River restoration based on natural channel characteristics: how to develop restoration designs for different rivers and riparian plant communities

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Abstract

Undisturbed river sections in various reserves exhibit natural channel morphologies, intact riparian vegetation and natural loads of large wood. The characteristics of such remnant river reaches have not been meaningfully applied to river restoration design in Australia. Laterally stable, unconfined, meandering streams with an *Allosyncarpia ternata*-dominated riparian vegetation community in the Alligator Rivers Region of northern Australia are characterized by a sinuous pattern (sinuosity > 1.5), stable river banks (rates of lateral migration not significantly different from zero), pools spaced much less than 5 channel widths apart, sandy boundary sediment, steep banks and dense in-channel trees and large wood. Large wood loadings vary between 184 and 302 m^3/ha of channel but vary by over one order of magnitude for each unit length of channel. Small diameters dominate in terms of large wood numbers but large diameters dominate the volume. Most large wood is relatively short in comparison to channel width and hence is readily moved. Blockage ratios of large wood are usually small (<0.06) and do not often impact on channel hydraulics. These detailed investigations of channel morphodynamics, riparian vegetation floristics and large wood characteristics are used to develop restoration designs where various disturbances have locally altered channel morphology and riparian vegetation.

Keywords

Ngarradj Creek, scour pools, riparian zone, afflux, refuges, fish habitats

Introduction

The characteristics of natural streams have been used as the basis for the design of river rehabilitation projects throughout the world (Newbury & Gaboury, 1993). However, only regional hydraulic geometry relationships for specific stream types usually form the template for stream rehabilitation projects (Newbury & Gaboury, 1993; Rutherfurd *et al.*, 2000) and little consideration is given to the influence of riparian vegetation on channel morphology and dynamics. Rutherfurd *et al.* (2000) recommended that the physical or biological characteristics of a river reach in good condition should be copied in restoration designs but both characteristics exhibit significant interactions. The nature of channel morphodynamic-riparian vegetation interactions varies with each riparian plant community and little is known about most riparian plant communities in Australia. The purpose of this paper is to demonstrate how a detailed understanding of the interactions between channel morphodynamics, riparian vegetation and large wood for essentially undisturbed stream reaches can be used to develop a customised restoration design for short disturbed sections of similar streams.

We investigated the channel morphodynamics of ‘laterally stable unconfined meandering rivers’ (Erskine *et al.*, 2005), the floristics of an *Allosyncarpia ternata* S.T.Blake riparian rainforest and the characteristics (loading, spatial distribution, orientation, composition, arrangement, blockage ratios) and recruitment processes of large wood on two tributaries in the Ngarradj Creek catchment near Jabiluka, Northern Territory, Australia (Figure 1). Laterally stable unconfined meandering rivers are defined as sand-bed streams with a sinuous pattern, a continuous but narrow floodplain and a narrow, well-vegetated riparian corridor (Erskine *et al.*, 2005). Ngarradj Creek is located in Kakadu National Park and flows into the wetlands of lower Magela Creek that are listed as Wetlands of International Importance under the RAMSAR Convention and recognised under the World Heritage Convention. Nevertheless, short sections of these streams have been disturbed by dry season fires, buffalo wallowing, pig rooting, sand extraction and track construction. The two study reaches were located on East Tributary and upper Ngarradj Creek at automatic gauging stations (Figure 1) where the respective catchment areas are 8.5 and 18.8 km^2 (Erskine *et al.*, 2001). The present work forms part of a comprehensive geomorphic research program by the Environmental Research Institute of the Supervising Scientist in the Ngarradj Creek catchment (Erskine *et al.*, 2001), in which the Jabiluka project area is located, in the seasonally wet tropics of northern Australia (Figure 1).

