

Things of stone, wood and running water: Twenty years of River Rehabilitation on NSW North Coast

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Key Points

- Rehabilitation objectives to increase geomorphic complexity through pool scour and deposition are best achieved by intervention works (or a combination of complimentary structures) that effectively induce a hydraulic response rather than simply imposing a 'control' on bed and or bank position.
- Development of hydraulic rehabilitation objectives has much value in guiding design of intervention works and monitoring their effectiveness.
- Conceptual understanding of hydraulic behaviour and response to channel geometry and obstacles to flow is critical to development of hydraulic objectives and predicting likely geomorphic outcomes of intervention works.
- Monitoring the relationship between hydraulic and geomorphic responses to intervention works improves conceptual understanding and confidence in developing large scale projects to achieve multiple rehabilitation objectives and geomorphic outcomes at multiple scales.

Abstract

The importance of developing river rehabilitation objectives consistent with river behaviour and character became very topical in the mid 1990's. Improved understanding of river health led to the broadening of asset protection objectives to include ecological function. Ability to rehabilitate in stream structure and aquatic habitat in geomorphically degraded systems is often reliant upon understanding the effectiveness of available structural works interventions to achieve desired outcomes.

On the North Coast of NSW, the period between 1996 and 2015 involved much innovation, experimentation and collaboration between researchers and practitioners in refining rehabilitation objectives, planning and monitoring programs and developing intervention options. Long term monitoring and independent performance assessment of a diverse range of in-stream works including more than 250 individual structures against rehabilitation objectives, has been critical to this development.

Traditional design principles of the 1990's, such as bed control and smooth channel alignments, are replaced with a greater appreciation and capacity to predict and influence flow paths and hydraulic gradient. Innovative designs and strategic placement of complimentary structures in relation to channel geometry and flood flow paths have enabled specific hydraulic response objectives to be developed and realised relating to multiple desired geomorphic responses at the site and reach scale.

Keywords

Hydraulic gradient, river rehabilitation, objectives, intervention works, monitoring.

Introduction

Rehabilitation of channel structure in freshwater reaches of north coast NSW rivers from 1994 to 2016 was preceded by a period of at least 25 years in which river management objectives focused largely upon flood mitigation, asset protection and access to sand and gravel resources. Sand and gravel extraction from in-stream bars was often prescribed to address bank erosion (Resource Planning Pty Ltd, 1990). Commercial

extraction operations, sometimes promoted as a means by which river rehabilitation could be funded, have been identified as significant destabilising influences on channel structure on various north coast rivers (Broderick and Outhet, 1999a; Cohen and Telfer, 2006; Lyall & Macoun and University of Wollongong, 1998). Increased flow velocities and channel enlargement associated with desnagging and channel straightening works to increase hydraulic efficiency in conveying flood waters are well documented (Brooks 1999, Erskine and Webb, 2003, Brooks et al 2004). North coast rivers subjected to these works have experienced up to two metres of bed lowering and widespread channel instability (Broderick and Outhet, 1998; 1999a, 1999b).

A philosophical shift in river management objectives has been prompted by accumulating knowledge of geomorphic, hydraulic and ecological values and processes and the adverse impacts of management practices such as removal of riparian vegetation and large woody debris (LWD) on flow velocities (Gippel et al, 1996), channel expansion (Brooks, 1999) and habitat. Gippel et al, (1996) proposed a method to reintroduce or manage existing in stream LWD without significantly influencing hydraulic efficiency. River rehabilitation guidelines (Newbury and Garboursy, 1993) have discussed the value of maintaining hydraulic efficiency around bends, recommending a smooth radius of curvature. Disturbance impacts on many south eastern Australian rivers, however, have vastly increased channel capacity to convey floodwaters (Reinfelds et al, 1995; Cohen, 2003; Brooks 1999), often negating the maintenance of hydraulic efficiency for flood mitigation as a key consideration in rehabilitation projects. Further, significant influence on hydraulic efficiency is required to achieve objectives of increased geomorphic complexity through the influence of scour and deposition.

Gallisdorfer et al (2013) identified that whilst design, construction and installation criteria exist for Engineered Log Jams (ELJ's) understanding of how these influence river morphodynamics is limited. Initiating desired geomorphic responses through design of intervention works requires an understanding of localised hydraulic behaviour and response to variable channel dimensions and obstacles to flow. Analyses to predict hydraulic responses require reach scale estimates of channel roughness and assume uniform flow depth with the hydraulic slope being parallel to the streambed. However, flow velocities, direction and depth under which bed load movement is initiated in a natural channel are not uniform (Newbury and Garboursy, 1993) and localised influences of afflux can create significant variations in hydraulic gradient (Gippel et al, 1996), which in turn influences the potential for localised scour and deposition.

2D modelling of natural channels has proved effective in identifying varying downstream flow velocities and depths within a reach at different flow rates (Bonetti, et al, 2016; Cambridge and Morden, 2012) and physical flume and physical scale models have increased our conceptual understanding of the general interactions between flow dynamics and channel morphology (Hsu, 1950; Moore and Morgan, 1959; McLaughlin and Grenier, 1997; Gallisdorfer et al., 2013). However, application of this understanding to designing intervention works to meet specific objectives in a natural channel remains uncertain and a significant challenge for river rehabilitation practitioners. The following paper describes the incorporation of conceptual understanding of hydraulic behaviour and response into the development of rehabilitation objectives and design of intervention works on the NSW north coast.

Experiences and key lessons on the North Coast

On the North Coast of NSW, the period between 1994 and 2015 involved much innovation, experimentation and collaboration between researchers and practitioners. Collaborative projects (Brooks, 2006a, Brierley et al, 1999) and long term monitoring and independent assessment of the effectiveness of intervention works, guided adaptive management and refined rehabilitation priorities and objectives. Effectiveness assessments were undertaken on more than 250 individual structures installed within tributaries of the Orara river, Clarence catchment (Babakaiff, 2003; Cohen, 2004) and the Wilson River (Cohen and Telfer, 2006; Daley 2012), a major tributary of the Hastings catchment, all of which had experienced channel incision and expansion. Rehabilitation objectives to increase geomorphic complexity through pool scour and deposition were best achieved by structures (or a combination of complimentary structures) that effectively induced a

hydraulic response rather than simply imposing a 'control' on bed and or bank position. Hydraulic rehabilitation objectives were developed to guide future design of intervention works and added much value in assessing works effectiveness and in progressing conceptual understanding of hydraulic behaviour and response.

