2. Habitat enhancement via creation of bank structure akin to an overhang.

5.4 Log sill bed controls (LS1- 5) & Log sill complex LSC1)

Triple log bed-control structures located perpendicular to flow and buried almost flush with the bed (raised above the bed by less than a quarter of the diameter of the upper log). The logs are placed one on two in a pyramid-like fashion. Ideally these structures will be located in conjunction with DFJs and/or BAJs, such that the larger jam structures abut either side of the log sill to minimise the possibility of outflanking and/or log sill removal. As a minimum, the log sills are set in place with longitudinal logs on either side of the channel.

Purpose

1. Grade control structures.
2. Prevent bed mobilisation in small flows—particularly into scour pools.

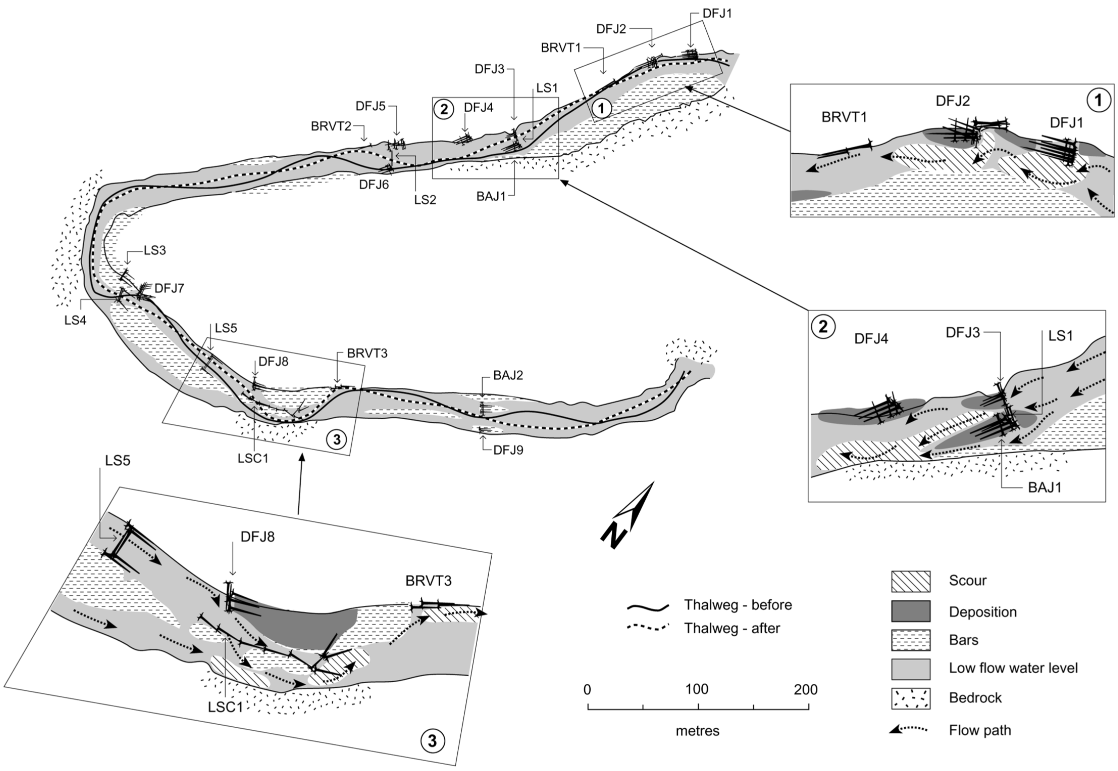

Figure 2: *Map of Munni Test Reach showing reach-scale rehabilitation strategy and ELJ structure locations with predicted geomorphic changes*

