It's a good news story! Tracking geomorphic recovery of rivers in eastern New South Wales as part of process-based river management

Kirstie A Fryirs[1]*, Gary J Brierley[2], Fergus Hancock[3], Tim J Cohen[4,5], Andrew P Brooks[6], Ivars Reinfelds[7], Nick Cook[3], Allan Raine[3]

[1] Department of Environmental Sciences, Macquarie University, North Ryde, NSW, 2109, Australia. Email: kirstie.fryirs@mq.edu.au
[2] School of Environment, The University of Auckland, Auckland, New Zealand
[3] NSW Department of Industry, Crown Lands and Water Division, Newcastle
[4] ARC Centre of Excellence for Australian Biodiversity and Heritage, University of Wollongong, Australia
[5] GeoQuest Research Centre, University of Wollongong, Australia
[6] Griffith Centre for Coastal Management, Griffith University
[7] NSW Department of Industry, Crown Lands and Water Division, Wollongong

Key Points

- Geomorphic river recovery has been underway for decades in some coastal catchments of NSW.
- Key types of geomorphic units and the timing of their appearance can be used as indicators that geomorphic river recovery is underway along different types of rivers.
- Modern day process-based river management utilises a recovery-enhancement approach.
- River recovery has been mapped across 216,000 km of stream length in NSW. Recovery maps are used in river management prioritisation for on-ground rehabilitation, and to decide if and how much intervention is required, and when to opt-out of management and leave the river to self-heal.

Abstract

Along many alluvial river reaches in south eastern Australia, clearance of forests and riparian vegetation, and removal of wood from channels in the 19th and 20th centuries induced widespread geomorphic impacts. However, since the 1970s there has been a noticeable and significant shift in the geomorphic condition of many rivers. This reflects increases in groundcover and re-establishment of woody vegetation within riparian and in-channel zones associated with a reduction in land-use pressures and improved farming practices on the one hand, and adoption of recovery enhancement approaches to river conservation and rehabilitation by management authorities on the other. Following a brief review of river change in eastern NSW since European settlement, we outline an approach to identify and measure key geomorphic indicators of river recovery for different river types. We use case studies to demonstrate examples of geomorphic river recovery and the 'things to look out for' when assessing geomorphic river recovery. For example, the formation and stabilisation of benches, pool scour and re-establishment, and the reorganisation of bed materials into well-defined low flow channels are key indicators of geomorphic river recovery for some river reaches. We present how this approach to monitoring and tracking changes in condition can be used to identify when geomorphic recovery is occurring so that decision-support frameworks can determine *whether* river management is required, *where*, *when* and *how much* to intervene to enhance river recovery and when to *opt-out* of management because the system requires little (or no) intervention. Broader implications of this 'good news story' are discussed.

Keywords

anthropogenic disturbance, river restoration, riparian vegetation, river condition, river evolution

Introduction

The effects of 220+ years of post-European settlement land-use practices have had a catastrophic effect on many river systems in southeastern Australia (Fryirs *et al*., 2013; Rutherfurd, 2000). The clearing of riparian vegetation, removal of wood and channelisation of many river courses has produced widespread geomorphic consequences, such as incision and channel expansion, sediment slug formation, gullying, and disconnection of channels from their floodplains. Even a cursory look at aerial photographs from the 1940s reveals degraded channels with a scant cover of riparian vegetation cover. In many instances, changes to river morphology are irreversible in practical terms, such that predisturbance states no longer provide viable target conditions for management efforts (Dufour & Piégay, 2009; Montgomery, 2008). However, since the 1970s, there has been a noticeable shift in the geomorphic condition of many of these rivers. This reflects changes in rural land-use, improved farming practices and progressive implementation of recovery enhancement approaches to river conservation and rehabilitation that work with the character and behaviour of rivers, rather than promoting stability and equilibrium (Brierley & Fryirs, 2005, 2009; Fryirs & Brierley, 2009).