Conceptual understanding of both hydraulic behaviour and post channel incision recovery processes, which typically involve the development of bars and islands within the enlarged channel (Schumm, 1994; Broderick & Outhet, 1999) guided development of intervention works designed to induce a hydraulic response similar to that of that LWD falling into the channel and the growth of river oak vegetation on gravel bars. Expected rehabilitation timeframes were informed by an understanding of the dependence upon timing, frequency and duration of geomorphically effective flood events, regeneration of riparian vegetation on banks, bars and islands and the available supply of bedload.

Hydraulic behaviour, trials and design development.

Elevated Log Sills, backwatering effects and implications for LWD management

Log sills (single and / or multiple logs trenched into the bed and banks, aligned perpendicular to the low flow channel) have been installed in many north coast river reaches with the objective of providing a bed control to prevent ongoing channel incision. Typically channel blockage ratios associated with log sills is minimal (<10%) as is the effective influence on upstream hydraulic gradient. Further, log sills, often located on riffles deemed to be unstable, commonly fail largely by outflanking due to lack of bank resistance or undermining (Nambucca report, 2002) caused by plunging flows creating scour downstream and under the structure.

Incorporation of reach scale anticipated scour depths can refine design criteria and durability, however, an alternative to increasing the depth the structure is keyed into the bed is to elevate the logs above the bed. Elevation of the logs above the bed increases the range of flows at which upstream hydraulic gradient can be influenced and enables low flows and fish passage beneath the structure. Whilst elevated, proximity of logs to the bed can reduce upstream velocity similar to the 'dead zones' described by Gippel et al (1996), promoting upstream deposition. Monitoring results, discussed below, show that given bedload supply, this deposition eventually moves downstream smothering the logs and creating a new riffle feature at an elevated level.

Elevated log sills (ELS), previously described in Brooks et al (2006a), are essentially logs secured above bed level to span the low flow channel. This design was first initiated in a trial to maintain large river oaks perpendicular to low flow in the cross channel alignment, in which they had fallen, downstream of a riffle in a reach with suspected riffle instability. The trial involved lowering the height of logs to that approximated as being lower than flood water levels capable of entraining LWD so as to reduce risk of further mid channel flood debris accumulation and associated flow deflection induced bank erosion. In anticipation of increased bed levels associated with the ELS in the river right low flow channel, timber pin rows were driven into the bed across the river left flood chute to maintain its relatively higher elevation and the river right alignment of the low flow channel.

The success of the trial in reducing upstream hydraulic gradient and raising upstream riffle crest levels provided insight into future LWD management options and led to the ELS design and the timber pin rows being installed in a variety of locations on the north coast. Two ELS's (ELS1 and ELS2) were installed on a reach in the Orara river, where upstream progression of riffle crests had been observed to lower bed levels. Comparative analyses of pre and post construction bed levels (see figure one) indicate riffle crest height upstream of ELS1 increased by ~0.1m and moved 8m downstream with an additional riffle formed immediately downstream of ELS1, yielding a localized 25% reduction in bed gradient (Cohen, 2004).

Whilst Cohen (2004) suggests the lower bed levels (0.2m) recorded upstream of ELS 2 were more likely due to localised changes in upstream low flow planform than bed level incision, observations during flood events indicated ELS2 influenced minimal backwatering effects due to the relatively large cross sectional area

immediately upstream. Additionally, unlike ELS2, ELS1 included timber pins radiating from both flanks, increasing the channel blockage area and providing more effective upstream backwatering (see figure two). Future application of the ELS design considered upstream cross sectional area and incorporated timber pin radials and where considered appropriate, timber pin rows in adjacent flood chutes.

Figure 1: Changes in bed level elevation between 2001 and 2004 following installation of 2 elevated log sills (ELS) as presented in Cohen (2004). Red and black arrows indicate changes in local gradient at ELS1.