6. EARLY RESULTS AND SOME LESSONS

6.1 Reach Hydraulics

A common concern amongst landholders and river managers is the perceived impact that WD reintroduction may have on flood levels. Leaving aside the issue of whether increased water surface elevation in some parts of catchments is necessarily 'bad' from a flood mitigation perspective (a debate to be addressed elsewhere), we simulated a post-ELJ-placement flood along the test reach using HEC-RAS. The modelled flow was calibrated with a known water surface profile measured in the field during a ¾ bankfull flow (Q=352 m^3sec^{-1} —an 8 year ARI event) before ELJ placement. Flow afflux was assessed for the measured flow by both modifying the cross sections and manipulating Manning's *n*. Calibrated Manning's *n* averaged 0.047 for the reach and ranged from 0.03–0.08. The reach average value of modified *n* was 0.049. Placement of the ELJs increased the water surface elevation by an average of 0.06 m where *n* was unchanged or 0.1 m for the modified *n* model run (see **Figure 3**). The model output indicates that the greatest effect occurs in the upper third of the test reach where most of the ELJs were located.

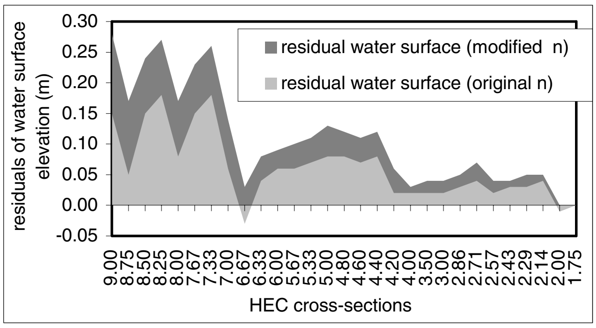

Figure 3*:* *Modelled residual water surface elevation (pre - post ELJs) downstream in Munni Test Reach for Q=352 m^3sec^{-1} event. HEC XS9 = upstream end of test reach.*