In recovery-enhancement approaches to prioritisation, consideration is given to where river recovery is occurring, and how this can be advanced by 'working out' from reaches with high recovery potential (Brierley & Fryirs, 2005; Rutherfurd *et al*., 1999). In the work reported here, river recovery is defined as an improvement in geomorphic condition, typically over decadal timeframes (Fryirs & Brierley, 2016). However, river recovery is not simply the reverse of river degradation. Processes, forms and rates of geomorphic river recovery vary for different types of river and improvement can take place along a range of trajectories (Brierley & Fryirs, 2005, 2016). Therefore, recovery is a natural process that reflects the capacity of river systems to adjust to prevailing boundary conditions, with enhancement and 'directed adjustment' through proactive and adaptive river management practices (Beechie *et al*., 2008; Dufour & Piégay, 2009; Kondolf, 2011).

While river systems may be showing signs of geomorphic recovery, forecasting exercises are required to determine whether recovery can be enhanced or constrained by limiting factors or pressures such as sediment undersupply or oversupply, or the type and quality of riparian vegetation or seed sources, or factors such as environmental management policy and practice, and climate change.

This paper highlights some of the key indicators that can be used to determine when geomorphic river recovery is occurring for different river types. Using case studies we show some key characteristics of recovery that have occurred in recent decades along rivers in eastern NSW. We then present work of NSW Department of Industry, Water (DoI Water) showing how geomorphic concepts are used in management.

Methods: How to identify geomorphic river recovery

Differing forms of geomorphic recovery for various rivers in eastern NSW are shown on **Figure 1**. Depending on the type of river under consideration, differing geomorphic units (i.e. landforms) can be considered to represent 'landforms of recovery'. Analysis of the trajectory of response in geomorphic river condition to impacts of human disturbance, whether deteriorating or recovering is determined by the presence, absence or reconstruction of the assemblage of geomorphic units, which are expected to occur for different river types (Fryirs, 2015; Fryirs & Brierley, 2016). The recovery or reconstruction of those features which were previously missing, or the rate at which those features are re-emerging, provides an indication of the effectiveness of recovery processes and the rate at which geomorphic recovery is proceeding. As various geomorphic units (re)appear at different stages of the recovery process, and at different rates, the presence/absence and stability of these features indicates whether a reach is at an early recovery stage or an advanced recovery stage. This method of using geomorphic units as indicators of recovery at the reach scale forms one part of assessments of river recovery potential across NSW (see later).

Formation of benches via sediment deposition along channel margins and flow separation zones reduces the capacity of enlarged (incised and widened) channels, indicating that channel contraction is underway (**Figure 1a**). Multiple forms of recovery in highly disturbed macrochannel systems include the deposition and storage of sediment in compound bank-attached bars and benches (**Figure 1a**). These features provide bank toe protection for previously over-steepened banks that were prone to mass failure. The re-definition of a distinct low flow channel is an important form of recovery in instances where the bed has been highly disturbed (e.g. via incision, over-widening, sediment smothering/slug formation) (**Figure 1b**). Distinct low flow channels tend to have lower width-depth ratios than their indistinct counterparts. This form of recovery is often accompanied by the return of features such as pool-riffle sequences in active meandering rivers (**Figure 1c**) or the re-emergence of pools in bedrock reaches. The appearance of well-vegetated and stable bars and islands increases bed heterogeneity relative to the planar bed conditions of some pre-recovery systems (**Figure 1d**). Along macrochannel reaches that have experienced significant over-widening and an oversupply of sediment, the reorganisation and selective transfer of sediment, and the stabilisation of bars and islands, produces a multi-channel low flow network in a formerly sediment slug affected reach (**Figure 1e**). Elsewhere, for quite different types of river, re-formation of swampy (wetland) conditions on the bed of an incised channel within valley fill deposits marks recovery to a discontinuous watercourse (**Figure 1f**).