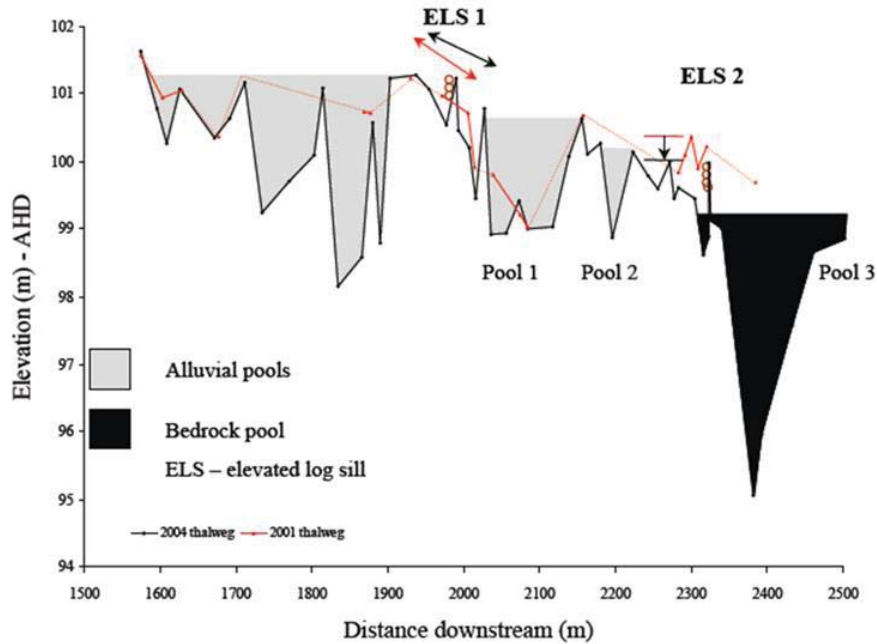


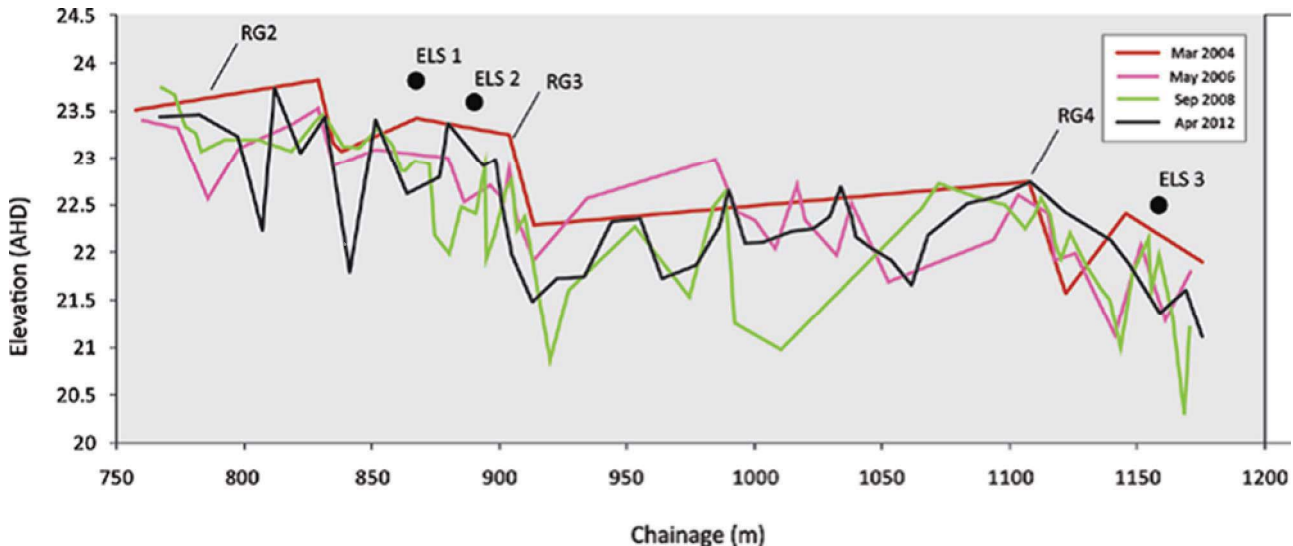
Figure 2: Elevated Log sill (ELS1) with timber pin radials, Orara river with approx 0.6m flow depth above the ELS. Note the influence of timber pins on upstream backwatering and wave formation downstream.



In 2001 four cross spanning rock girdles were constructed on the Wilson river (Hastings catchment) at bed level with a key bed depth of one metre, to control bed levels in a ‘knickpoint zone’ in which comparative analysis of bed level changes indicated 0.25-0.5m of bed degradation of 0.25-0.5m between 2004 and 2006 between the girdles (Cohen and Telfer, 2006). Three ELS’s with timber pin radials were installed in July 2007 to reduce upstream hydraulic gradient and risks of girdle undermining. Analyses of post works monitoring

surveys (Daley, 2012) undertaken in 2008 and 2012, indicated no further bed degradation and that riffle crest elevations increased back to 2004 levels (see figure 3). Recent field observations (March 2016) have shown increased bed level elevations with aggradation smothering ELS 1 and 2.

Figure 3: Changes in bed level elevation, Wilson river ‘knickpoint zone’, as presented in Daley (2012). Note increased bed levels upstream of three elevated log sills (ELS) in 2008 following installation in 2007. Surveys were undertaken in March 2004, May 2006, September 2008, April 2012. Locations of four rock girdles (RG) constructed in 2001 are identified.



Constriction structures, timber pin rows and moving water upstream and downstream

Constriction structures, previously described in Brooks et al (2006a), and timber pin rows have been successfully trialed as alternatives to achieving objectives usually addressed with expensive rock ramp bed control structures. Three channel constriction structures (not depicted herein), installed in Blaxland Creek, a tributary of the Orara river, have promoted backwatering and deposition upstream and a hydraulic jump, eddying currents and pool scour downstream. Constriction of up to 60% of channel capacity during mean annual flood events elevated water levels upstream of the three structures by 0.3metre on average and created downstream pool scour of 1.8 – 2metres. Complimentary groyne structures, installed on both banks downstream, promoted eddying currents, ‘feeding upstream water’ to meet downstream super critical flows at the constriction, enhancing development of the hydraulic jump and pool scour. It was observed that locating groynes closer to the constriction created a deeper but shorter pool downstream.

Timber pin rows installed perpendicular to flow downstream of active ‘knickpoints’ in two flood chutes on the Orara river, have been effective in preventing further knickpoint progression by promoting upstream deposition through backwatering effects, minimizing required key bed depths and costs associated with traditional rock ramp alternatives.

Case Study: Application of hydraulic objectives to large scale meander reinstatement: ‘Skews Quarry’, Orara River, Karangi.

The headwaters of the Orara river, a tributary of the Clarence catchment NSW located west of Coffs Harbour, supports remnants of endangered sub-tropical lowland rainforest community, a diverse fish community (20 native freshwater species) including the endangered eastern freshwater cod and provides a water supply source to community of Coffs Harbour City Council. Excessive gravel extraction in the mid 1980’s from a low floodplain adjacent to a secondary flood channel on the Orara river, Karangi, led to channel avulsion and shortening and the upstream progression of bed degradation in mid and upstream reaches of the secondary flood channel (Cohen, 2004). The threat of a major meander cutoff through this flood channel was identified in late 2000. Bed level surveys were undertaken to inform rehabilitation design and funding requirements,

however, during the March 2001 flood event, flows through the primary channel were ‘captured’ by the flood channel resulting in a major meander cutoff (see figure 4). The primary channel (1300m in length), previously supporting high value aquatic habitat became a stagnant backwater and began filling with fine sediment. Channel enlargement increased flood channel capacity to convey flows far beyond that of the primary channel. The meander cutoff channel represented a 40% reduction in low flow channel length (Cohen, 2004) with a likely greater proportional increase in hydraulic gradient.

Changes in the alignment and increased volume and velocity of flows through the meander cutoff, led to river right bank erosion and further channel shortening in the Orara river immediately downstream of its downstream confluence with the meander cutoff (see figure 4). The cutoff channel, a source of large volumes of eroded coarse and fine sediment led to downstream aggradation. Upstream of the meander cutoff, knickpoint retreat threatened to erode bed levels supporting large areas of aquatic habitat, a road crossing and a stream gauging station.

Figure 4: ‘Skews Quarry’ rehabilitation reach, Orara river, Karangi showing project areas within the upper and lower areas of the meander cutoff. Three log jam locations (LJ1, LJ2, LJ3) are identified at the two flow exit points from the primary channel to the meander cutoff channel. The flood channel identifies the former flow path prior to gravel extraction, associated avulsion and downstream channel shortening.