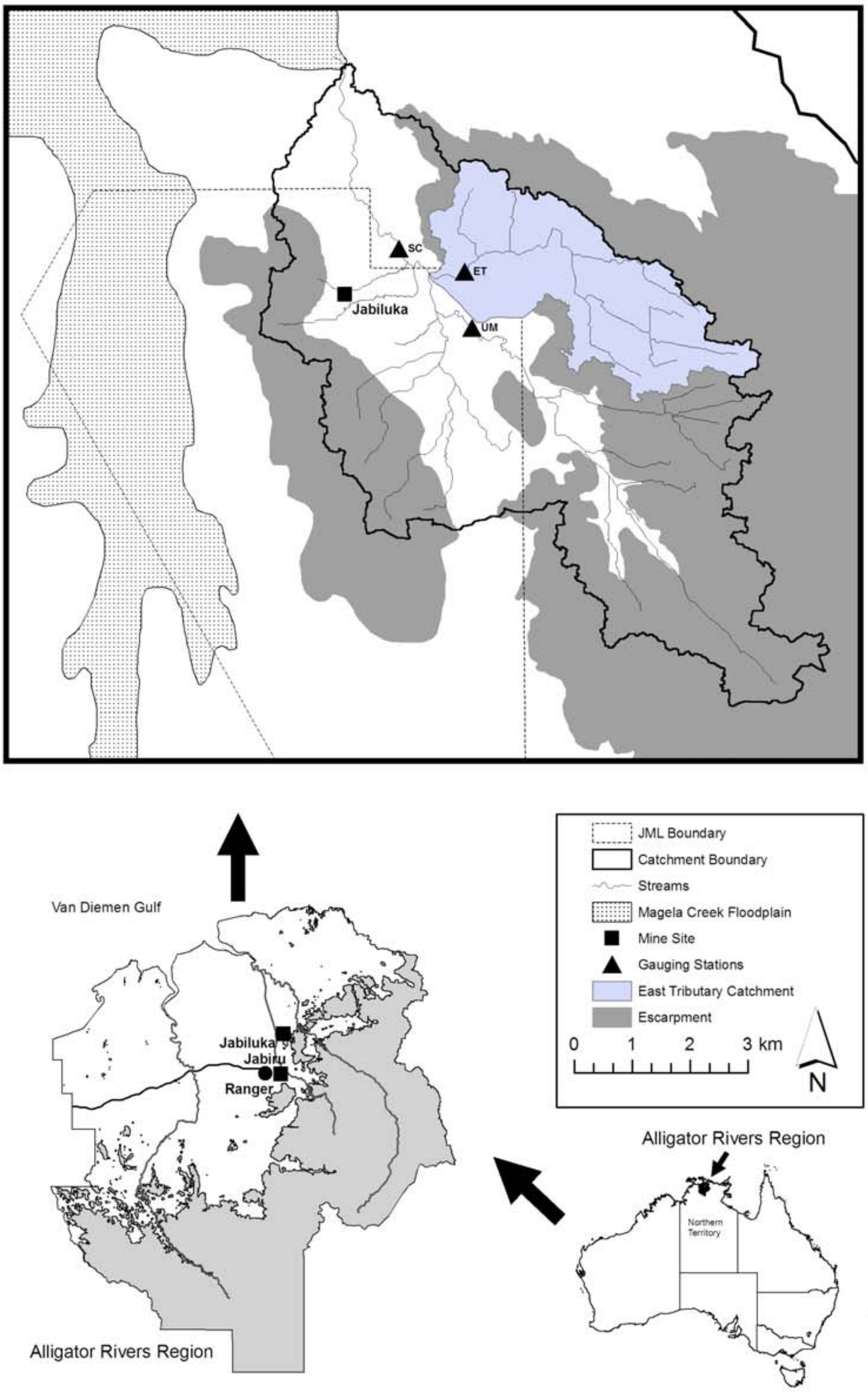

Figure 1. Ngarradj Creek catchment near Jabiluka, Northern Territory. The study reaches were located at the East Tributary (ET) and upper Ngarradj Creek (UM) gauging stations.