Figure 1 Some forms of geomorphic river recovery. (a) Left: Hunter River at Dartmouth in 1959; Source; DPI Water archive; Right: Macdonald River, NSW; Source: K. Fryirs; (b) Left: Pages River, NSW; Source: K. Fryirs; Centre: Upper Hunter River at Key's Bridge, NSW; Source: K. Fryirs; Right: Pages River, NSW; Source: K. Fryirs; (c) Left: Mulloon Creek, NSW; Source: K. Fryirs; Centre: Mulloon Creek, NSW; Source: K. Fryirs; Right: Upper Hunter River, NSW; Source: Fergus Hancock; (d) Left: Hunter River at Bureen in 1976; Source: DPI Water archive; Right: Wollombi Brook at Warkworth, NSW; Source: Nick Cook; (e) Left: Bega River, NSW; Source: Andrew Brooks; Right: Bega River, NSW; Source: Google Earth^{TM}; (i) Left: Wolumla Creek, NSW; Source: K. Fryirs; Centre: Wolumla Creek, NSW; Source: K. Fryirs; Right: Reedy Creek, NSW; Source: K. Fryirs. For a full version, see Fryirs et al. (2018).

Caution is required when assessing geomorphic indicators of river recovery, as similar features may represent either degradation or recovery depending on the type of river under investigation and the stage of geomorphic adjustment. For example, the presence of step-like features along the margins of a macrochannel can represent either degradation or recovery. If these features are identified as erosional ledges, channel expansion is underway and the river is likely in a degraded state (see Fryirs & Brierley, 2013). If they are identified as depositional benches (**Figure 1a**), geomorphic recovery is underway as these units are narrowing a previously enlarged channel, thereby reducing channel capacity (Fryirs & Brierley, 2013). Similarly, the definition and alignments of a low flow channel may indicate degradation (e.g. where incision has been triggered), or recovery where flow paths become better defined in a reach affected by a sediment slug. Careful identification and interpretation of these features entails field observations alongside appraisals of historical aerial imagery.

Riparian vegetation and instream wood directly induce the formation of some fluvial landforms which trigger and 'engineer' river recovery. In eastern NSW, upstream seed sources and recruitment from the seed bank has brought about recovery in riparian vegetation cover; elsewhere, this has been supplemented by direct planting and management. Wood, for the most part, is recruited from local riparian sources over long timeframes or is installed in rivers as engineered log jams. Cohen *et al*. (unpublished) refer to the dual role of landform-vegetation interactions in driving geomorphic river recovery along almost all river systems in eastern NSW in the last 25+ years as the 're-greening' of river systems.

Results

Case study examples of geomorphic river recovery in eastern NSW

Figure 2 presents case study examples spanning seven river types that demonstrate some of the common characteristics of geomorphic river recovery that has been experienced along many river systems in eastern NSW in recent decades. Some of these forms of river recovery have occurred without intervention (marked with a * on **Figure 2**), while others have been assisted by active rehabilitation, such as direct vegetation planting, bank protection, fencing off and stock exclusion (marked with a # on **Figure 2**). All examples occur in a range of coastal catchments from the Manning catchment in the north, to the Hunter catchment and Wollombi Brook on the mid-north coast, to the Bega catchment in the south. Most of the pre-recovery timeslices date to the 1960s or earlier, and most of the recovery timelines date to the 1980s, 1990s, and 2000s. Quite clear improvements in geomorphic river condition have occurred over the last several decades. Further research is required to determine the range of measures that can be used to quantify the magnitude and rates of geomorphic river recovery, the direction of change, and the process responses for different river types.