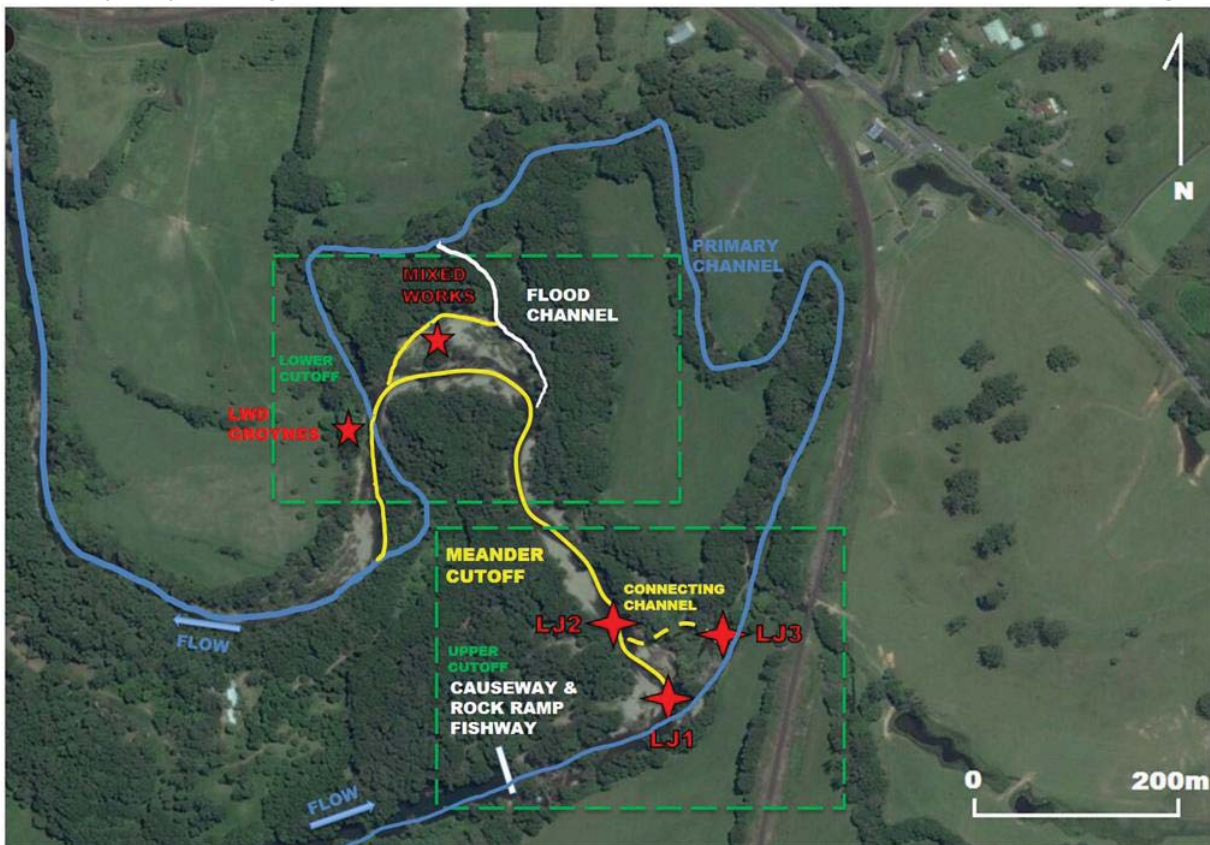


Table 1 identifies four reach scale rehabilitation objectives developed to guide rehabilitation planning and the delivery of a large scale structural works program from 2000 to 2013. Topographic long and cross sectional baseline and monitoring surveys were undertaken in 2000, 2004, 2007/8 and 2011. Survey data, monitoring photos, videos and observations of the hydraulic effectiveness of various works and geomorphic responses guided future intervention works in the rehabilitation program. Individual structures were designed to achieve hydraulic objective/s to address reach scale rehabilitation objectives (see table 2).

Table 1: Reach scale rehabilitation objectives for Orara river, Karangi: ‘Skews Quarry’ reach

| Reach Scale Objectives | |
|------------------------|--|
| 1 | reduce aggradation of the primary channel so as to promote its continued use during flood events and as the primary low flow channel to maintain fish habitat connectivity within 1300m of the primary channel and two local tributaries, Karangi and Poperaperin creeks |
| 2 | to stabilise bed and bank erosion in the meander cutoff channel and reduce channel capacity |
| 3 | reduce risk of bed lowering progressing upstream and undermining an elevated weir type road crossing and draining the upstream pool habitat |
| 4 | reduce aggradation and bank erosion on the Orara River downstream of the confluence of the cutoff and primary channel. |

Table 2: Installation dates of various intervention structures at Skews Quarry rehabilitation reach, Orara river. Hydraulic objectives of each structure to address reach scale rehabilitation objectives are identified.