Methods

The surveyed reaches were 15.1 channel widths long on East Tributary and 28.6 channel widths long on upper Ngarradj Creek. Eight permanently marked cross sections were installed in each reach and surveyed annually for 6 years. Five metal scour chains were installed in the East Tributary and six in the upper Ngarradj Creek study reaches. They were relocated and excavated every dry season for the same time period as the cross sections. A total of 22 and 28 erosion pins were installed and measured at the start of the wet and dry season every year for three years in the East Tributary and upper Ngarradj Creek reaches, respectively. Bulk bed-material samples were collected at each cross section every dry season for 6 years, sieved and grain size statistics calculated. The width of the monsoon rainforest from the top of the channel bank to the outer edge of the canopy on the floodplain was measured on each side of the channel. Contiguous 5 m x 5 m quadrats were located on a transect from woodland on one side of the channel to woodland on the other side of the channel at one of the cross sections in each reach. Canopy cover was recorded for each stratum in each quadrat along with all tree and shrub species and their diameter at breast height over bark. Large wood was defined as any type of wood of any length greater than 0.1 m in diameter. An inventory of the total amount of large wood, its location and orientation within the bankfull channel was conducted. The large wood was split into dead wood and living trees, and each tree was identified to species level.

Channel morphodynamics

East Tributary and Ngarradj Creek are seasonal streams that commenced flowing in late November after between 250 and 440 mm of rainfall had been recorded (Saynor *et al.*, 2006a). Streamflow persisted until at least April (Saynor *et al.*, 2006a). Bankfull discharge occurred at least once during each wet season and the rating curves at each gauging station did not change over the 6 years of monitoring (Saynor *et al.*, 2004). Measured annual channel changes at the 8 permanently marked cross sections in each reach were minor (usually < 10% and often < 6% in all measures of hydraulic geometry) over the 6 years between 1998 and 2003 (Saynor *et al.*, 2004). Mean annual bed scour, as determined by scour chains, ranged within plus or minus twice the standard error of estimate of the mean annual fill (Saynor *et al.*, 2004). We have previously shown that measured bank erosion rates over three years at both sites were not significantly different from zero (Saynor and Erskine, 2006). Graphic mean size of the bed material was medium sand at East Tributary in 1998 but increased to coarse sand in 1999 which persisted to 2003 (Saynor *et al.*, 2006b). At upper Ngarradj Creek, the graphic mean size was medium-coarse sand in 1998 and increased to coarse sand in 1999 which again persisted to 2003 (Saynor *et al.*, 2006b). While these channels transport a large proportion of their total sediment as sandy bedload (Erskine *et al.*, 2006; Saynor *et al.*, 2006a), they are stable because bankfull specific stream power is low to moderate (<25 W/m^2) and the banks are well protected by living trees and high roughness associated with high loads of large wood (Saynor *et al.*, 2004; Erskine *et al.*, 2005).

Floristics of Allosyncarpia ternata *monsoon rainforest*

A. ternata is an evergreen tree up to 18 m high with grey fissured fibrous bark that is endemic to western Arnhem Land, Northern Territory, Australia (Blake, 1977). The monsoon rainforest comprises a narrow strip bordering the immediate river channel. On East Tributary, the riparian rainforest was 21.7 ± 2.7 m wide from the top of the bankfull channel to the landward edge of the canopy on the left bank and 18.5 ± 1.6 m wide on the right bank. Mean bankfull channel width was 8.6 ± 0.4 m. On upper Ngarradj Creek, the respective values were 12.8 ± 2.0 m, 11.5 ± 0.9 m and 10.2 ± 0.3 m. There was no significant difference in the width of the riparian corridor between left and right banks at each site. The quadrat surveys of trees in the monsoon rainforest on contiguous transects perpendicular to the channel at both sites found that *A. ternata* was the dominant tree (42 – 85 %), with *Lophopetalum arnhemicum*, *Syzygium forte* ssp *potamophilum*, *Calophyllum sil*, *Carellia brachiata*, *Erythrophlem chlorostachys* and *Xanthostemon eucalyptoides* also being present. This rainforest corresponds to Group 7 of Russell-Smith's (1991) classification of monsoon rainforests of northern Australia. Good recruitment of *A. ternata* seedlings was found by the quadrat surveys. Fire seems to be an important cause of death of *A. ternata* with the quadrat surveys revealing 400-2000 trees/ha with fire scars on East Tributary and 400 trees/ha on upper Ngarradj. In addition, 12.6 % of the large wood in the bankfull channel at East Tributary exhibited fire scars and 16.2 %, at upper Ngarradj. Nevertheless, there was a large range in diameters of *A. ternata* trees growing within the bankfull channel. The frequency distribution of diameter at breast height over bark of every *A. ternata* tree within the bankfull channel in the surveyed reaches revealed a reverse J-shape curve at both sites because there is continual recruitment of riparian trees (Woolfrey & Ladd, 2001). While the greatest numbers of *A. ternata* trees are less than 0.3 m in diameter, there are some very large trees present with diameters greater than 0.75 m.