Prior to the 1970s, most of the laterally-unconfined and partly-confined, sand and gravel bed river examples were characterised by wide, symmetrical channels that had relatively homogenous sand/gravel sheets and bars and evidence of mass failure on banks (especially concave banks with no toe protection). These channels were actively widening and had a high width-depth ratio (**Figure 2A-E**). The channel beds were dominated by planar runs, sometimes with braid-like low flow channels. There was little riparian or within-channel vegetation or wood. The formation and stabilisation of bank-attached benches and increases in the complexity of bank-attached bars (transition from unit to compound forms) has produced a macrochannel (alternatively referred to as a compound channel) which represents geomorphic river recovery in these systems. Instream units now protect the toe of macrochannel banks from erosion, limiting prospects for further channel expansion. Revegetation of the macrochannel banks further stabilises these features. Sediment trapping and retention on bench and bar surfaces induces channel contraction. Most geomorphic activity is now limited to reorganisation of materials within the macrochannels, rather than wholesale changes to the macrochannels themselves. Macrochannels now act as floodway corridors for moderate to large flood events. Sediment reworking and reorganisation has created a well-defined, low width-depth ratio low flow channel. In some places, pools have been scoured into formerly planar sand/gravel sheets, and riffles are much better defined. Dense vegetation within the macrochannel has supported these geomorphic adjustments. Often this is dominated by thick stands of early successional woody species, such as *Casuarina cunninghamiana* or exotic pioneer species. Elsewhere, where recovery is more advanced, a diverse assemblage of groundcover, understorey and overstorey species has become established. Typically this is comprised of a mix of exotic and native vegetation. In areas where the riparian vegetation is better established, some simple and/or complex wood structures may form.

Other forms of geomorphic river recovery have occurred along different river types. For the laterally unconfined low sinuosity sand bed river of the lower Bega River, the pre-recovery condition was characterised by a symmetrical, high width-depth ratio channel that was infilled with a sand slug (**Figure 2F**). The homogenous channel bed had little geomorphic heterogeneity, abundant unit bars and an indistinct low flow channel. There was very little riparian or instream vegetation or wood. The recovery phase, has seen the formation of bank-attached benches and well-vegetated, stable islands separated by multiple well-defined, low width-depth ratio low flow channels. This has produced an anabranching-like planform, with pool-riffle features in areas of concentrated flow. To date, most of this geomorphic recovery has been triggered by the incursion of exotic vegetation into the channel (mainly willows; see Brooks & Brierley, 2000). Hence, although geomorphic river recovery is occurring, vegetative diversity and endemism is low.