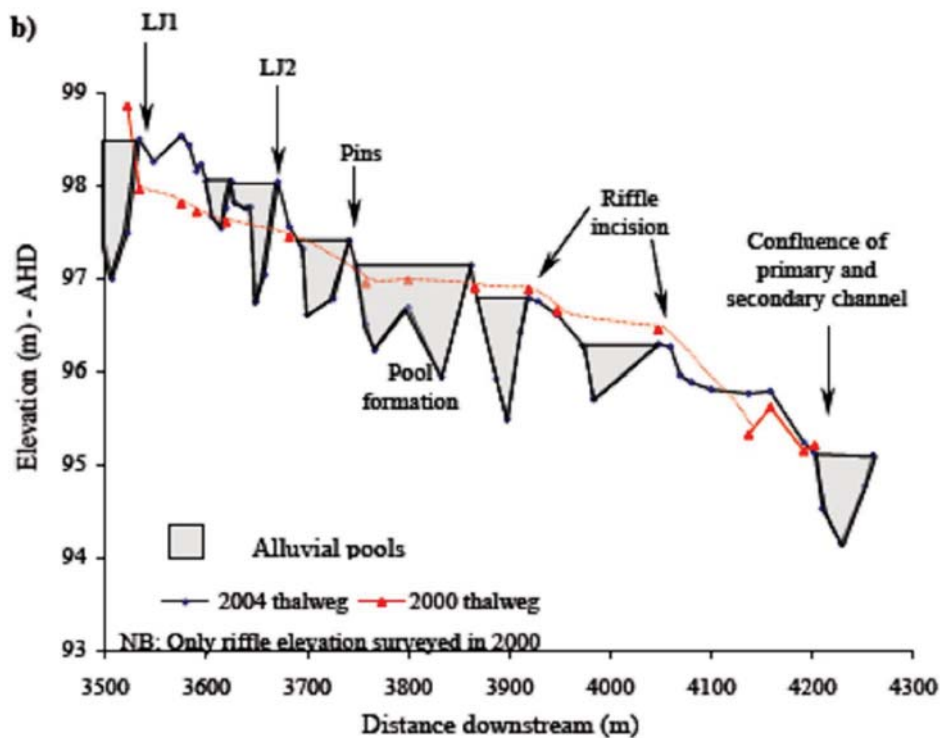
| Date | Structures | Hydraulic rehabilitation objectives of structure | Reach objective |
|------------|------------------------------|--|-----------------|
| Late 2001 | LJ1 & LJ3 | Provide geomorphically effective flows through the primary channel | 1, 2 & 4 |
| | | Maintain upstream backwatering effects to promote crossing flood out, reducing duration in which plunging flows prevail downstream of the crossing. | 3 |
| | | Reduce hydraulic gradient in lower end of cutoff channel by enabling floodwater to travel through primary channel and backwater into the cutoff channel. | 2 & 4 |
| July 2002 | LJ2 | Reduce upstream hydraulic gradient in upper area of meander cutoff, downstream of LJ1 and LJ3. | 2 |
| | Timber pin row 1 | Reduce hydraulic gradient upstream of structure to promote deposition in middle area of meander cutoff | 2 & 4 |
| March 2005 | LWD ‘flow attraction’ groyne | Divert partial flows from the meander cutoff through ‘original’ flood channel to the primary channel and flows away from eroding right bank | 1 |
| | LWD & timber pin groynes | Deflect flows away from eroding river right bank | 2 |
| | ELS & timber pin rows | Reduce hydraulic gradient upstream to flood out areas identified as incising in lower area of meander cutoff and promote deposition | 2 & 4 |
| | LWD deflection groynes | Deflect flood flows from cutoff channel away from eroding river right bank in primary channel downstream of its confluence with cutoff channel. | 4 |
| Early 2009 | Rock ramp fishway | Prevent undermining of crossing structure and maintain fish passage. | 3 |
| 2012 | Rock ramp inset into LJ1 | To ensure level and location of flows overtopping LJ1 on rising limb of flood. | 1, 2 & 4 |
| 2012 | Timber pin rows | Reduce hydraulic gradient upstream to flood out areas identified as incising in lower area of meander cutoff and promote deposition | 2 & 4 |

Works and results 2000-2004

Management of stock impacts on riparian vegetation was actively encouraged and supported, particularly to stabilise gravel bars to promote channel contraction within the meander cutoff and to reduce the extent of pool infilling in the primary channel downstream of its confluence with the meander cutoff. Rehabilitation works commenced with available resources in late 2001 with the construction of two log jam block walls (LJ1 and LJ3) at each of the two exit points from the former primary channel to the meander cutoff (see figure 4). The purpose of LJ1 and LJ3 was to 'force' flood waters past these two exit points into the cutoff channel and through the 1300m length of the primary channel prior to LJ1 and LJ3 overtopping. Table two identifies the hydraulic rehabilitation objectives of LJ1 and LJ3 and the intended reach scale objective each addressed. Both LJ1 and LJ3, particularly LJ1 averaging approximately 1.5m in height across its 70m width, required numerous maintenance efforts (not detailed herein) with the LWD being replaced with rock over time as funds became available. Various LWD and timber pin rows were installed immediately downstream of LJ1 and LJ2 to dissipate energy, promote deposition, guide flow paths, manage eddying currents and localised bank erosion.

To reduce upstream hydraulic gradient and velocities through the cutoff channel, a 55m wide LWD jam (LJ2) was constructed in July 2002 across the width of the cutoff channel immediately downstream of where flows overtopping LJ1 and LJ3 converge (see figure 4). Approximately 80m downstream of LJ2, a row of timber pins, were driven into the bed across the width of the channel at an approximate height of 0.9m, to reduce upstream hydraulic gradient and promote upstream deposition, bar development and riffle crest elevation. Whilst, the middle of the cross channel spanning LJ2 was washed away in October 2004, the remaining structure continued to serve as a channel constriction reducing the channel cross sectional area to approximately 65% of the previously eroded channel in this location. Comparison of before (2000) and after works (2004) long section survey data (Cohen, 2004) showed increased riffle crest elevations of 0.5m and 0.3m upstream of LJ2 constriction and pin row, respectively, with pool development at the LJ2 constriction (60m x 1.5m deep) and downstream of the pin row (90m x 1m deep). However, channel incision and lateral bank migration continued in the lower 300m of the cutoff (see figure 5), prompting further works (see figure 6).

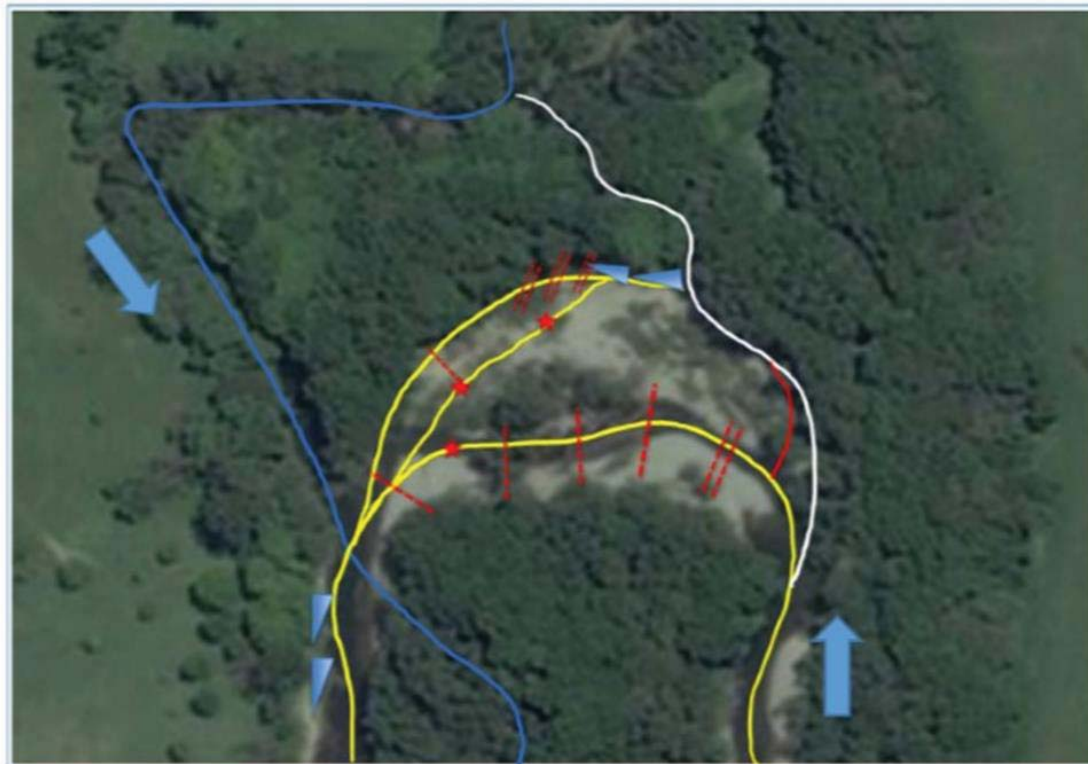
Figure 5: Comparative bed level elevations between 2000 and 2004 survey data showing bed level rise in the upper area of the cutoff channel associated with works and riffle incision in the lower cutoff channel.