Large wood characteristics
In-channel large wood loads varied between 184 m^3/ha and 302 m^3/ha. We believe that there is an inverse relationship between bankfull specific stream power and total large wood load for each riparian vegetation community and river type. At high stream powers (>70 W/m^2), large wood can be transported and removed from the reach in which it recruits whereas at low stream powers (<5 W/m^2), large wood accumulates where it recruits. At upper Ngarradj Creek, dead wood comprised 61.3 % and living trees comprised 38.7 % of the total large wood load, whereas at East Tributary, the percentages were 34.5 and 65.5 %, respectively. Most living trees were located on the river banks within the bankfull channel. Between 94 and 97 % of living trees were located on the banks and only between 3 and 6 % were found in the river bed. The roughness created by dense bank-side trees is responsible for low flow velocities along the channel margins and hence the measured zero bank erosion rates over three yeas (Saynor & Erskine, 2006). Large wood loadings varied greatly longitudinally with up to three orders of magnitude variation at one channel width lengths down the channel. At upper Ngarradj Creek, the mean large wood load per unit channel width of length was 1.87 ± 0.28 m^3 and the range was 0.06 to 5.4 m^3. At East Tributary, the mean was 1.90 ± 0.46 m^3 and the range, 0.65 to 6.8 m^3. Clearly there are large spatial variations in large wood load with occasional debris dams interspersed with sections exhibiting relatively low loads.

Large wood was usually orientated downstream but there was also a small second mode at right angles to the flow direction. Downstream orientations are only possible where rivers have the stream power to reorient a significant proportion of the recruited large wood and where the large wood is too short to be wedged across the cannel. Small diameter wood (<0.3 m) dominates in terms of the number of pieces but large diameter wood (>0.3 m) dominates in terms of volume in both reaches. The dominant lengths of large wood are much less than the bankfull channel width and hence can be mobilised. Debris dams were uncommon but, when present, caused significant localized expansions in channel width. Blockage ratios are usually less than 6 % but the few debris dams present do block a significant proportion of the bankfull channel area (>16 %). Significant afflux should result from such large blockages. Outflanking and under scour of debris dams were important river responses at these high blockage ratios.

Natural large wood recruitment in northern rivers occurs by a range of processes that are often closely linked to floods and tropical cyclones. Tree senescence, localized bank erosion during floods, wind throw and branch shedding during tropical cyclones have all been observed at both sites over the last 8 years. However, other processes are also important, where dry season fires and wet season lightning strikes kill or significantly damage riparian trees. Recruitment frequency is currently unknown although three significant recruitment events in 8 years have now been documented in the East Tributary study reach (rain storm in January/February 2002; fire in November 2003; Cyclone Monica in April 2006) and one in 8 years in the upper Ngarradj Creek reach (Cyclone Monica in April 2006).