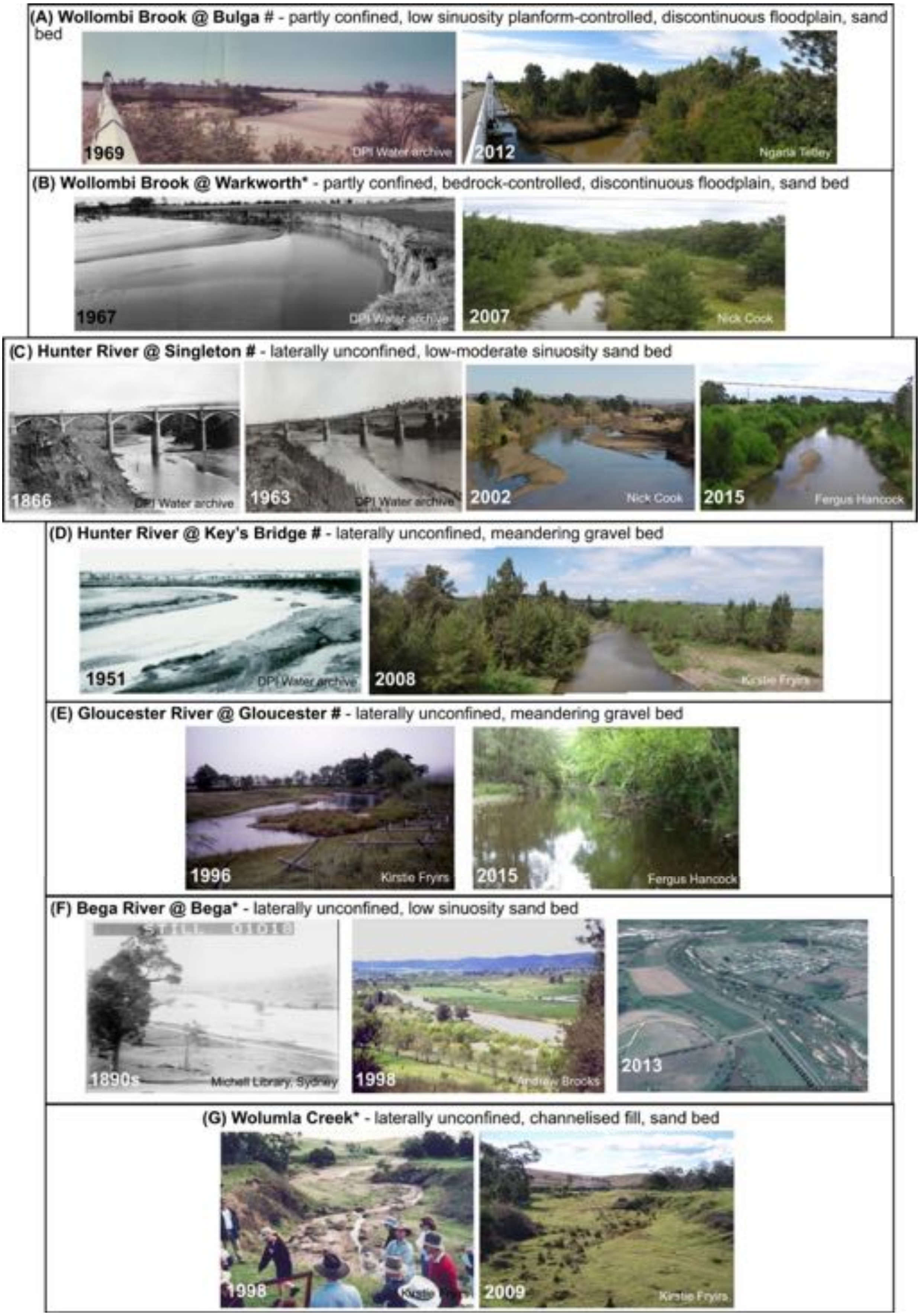

Figure 2 A selection of pre-recovery and recovery photographs for selected case study rivers from coastal valleys of NSW. All photographs are taken from the same reaches and approximately the same location in each timeslice. These case studies come from the Hunter catchment (A-D), the Manning catchment (E) and Bega catchment (F-G). For a full colour version, please see Fryirs et al. (2018).

For the channelised fill rivers in Bega catchment, incision and channel expansion into former swamps produced a wide, deep symmetrical channel (**Figure 2G**). Channel beds were characterised by sand sheets with a distinct low flow channel. Recovery for this type of river is being manifest through the trapping of sediment and infilling of the incised channel, recreating swamps and wetlands with an indistinct and discontinuous low flow channel in some instances.

Assessment of geomorphic river recovery across NSW

Since 2004, the NSW Department of Industry, Water (formerly NSW Department of Primary Industries Water, NSW Office of Water and Catchment Management Authorities) has co-ordinated analysis of River Styles, river condition and recovery potential across NSW. The dataset is used to prioritise river management activities and as a basis to monitor geomorphic recovery (and condition) of rivers as part of catchment action plans, water sharing plans and State of the Environment reporting (Brierley *et al*., 2002, 2011). Geomorphic indicators such as those in **Figure 1** are embedded within the recovery assessment process.