Works and results 2005-2008

In March 2005 constructed works included two elevated log sills (ELS) and timber pin rows to address bed incision and and a series of LWD deflector and timber pin groynes to address river right bank erosion in the cutoff channel. The first LWD groyne was located at the exit to the 'original' flood channel (see figure six) with the additional objective of 'attracting' flows into the flood channel to maintain hydraulic connectivity with the primary channel (see table two). Two LWD deflection groynes were also constructed where altered alignment of flood flows through the meander cutoff eroded the river right bank of the primary channel downstream. Comparative analysis of long section bed level elevation data shows ELS's and associated timber pin rows were effective in addressing upstream channel incision (see figure 7). Between 2004 and 2008 riffle crest levels, ~20m upstream of ELS1 and ELS2, increased by up to 0.25m and 0.15m, respectively with downstream pool scour of ~0.6m (see figure 8). For the same period, the timber pin row constructed at the downstream end of the meander cutoff promoted bar formation of up to 0.9 m in height and 30m in width and raised bed levels in the low flow channel by 0.18m, providing significant gravel accumulation and channel contraction.

Figure six: Works undertaken in the lower meander cutoff and the primary channel downstream of the confluence. LWD groynes (—) timber pin groynes and rows (//) ELS's (★) were constructed on river right of the cutoff and primary channel in 2005. In 2012 timber pin rows were constructed through the incised river left flood chute and gravel was relocated to reopen the low flow path (—) to river right and flood channel. Flow path is indicated by arrows →

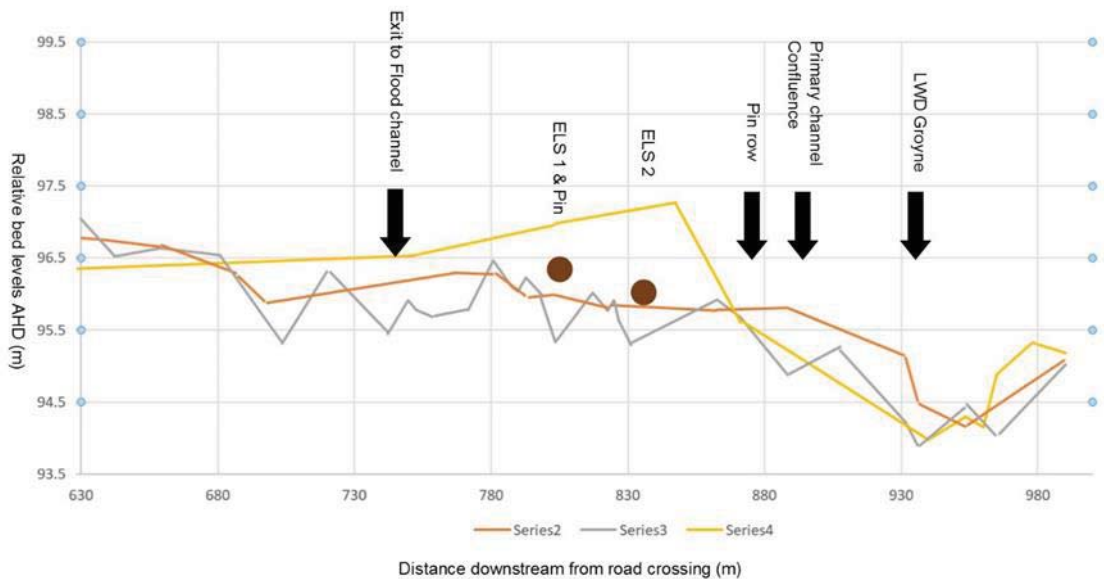


River right bank protection works were effective and data comparisons from three cross sections (not presented here) in the lower meander cutoff indicated up to 0.5m increase in adjacent bar height. Pool scour of ~0.5m at the exit to the flood channel (see figure 7) indicates the effectiveness of the LWD ‘attraction groyne’ in flow deflection and promoting the conveyance of flood flows through the flood channel. Flow deflection by the LWD groyne in the downstream primary channel increased pool scour by 0.6m, shifted thalweg location 9m to river left of the bank toe and increased pool cross sectional area by more than 25%. Cross sections located approximately 60m and 150m downstream of the LWD groyne showed bar elevation increases of up to 0.5m and long section data showed no change in riffle crest height.

Channel contraction in the upper area of the cutoff channel continued between 2004 and 2008 with bed and bar level elevations increasing by up to 0.9m downstream of LJ2 constriction at the timber pin row. Bed levels in the primary channel immediately downstream of the road crossing (refer to figure 4) increased to reflect those recorded in 2000 prior to the meander cutoff becoming active, indicating upstream backwatering objectives of LJ1 were effective in addressing the risk of bed lowering. Conveyance of flood flows through the primary channel downstream of LJ1 and LJ3 maintained bed scour, channel capacity and its continuation as the dominant low flow channel. In summary, monitoring results for the period 2000-2008 indicated intervention works to be effectively achieving hydraulic and reach scale objectives.

Figure 7: Comparative bed level elevations in the lower meander cutoff area. Note the increased bed level elevation between 2004 (series 2) and 2007/8 (series 3) upstream of ELS1 & pin row, ELS2 and pin row.

Increased pool scour was recorded at the exit to the flood channel and downstream of the LWD groyne in the primary channel for the same period. Increased bed elevations in 2011 (series 4) were associated with channel incision and shortening through an adjacent flood chute on river left.



Works and results 2009-2015

To mitigate risk of progressing bed erosion upstream of the meander cutoff and to facilitate upstream fish passage, a rock ramp fishway (1.1m high x 22m length x 39m wide) was constructed downstream of the weir type road crossing in early 2009. Consistent with rehabilitation objectives, continued gravel accumulation in the lower cutoff channel resulted in both ELS1 and 2 being buried following flood events in February and March 2009.