Given the extreme old age of the Kakadu landscape, sand dominates bed material (Erskine *et al.*, 2001; Saynor *et al.*, 2006b; Erskine *et al.*, 2006) and large wood-induced scour is an important process of pool formation. Pools are significant fish habitat and cause greater river complexity. Many sand-bed streams exhibit flat ecologically featureless beds and only develop complexity where large wood induces local scour. At East Tributary, there were 13 pools in the surveyed reach with an average spacing of 1.75 channel widths. This is much less than the 4-8 channel widths commonly associated with pool-riffle sequences. Of these 13 pools, only two were dominantly produced by bend processes, the remainder being caused by localized scour due to the presence of large wood. Scour mechanisms included under scour, over scour, lateral scour and constriction scour. Each scour mechanism produced a distinctive pool type, namely transverse scour pool, log step pool, longitudinal pool and convergence pool, respectively. The close spacing of pools reflects the addition of pools between bends in sinuous streams due to localized scour induced by the high large wood load. While bend pools are usually the deepest, scour induced by large wood can also extend and deepen pre-existing pools as well as create new pools where none previously existed. Loss of pools reduces fish abundance. Larger fish species are found in pools as are larger specimens. Therefore, high large wood loads are significant for the maintenance of river complexity in tropical, forested, sand-bed streams.

Developing restoration designs based on natural channel characteristics
The significance of riparian vegetation for bank stability and bed complexity in the Ngarradj Creek catchment has been clearly established. Laterally stable unconfined meandering streams exhibit low to

moderate specific stream powers because of the sinuous channel pattern (sinuosity > 1.5), high large wood loads, dense stands of trees along the river banks and frequent log steps in the bed. Therefore, it is important that restoration efforts incorporate all these natural features into the design.

Various types of forest and vegetation reserves should be evaluated for their suitability as restoration templates. Restoration efforts should be initiated in good quality channel remnants which should be extended into areas which have been disturbed by repeated fires, buffalo wallowing, pig rooting or human destruction. Erskine *et al.* (2001; 2005) noted that laterally stable unconfined meandering rivers in the Alligator Rivers Area are preferentially located between upstream gorges and downstream floodouts and ridge anabranching reaches. Therefore, there are minor variations in catchment areas and stream orders between different reaches of laterally stable unconfined meandering rivers. Scaling issues between template and treatment are not significant in this case. Furthermore, vegetation re-establishment must include plantings within the bankfull channel and should mimick the species mix and abundance present at undisturbed sites. The most important source of large wood which recruits to the channel is from the riparian rainforest. Therefore, the monsoon rainforest must be maintained and/or restored to ensure a continuous seed source for trees and an ongoing supply of large wood to the channel.

When resnagging or reintroducing large wood into laterally stable unconfined meandering streams with *A. ternata* riparian rainforest, the following features, which are documented in earlier sections, should be adopted:

- Large wood should include a range of diameters (0.1 to >0.5 m) because the number of pieces of large wood is dominated by small diameters but the total volume is dominated by large diameters.
- Large wood should include a range of lengths (<0.1 to 10 m) so that individual pieces can either be wedged between the channel banks, forming complex large wood accumulations or can be readily transported and rearranged within the bankfull channel.
- The spacing between pieces of large wood should never be fixed at a constant distance but should vary longitudinally in a random manner similar to the natural distribution.
- The load of large wood should also vary longitudinally in a random manner similar to the natural distribution.
- The orientation of large wood should be dominantly downstream but must also incorporate a significant number of transverse pieces similar to the natural distribution.
- Debris dams are relatively rare and, where they exist, usually exhibit blockage ratios less than 6 %. Only when afflux and associated flooding and damage to infrastructure are significant considerations should large debris dams be excluded from the design. Otherwise, their density and location should replicate the natural distribution.
- Local bed scour is a very important mechanism of increasing the number of pools and hence available fish habitat. Large wood is a significant cause of bed scour and should be selected and located to induce pool creation. Large wood also increases the complexity of bend pools.
- As a general rule, more large wood is better than less wood and it can be spaced very close together.
- Where large wood must be anchored to avoid its loss from the treated site, wooden piles should be used in preference to other materials because they are a natural component of such streams.

Greater use needs to be made of relatively undisturbed channel reaches in various types of reserves in Australia as the basis for the design of more appropriate river restoration templates. Different templates will be required for different river morphologies and riparian plant communities. For river types other than laterally stable unconfined meandering rivers, scaling issues will need to be addressed to apply the restoration template to treated sections of stream of different size.

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