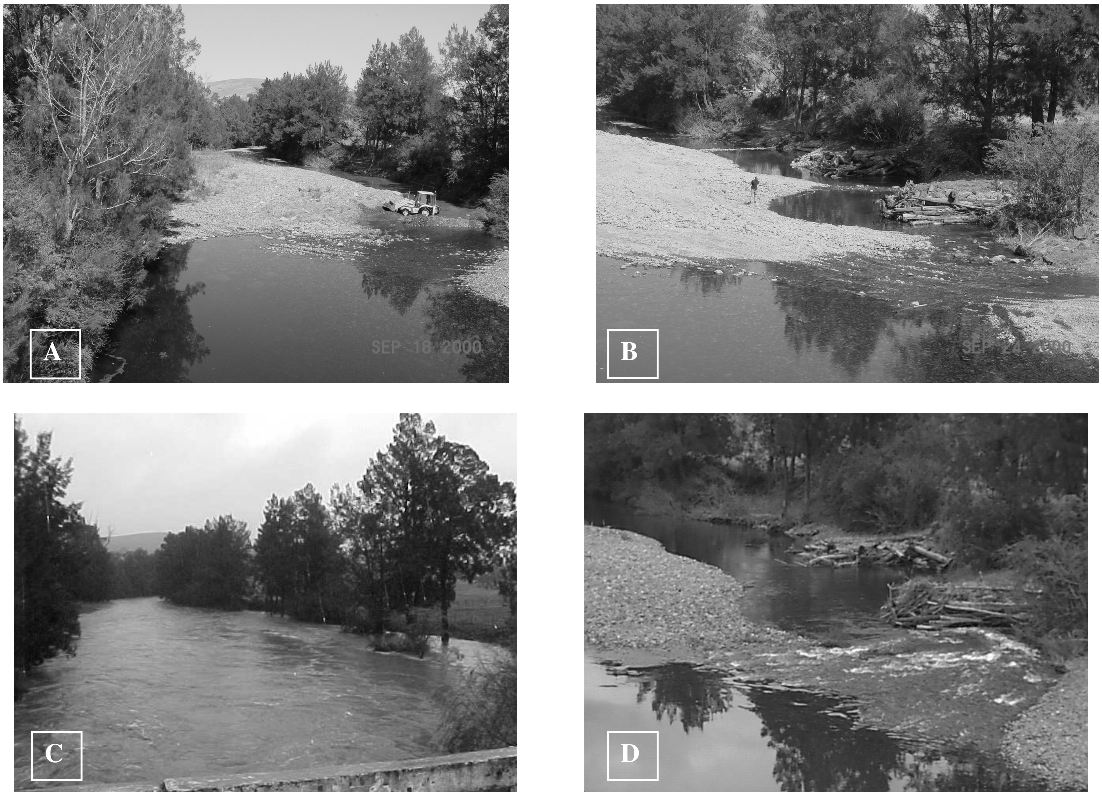

Figure 4: *(A) Upper section of Munni test reach at the commencement of construction of DFJ1. Note a 4 m high actively eroding bank was located to the right of the tractor; (B) DFJ1 & 2 at the completion of construction; (C) Same view in flood (270 m^3 sec^{-1}, 7/05/01) at about 1 m below peak stage; (D) DFJ1 & 2 after the second major flood since construction—note the aggraded bar upstream of first structure and the increased scour around the two structures. The riffle crest in the foreground was raised, we presume due to backwater effects associated with the structures.*

While we are unable to present the full post-flood field results here, the majority of the structures are largely intact and performing as designed (**Figure 4**). Of the 430 unanchored logs placed within the 20 structures, 13 logs have shifted from structures during the flooding since construction. However, none have moved out of the test reach. The majority of the mobilised logs were 'rack' logs placed laterally at the front of the larger structures to decrease permeability. The only structural logs that moved came from log sill structures that were not flanked by larger deflector jams (i.e. 3 logs from LS4 and 1 from LS5), and one of the outer key logs was also removed from DFJ8.

6.2 Project Costs

The total cost for the works-related component of the project (i.e. excluding design and research costs) amounted to $70 000 for the reach. This includes the cost of log transport (the logs were obtained free of charge from land clearance sites), hire of machinery and labour costs. These costs are comparable with rock and other strategies that might have been traditionally employed to address the bank erosion problems within the reach (G. Evans pers. comm., 2001)

6.3 Overview

The numerous recent floods have spawned a large volume of data in the first six months of this field experiment. Clearly, there is insufficient space to present the majority of the scientific results here. However, on a number of fronts the project appears to be a resounding success. The fact that the log structures have survived a fairly rare run of sizeable floods, has in itself won over many in the local community to the concept of WD reintroduction—people who were at first highly sceptical of the project. Substantial increases in morphologic and hydraulic diversity have been induced in the test reach, which are not replicated in the control reach. Two post-construction fish surveys have been completed, and while it is not yet possible to draw conclusions from these data, the results show an increase in fish numbers. Similarly, the stability of the WD structures has been thoroughly tested, and useful insights into minor modifications have emerged.

7. IMPLICATIONS FOR OTHER PROJECTS

Experience already gained from this experiment highlights the need for rigorous pre-construction planning and design. Before any WD reintroduction occurs, a comprehensive range of baseline data is required to inform the reach rehabilitation strategy as well as the design of individual structures. It is recognised that the rigour employed in this study is not necessarily appropriate in all future WD reintroduction strategies (e.g. a full 3D survey of the reach), however, some minimum requirements can be identified:

7.1 Catchment Scale

- Understanding of the reach setting within a catchment framework i.e. river style and upstream disturbance conditions.
- Some sense of the historical channel changes and evolutionary pathway.

7.2 Reach scale data

- Channel cross section surveys (sufficient to enable hydraulic modelling of the reach with HEC-RAS or similar) i.e. XS spacing should be < 50m, although this varies depending on channel scale, gradient and morphological variability.
- Thalweg long profile survey.
- Reach planform and geomorphic map to provide the basis for the rehabilitation strategy design.
- Bed material size data (sufficient to determine reach-average statistics).
- Reach flood magnitude/frequency data—determined either from a nearby gauge or estimated from a suitable regional runoff function.

7.3 Structure Design

- Structure designs should be based on the actual logs to be used.
- Where possible, use logs of known species so that wood density can be estimated. Dry density should be used in all design work to ensure the worst case stability scenario is assumed.