Consecutive flood events between June and November 2009 progressively removed LWD and overlying rock from LJ1 resulting in a major breach, which by June 2010 was approximately 25m wide with nearly all flows being conveyed through the meander cutoff, preventing beneficial backwatering effects from the primary channel downstream into the lower area of the cutoff channel, as outlined in table 2. Consequential increase in hydraulic gradient led to shortening of flow paths through an incised 80m long flood chute on river left (see figure 6) and aggradation of the river right low flow channel with bed level rises of between 0.5m and 1.0m higher than ELS1 and 2 crest levels, respectively (see figure 7). Comparison of 2008 and 2011 cross section data, showed river left flood chute incision of up to 2-3m deep and 15-18m wide through 2008 gravel bar heights. The altered flood flow path through the river left flood chute did not align with LWD groyne locations downstream in the primary channel (see figure 10), compromising LWD groyne effectiveness in flow deflection and river right bank protection.

Figure 8: Elevated Log sill 1 (ELS 1) and timber pin row in lower area of meander cutoff channel in June 2005 (left) and March 2006 (right). Note backwatering effects upstream of ELS1 and timber pins in June 2005 and deposition (see arrow) in March 2006 elevating upstream bed levels.



Comparative cross section analysis (2008 and 2011) at this LWD groyne location showed lowering of river left gravel bar heights by up to one metre (previously aggraded by 0.5m between 2004 & 2008). Similarly, bar level heights on river right approximately 110m downstream were lowered by up to two metres. Reduced elevations of these alternate bars indicated high velocity flow paths associated with the LJ1 breach upstream.

Figure 9: View upstream (February 2013) towards upper area of meander cutoff channel with LJ1 in the background. Timber pin row 1, constructed 0.9m above natural surface in 2002, located approx. 20m upstream of photo point. Some pins are evident on right of photo, the remainder buried under gravel.



The breach in LJ1 also diminished upstream backwatering effects in flooding out the rock ramp fishway, increasing the flood heights and velocities in which scouring hydraulic wave formation occurred over and downstream of the ramp, resulting in the formation of high velocity eddying currents and associated river right bank erosion. 2011 long section survey data showed downstream riffle crest and low flow pool levels to have eroded 0.6m below fishway design level and therefore compromising fishway effectiveness. The rock ramp bed control structure remained effective in preventing upstream progression of bed erosion. Pool length associated with LJ2 constriction increased and downstream bed levels in the mid reaches of the cutoff channel (see figure 9) increased by 0.4m since 2008 (1.4m since 2004) at the timber pin row and 0.1m in riffle crest elevation 20m upstream (~0.2m since 2004).

Figure 10: View downstream through river left flood chute of lower cutoff channel towards its confluence with the primary channel showing aggradation upstream of the timber pin row. River right low flow cutoff

channel is located behind the trees on right of photo. Note the near perpendicular alignment from this river left flood chute towards erosion on right bank of primary channel downstream in the background of photo.



Figure 11: View upstream through the river left flood chute of the lower cutoff channel (3 February 2012). The photo shows gravel aggradation upstream of a series of timber pin rows constructed at 0.9m above natural surface. The timber pins in the foreground were subsequently buried during a flood event one week later and an additional pin row was installed in late 2012 between these two rows, resulting in further aggradation and elevation of the incised flood chute following 2013 floods.



In Oct 2011 the LJ1 breach was repaired with an inset rock ramp structure, whilst works in the lower area of the cutoff channel focused upon shifting the thalweg back to river right to promote flows through the flood channel, reducing gradient and aligning flood flows exiting the cutoff channel with the river right LWD deflection groynes downstream in the primary channel. This involved the relocation of gravel deposits to reopen the river right low flow path in the meander cutoff channel and the construction of timber pin rows across the incised flood chute on river left (see figure 6). The most upstream timber pin row was strategically located so backwatering effects would promote the flood flow path to river right and deposition on river left (see Figure 12). Distance between each timber pin row was primarily determined by anticipating the upstream extent of backwatering effects so as to reduce velocity between the pin rows.

Monitoring observations following consecutive flood events throughout 2012 and 2013 showed LJ1 and LJ3 to be effective in forcing flows through the primary channel enabling backwatering effects to reduce hydraulic

gradient through the cutoff channel. Timber pin rows raised bed levels by up to one metre throughout the 80m length of the river left flood chute in the cutoff channel (see figures 10 & 11) with backwatering effects of the most upstream timber pin row effectively promoting flow to river right (see figure 12). Observations indicate the river right to have once again become an active flood flow path in line with rehabilitation objectives. Overall aggradation in the lower half of the cutoff channel since the beginning of 2012 has led to low flow connectivity to the primary channel being through the ‘original’ flood channel.

Long term monitoring of rehabilitation works against hydraulic and geomorphic objectives for “Skews Quarry reach” has highlighted the importance of LJ1, and to a lesser extent LJ3, in achieving all four reach scale rehabilitation objectives. However, it is apparent that reach scale objectives 2 (bed and bank stability and channel contraction in the meander cutoff channel) and 4 (reduced bank erosion and downstream aggradation) would not have been achieved without the complimentary role of other intervention works in addressing hydraulic gradient, particularly in the lower area of the meander cutoff channel.

Figure 12: Cross section view showing up to 0.9m bed aggradation upstream of timber pin row in the cutoff channel river left flood chute after a second flood event in February 2012. In the background on right of the photo is the river right low flow channel which exits to the ‘original’ flood channel in the middle of photo indicated by the arrow.



Conclusions

On the NSW north coast, a philosophical shift in river rehabilitation from an asset protection focus and ‘controlling’ bed and bank position to one of influencing hydraulic behaviour to affect geomorphic outcomes has been assisted by collaboration with leading practitioners from Australia and North America. Improved conceptual understanding of hydraulic behaviour and ability to predict hydraulic and geomorphic responses to intervention works has increased technical capacity and confidence in trialing alternative designs and approaches to managing LWD. Lessons from these trials have informed the rehabilitation objectives, design, implementation and monitoring efforts of ambitious large scale rehabilitation projects, such as the ‘Skews Quarry rehabilitation reach’ case study outlined within this paper. Incorporation of hydraulic objectives at the reach, site and structure scale promotes consideration of the role of individual structures in complimenting one another to achieve reach scale geomorphic objectives. There is much opportunity in applying conceptual understanding of hydraulic behaviour to rehabilitating geomorphic complexity within incised enlarged channels using low elevation intervention works designed with high channel blockage ratios to operate during small flood events (eg. mean annual floods) without compromising flood mitigation or asset protection objectives.