Across NSW, 50 River Styles have been identified along 219,500 km of stream length that includes 3rd order and larger streams (NSW DPI Water, unpublished data). Confined rivers comprise 28% of stream length, partly confined rivers 22%, laterally unconfined rivers with continuous channels 27%, and laterally unconfined rivers with discontinuous channels 15% (8% is still to be classified). Of these streams, 36% are classified as conservation reaches, 4% are strategic (contain threatening processes where interventions are required), 3% have rapid recovery potential, 12% high, 2% moderate and 14% low recovery potential (7% is still to be classified) (**Figure 3**). Across NSW, around 51% of stream length is showing signs of geomorphic recovery. These reaches are considered high priorities for conservation and passive management action.

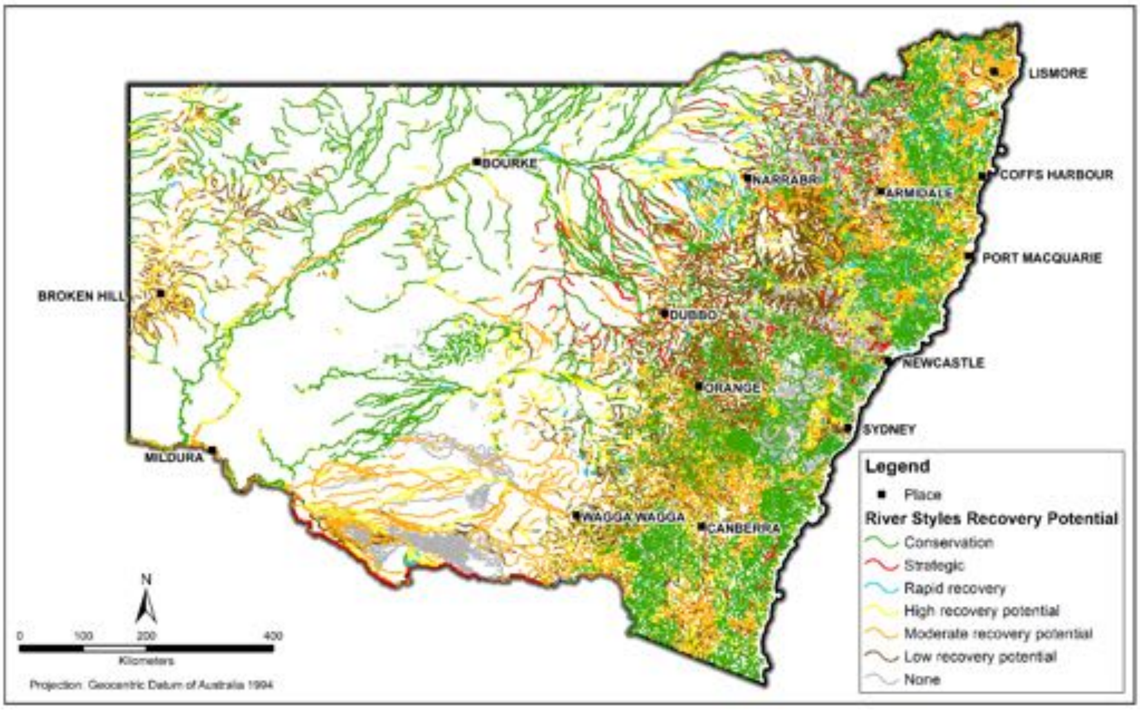

Figure 3 The geomorphic recovery potential of rivers across NSW. Some 216,000 km of stream length is depicted on this map. Source: NSW Department of Industry, Water Division. For a full colour version, see Fryirs et al. (2018).

When coastal NSW is extracted from the database a more specific picture of recovery potential for the rivers documented in this paper emerges. In this region, 80,997 km of stream length has been analysed. Forty-nine percent is comprised of confined rivers, 25% by partly confined rivers, 12% by laterally unconfined rivers with continuous channels, and 7% by laterally unconfined rivers with discontinuous channels (7% yet to be classified). In 2015, 39% of total stream length for these coastal catchments was classed as conservation, 2% as strategic, 5% as rapid recovery potential, 11% as high, 28% as moderate, 7% as low and 7% none (yet to be classified).