8. ACKNOWLEDGEMENTS

The research component of this project is funded through LWA Grant MQU9. The works component is funded by NSW Dept. Land & Water Conservation, Hunter Region and Hunter Catchment Management Trust. We wish to acknowledge input to this project by Scott Babakaiff, Allan Raine, Sharon Vernon, Peter Gehrke, Hugh Jones, David Outhet, Adolphe Parfait, Tony Broderick, Brett Anderson, Malcolm Bailey, Mark Elsley, Stuart Garrard the Williams work crew – Laurie Rumble Chris Muddle, Steve and Rob Argent. The project would not have been possible without the generosity of Edwin & Naida Smith of Munni who have allowed us unlimited access to their land.

9. REFERENCES

Abbe, T.B. (2000). Patterns, mechanics and geomorphic effects of wood debris accumulations in a forest river system. Ph.D. dissertation. University of Washington. Seattle, WA. 220 p.

Abbe, T.B. and D.R. Montgomery. (1996). Large woody debris jams, channel hydraulics, and habitat formation in large rivers. Regulated Rivers: Research and Management 12. 201-221.

Abbe, T.B., D.R. Montgomery, and C. Petroff. (1997). Design of stable in-stream wood debris structures for bank protection and habitat restoration: an example from the Cowlitz River, WA. In Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision. Wang, S.S.Y., Langendoen, E.J., and Shields, F.D. Jr., Editors. University, MS. University of Mississippi. 809-816.

Abbe, T.B., D.R. Montgomery, C.A. Adams, R.C. Riley, and E.L. Owens. (submitted). Bank protection and habitat enhancement using engineered log jams. Natural Resource Conservation Service. U.S. Department of Agriculture. Washington D.C..

Abbe, T.B., D.R. Montgomery, G.R. Pess, T. Drury, and C. Petroff. (1998). Emulating organized chaos: engineered log jams as a tool for rehabilitating fluvial environments. EOS, Transactions of the American Geophysical Union 79(45). F345-F346.

Bilby, R. E. (1984) Removal of woody debris may effect stream channel stability. Journal of Forestry, **82**, 609-613.

Brierley, G. J. and Fryirs, K. 2000 'River styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in Bega catchment, New South Wales, Australia'. Environmental Management, 25:661-79.

Brooks, A. P. (1999a) Pre- and post-European disturbance river morphodynamics in East Gippsand Australia. Unpub PhD, Macq. Univ.

Brooks, A. P. (1999b) Lessons for river managers from the fluvial tardis: direct insight into post-European channel changes from a near intact alluvial channel. In: Proceedings of the Second Australian Stream Management Conference, Vol. 1 (Ed. by I. Rutherfurd and R. Bartley), pp. 121 - 127, Adelaide.

Brooks, A. P. (1999c) Large wooody debris and the geomorphology of a perennial river in southeast Australia. In: Proceedings of the Second Australian Stream Management Conference, Vol. 1 (Ed. by I. Rutherfurd and R. Bartley), pp. 129 - 136, Adelaide.

Buffington, J. M. and Montgomery, D. R. (1999) 'Effects of hydraulic roughness on surface textures of gravel-bed rivers'. Water Resources Research, 35:3507-3521.

Cohen, T. (1999) Channel recovery mechanisms in a forested catchment, Jones Creek, East Gippsland: lessons for river management in southeastern Australia. In: Proceedings of the Second Australian Stream Management Conference, Vol. 1 (Ed. by I. Rutherfurd and R. Bartley), pp. 181 - 186, Adelaide.

Crook, D. A. and Robertson, A. I. 1999 'Relationship between riverine fish and woody debris: implications for lowland rivers'. Australian Journal of Marine and Freshwater Research, 50: 941-53.

D'Aoust, S. G. D. and R. G. Millar (1999). Large woody bebris fish habitat structure performance and ballasting requirements. British Columbia, Watershed Restoration Program, BC Ministry of Env. Lands & Parks and Ministry of Forests**:** 119pp.

Drury, T. (1999). Stability and pool scour of engineered log jams in the North Fork Stillaguamish River, Washington. Unpubl. M.S. Thesis. University of Washington. 62 p.