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References

- Babakaiff, S. (2003). *Effectiveness of instream rehabilitation: Orara and Urumbilum Rivers*. Report prepared for the Orara Valley Rivercare Management Committee.
- Bonetti, R. M., Reinfelds, I.V, Butler, G.L, Walsh, C.T., Broderick, T.J. & Chisholm, L.A (2016). A multi-scale GIS and hydrodynamic modelling approach to fish passage assessment: Clarence and Shoalhaven Rivers, NSW, Australia. *Geomorphology*. 260: 79-90.
- Brierley, G., Ferguson, R.J., Lampert, G., Cohen, T., Fryirs, K., Reinfelds, I., Goldrick, G., Crighton, P., Batten, P. & Jansen, I. (1999). *Summary overview of River Styles in North Coast catchments of New South Wales*. Report prepared for NSW Department of Land and Water Conservation by Department of Physical Geography, Division of Environmental and Life Sciences, Macquarie University.
- Broderick, T. and Outhet, D. (1998). *River management plan for the rehabilitation and maintenance of Goolang and Blaxland Creeks*. Report to North Power, Department of Land and Water Conservation, Grafton NSW, in press.
- Broderick, T. & Outhet, D. (1999a). *River management plan for the rehabilitation and maintenance of Orara and Urumbilum rivers*. A report prepared by NSW Department of Land & Water Conservation for Coffs Harbour City Council and the Orara Valley Rivercare Management Committee.
- Broderick, T. and Outhet, D. (1999b). *Rehabilitation of streams receiving inter basin transfers – NSW north coast. Proceedings of the Second Australian Stream Management Conference, Adelaide, South Australia*. 1: 113-120.
- Brooks, A.P. (1999). Lessons for river managers from the river tardis: Direct insight into post European channel changes from a near intact alluvial river, *Proceedings of the Second Australian Stream Management Conference, Adelaide, South Australia*. 1: 121-128
- Brooks, A.P., Gerke, P.C., Jansen, J.D. & Abbe, T.B. (2004). Experimental reintroduction of woody debris on the Williams River, NSW: geomorphic and ecological responses. *River Research and Applications*, 20: 513-536.
- Brooks, A.P., Abbe, T., Cohen, T., Marsh, N., Mika, S., Boulton, A., Broderick, T., Borg, D. & Rutherford, I. (2006a). *Design guideline for thereintroduction of wood into Australian streams*. Land and Water, Canberra.
- Brooks, A.P., Howell, T., Abbe, T.B., & Arthington, A. (2006b). Confronting hysteresis: Wood based river rehabilitation in highly altered landscapes of south eastern Australia. *Geomorphology*, 79: 395-422.
- Cambridge, A., Morden, R. 2012. *Designing a Basic Whitewater Canoe/ Kayak course using InfoWorks*

8ASM Full Paper

Tony Broderick – *Things of Stone, Wood and Running Water*

ICM: Case Study. Sinclair Knight Merz.

Cohen, T. (2003). Late Holocene floodplain processes and Post European channel dynamics in a partly confined valley of New South Wales Australia. Phd thesis. School of Geosciences. University of Wollongong, New South Wales, Australia.

Cohen, T.J. (2004). *A Geomorphic analysis of the Orara River – Cochran's Pool to Coramba.* A report prepared by University of Wollongong for the Orara Valley Rivercare Management Committee

Cohen, T. & Telfer, D. (2006). *Channel instability and rehabilitation options for the Wilson River, NSW.* A report prepared for Northern Rivers Catchment Management Authority.

Daley, J.S. (2012). Taming the hungry beast: the effectiveness of engineered log jams in an incising gravel-bed river. A research report submitted for partial fulfillment for the award of the degree of Bachelor of Environmental Science (honours). University of Wollongong.

Erskine, W. & Webb, A.A. (2003). Desnagging to resnagging: new directions in river rehabilitation in south eastern Australia. *River Research and Applications*.19 (3): 233-249.

Gippel, C.J., O'Neil, I.C., Finlayson, B.L., & Schnatz, I. (1996). Hydraulic guidelines for the reintroduction & management of large woody debris in lowland rivers. *Regulated Rivers: Research and Management*, 12: 223-236.

Gallisdorfer, M.S., Bennett, S.J., Atkinson, J.F., Mohammad Ghaneezad, S., Brooks, A.P., Simon, A. & Langendoen, E.J. (2013). Physical-scale model designs for engineered log jams in rivers. *Journal of Hydro-environment Research*: October: 1-14.

Hsu, E.Y., (1950). Discussion on control of the hydraulic jump by sills, by John W. Forster and Raymond. A. Skrinde. *Transactions, ASCE*, 115: 988-991.

Lyll & Macoun and University of Wollongong. (1998). *Nambucca Valley River and Catchment Management Study. Executive summary and management recommendations.* A report prepared by Lyll & Macoun Consulting Engineers and University of Wollongong, School of Geosciences for Nambucca Catchment Management Committee.

Moore, W.L. and Morgan, C.W., (1959). Hydraulic jump at an abrupt drop. *Transaction, ASCE*, 123: 507-516.

McLaughlin, R. E. and Grenier, R.R.Jr. (1997). *Low head drop structure hazards: modelling of an abrupt drop boat chute.* A report prepared for McLaughlin Water Engineers Ltd.

Nambucca Report (2002). *River restoration Activities in the Nambucca Valley. An overview.* A monitoring assessment booklet of structural works prepared for Natural Heritage Trust.

Newbury, R.W. & Gaboury, M.N. (1993) *Stream Analysis and Fish Habitat Design- a field manual.* Newbury Hydraulics Ltd. And the Manitoba Habitat Heritage Corporation.

Reinfelds, I., Rutherford, I. & Bishop, P. (1995). History and effects of channelisation of the Latrobe river, Victoria. *Australian Geographical Studies*.33 (1): 60-76.

8ASM Full Paper

Tony Broderick – Things of Stone, Wood and Running Water

Resource Planning Pty Ltd. (1990). *Orara and Urumbilum Rivers channel stability and gravel resources*.
Report prepared for NSW Department of Water Resources.

Schumm, S.A. (1994). Erroneous perceptions of fluvial hazards. *Geomorphology*. 10(1-4): 129-138.