Discussion: Working with river recovery as part of river management practice

Approaches to river recovery enhancement have been used to guide river conservation and rehabilitation in some parts of the world for a decade or more (Brierley & Fryirs, 2008). In these places, such principles support catchment-scale vision setting, planning and prioritisation. In other places, momentum is building for adoption of such practices. Solid understanding of the mechanisms that drive geomorphic changes, and understanding how these processes can be enhanced, is required to help develop the best available evidence-base to inform river management activities. Development of regional-scale databases, as shown in **Figure 3**, helps to contextualise local-scale variability in river dynamics and evolutionary adjustments, whether at the reach or catchment scale. This underpins efforts to design and implement strategies on the ground and assess the transferability of different forms of management intervention to similar places and situations.

Working with river recovery presents several new challenges for river practitioners. First, a balance needs to be struck between intervention-free and assisted recovery procedures. Many river reaches do not require high levels of intervention and a 'leave it alone' strategy may suffice. Focus can then be placed on areas where minimalist interventions can be implemented to trigger or enhance river recovery (e.g. stock exclusion, seedbank utilisation, direct planting, wood structures). Second, the 're-greening' of river systems (Cohen *et al*., unpublished) may present significant vegetation management issues, particularly associated with weed management. If enhancing native vegetation biodiversity is a key priority in river management, a balance needs to be struck (and maybe compromises made) between the role of various types of vegetation at different times and stages of the recovery process. Thirdly, significant work is required to convince communities that vegetation and wood are good things, and that most 'messy rivers' are not in poor condition. Similarly, process-based approaches to river management that apply erodible corridor and riparian corridor concepts present opportunities to support river recovery mechanisms. Slowing flood flows and reducing their erosive potential can support natural flood management and flood risk assessment programs, prospectively enhancing community engagement in a recovery enhancement approach to management.

Because analyses of river recovery capture the past trajectories of adjustment, provide a snapshot of how the system is performing today and provide a basis for forecasting future scenarios and possible river states, such datasets can be used to support decision-making that looks for 'windows of opportunity for recovery'. This allows decisions to be made about *whether* river management is required, *where*, *when* and *how much* to intervene and, probably more importantly, when to *opt-out* of management because the system is recovering without the need for intervention. In the examples presented in this paper, various reaches have been 'left alone', while local-community and State agency programs have facilitated recovery through implementation of rehabilitation measures in other instances (see # examples in **Figure 2**).

Decisions on if and where to intervene are critical in a resource-poor industry where prioritisation, cost:benefit and risk assessment are at the forefront of community and government agendas. Such analyses also provide a scientific rationale and evidence-base for monitoring programs that meaningfully track whether river recovery (and associated improvement in condition) is actually occurring. These are integral components of adaptive river management. While the promise of adaptive management is embedded in the psychology of river management, its application in practice is limited because the evaluation component is seldom completed. Tracking and documenting river recovery not only supports on-the-ground assessments of river health, it also helps guide agency and policy agendas to promote further success in such practices.

It is critical that the solid foundations set in place by this current phase of river recovery in coastal NSW are not 'lost' through poor practices, policy or a complacency towards the process. There is no 'endpoint' to river recovery at annual to decadal time scales, and measures of 'success' remain elusive. Hopefully, the analyses documented in this paper can trigger advances in policy, resource planning and community engagement as part of contemporary river management practice. After all it is a good news story!

Conclusion

Since the 1970s, geomorphic river recovery has been a key trait of many rivers in coastal NSW. This reflects increases in groundcover and re-establishment of woody vegetation within riparian and in-channel zones. A regional-scale case study developed by State Government Agencies in NSW has shown how this approach can be used to not only identify when geomorphic recovery is occurring, but also to provide a database that can feed into decision-support frameworks to determine *whether* river management is required, *where*, *when* and *how much* to intervene to enhance river recovery and when to *opt-out* of management because the system is recovering and requires little to no intervention. This information base provides foundation knowledge for prioritisation of river management activities and to measure and monitor river recovery.