Erskine, W. D. & White, L. J. (1996) Historical Metamorphosis of the Cann River, East Gippsland, Victoria. In: First National Conference on Stream Management in Australia (Ed. by I. Rutherfurd and M. Walker), pp. 277 - 282. C.R.C. for Catchment Hydrology, Merrijig.

Gippel, C.J., I.C. O'Neill and B.L. Finlayson. (1992). The Hydraulic Basis for Snag Management. Centre for Environmental Applied Hydrology. Department of Civil and Agricultural Engineering. University of Melbourne, Victoria, Australia, 116 p.

Harmon, M. E., Franklin, J. F., Swanson, F. J., Sollins, P., Gregory, S. V., Lattin, J. D., Anderson, N. H., Cline, S. P., Aumen, N. G., Sedell, J. R., Lienkaemper, G. W., Cromack, K. j. & Cummins, K. W. (1986) Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research, **15**, 133 - 302.

Keller, E. A. & Swanson, F. J. (1979) Effects of large organic material on channel form and fluvial processes. Earth Surface Processes, **4**, 361-380.

Klingeman, P.C., S.M. Kehe, and Y.A. Owusu. (1984). Streambank erosion protection and channel scour manipulation using rockfill dikes and gabions. Water Resources Research Institute Technical Report WRRI-98. Oregon State University. Corvallis, OR. 169 p.

Koehn, J. D. and O'Connor, W. G. (1990) 'Threats to Victorian native freshwater fish'. Victorian Naturalist, 107:5-12.

Lovett, S. 2000 (ed.). Land and Water Resources Research and Development Corporation Newsletter. RipRap, 16.

Marsh, N., Rutherfurd, I. & Jerie, K. (1999) Large woody debris in some Australian streams: natural loading, distribution and morphological effects. In: Proceedings of the Second Australian Stream Management Conference, Vol. 2 (Ed. by I. Rutherfurd and R. Bartley), pp. 427 - 432, Adelaide.

Maser, C. and Sedell, J. R. (1994) 'From the Forest to the Sea'. St. Lucie Press, Delray Beach. 200pp.

Miller, A.C., S. N. Kerr, H. E. Reams, and J. P. Sartor. (1984). Physical modeling of spurs for bank protection. In Elliott, C. M., Editor. River Meandering. Proceedings of the ASCE Conference on Rivers. New Orleans, 24-26 October 1983. American Society of Civil Engineers. New York. pp.996-1007.

O'Connor, N. A. (1992) Quantification of submerged wood in a lowland Australian stream system. Freshwater Biology, **27**, 387-395.

Rutherfurd, I., Jerie, K. and Marsh, N. (2000). A Rehabilitation Manual for Australian Streams. Volumes 1 and 2. LWRRDC Canberra.

Shields, F. D. & Gippel, C. J. (1995) Prediction of effects of woody debris removal on flow resistance. Journal of Hydraulic Engineering, **121**(4), 341-354.

Shields, F. D. & Nunnally, N. R. (1984) Environmental aspects of clearing and snagging. Journal of Environmental Engineering, **110**(1), 152-165.

Shields, F. D. & Smith, R. H. (1992) Effects of large woody debris removal on physical characteristics of a sand-bed river. Aquatic Conservation: Marine and Freshwater Ecosystems, **2**, 145 - 163.

Shields, F. D. J., S. S. Knight, et al. (2000). Large woody debris structures for incised channel rehabilitation. Proceedings of ASCE 2000 joint conference on water resources engineering and water resources planning and management, Reston VA, ASCE.

Treadwell, S., Koehn, J. and Bunn, S. (1999). Large woody debris and other aquatic habitat. (In) S. Lovett and P. Price (eds.) Riparian Land Management Technical Guidelines, Volume One: Principles of Sound Management, LWRRDC, Canberra, 79-96pp.

Triska, F. J. (1984) Role of wood debris in modifying channel morphology and riparian areas of a large lowland river under pristine conditions: a historical case study. Verhandl. Int. Verein. Theor. Angew. Limnol, **22**, 1876 – 189