Acknowledgements

This paper is an extract of a full paper published in Land Degradation and Development. For a copy of the full paper, contact Kirstie Fryirs. The work documented in this paper builds on over 25 years of foundation research on the impact of post-European settlement of river systems in Eastern NSW and a commitment by agencies to adopt a recovery-enhancement approach to river management. It also builds on a strong and lasting collaboration between researchers, scientists and managers at various universities and government agencies over that time. We wish to mention Land and Water Australia, the Australian Research Council, former Catchment Management Authorities, the former NSW Department of Land and Water Conservation, and former NSW Office of Water in particular.

References

Beechie TJ, Sear DA, Olden JD, Pess GR, Buffington JM, Moir H, Roni P, Pollock MM. 2010. Process-based principles for restoring river ecosystems. *BioScience* 60(3): 209-222.

Brierley GJ, Fryirs KA. 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell Publications: Chichester, UK; 398.

Brierley GJ, Fryirs KA (eds). 2008. River Futures: An Integrative Scientific Approach to River Repair. Island Press: Washington DC; 304.

Brierley G, Fryirs K. 2009. Don’t fight the site: three geomorphic considerations in catchment-scale river rehabilitation planning. *Environmental Management* 43(6): 1201-18.

Brierley GJ, Fryirs KA. 2016. The use of evolutionary trajectories to guide ‘moving targets’ in the management of river futures. *River Research and Applications* 32: 823-835.

Brierley G, Fryirs K, Cook N, Outhet D, Raine A, Parsons L, Healey M. 2011. Geomorphology in action: linking policy with on-the-ground actions through applications of the River Styles framework. *Applied Geography* 31(3): 1132-1143.

Brierley G, Fryirs K, Outhet D, Massey C. 2002. Application of the River Styles framework as a basis for river management in New South Wales, Australia. *Applied Geography* 22(1): 91-122.

Brooks AP, Brierley GJ. 2000. The role of European disturbance in the metamorphosis of lower Bega River. In River Management: The Australasian Experience, Brizga SO, Finlayson BL (eds). John Wiley & Sons: London; 221-246.

Cohen T, Suesse T, Skorulis A, Reinfelds I, Fryirs K, Carrigan A, Chisholm L, Belcher A. unpublished. The re-greening of eastern Australian rivers: Unprecedented riparian transformation.

Dufour S, Piégay H. 2009. From the myth of a lost paradise to targeted river restoration: forget natural references and focus on human benefits. *River Research and Applications* 25(5): 568-581.

Fryirs K. 2015. Developing and using geomorphic condition assessments for river rehabilitation planning, implementation and monitoring. *WIREs Water* 2(6): 649-667.

Fryirs K, Brierley GJ. 2009. Naturalness and place in river rehabilitation. *Ecology and Society* 14(1): 20.

Fryirs KA, Brierley GJ. 2013. Geomorphic Analysis of River Systems: An approach to Reading the Landscape. John Wiley and Sons: Chichester; 362.

Fryirs K, Brierley GJ. 2016. Assessing the geomorphic recovery potential of rivers: Forecasting future trajectories of adjustment for use in river management. *WIREsWater* 3: 727-748.

Fryirs K, Chessman B, Rutherfurd I. 2013. Progress, problems and prospects in Australian river repair. *Marine and Freshwater Research* 64(7): 642-654.

Fryirs, K.A., Brierley, G.J., Hancock, F., Cohen, T.J., Brooks, A.P., Reinfelds, I., Cook, N., and Raine, A. 2018. Tracking geomorphic river recovery in process-based river management. *Land Degradation and Development* (accepted 19/4/18)

Kondolf M. 2011. Setting goals in river restoration: When and where can the river “heal itself”? In Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses and Tools. Simon A, Bennett SJ, Castro JM (eds) American Geophysical Union, Geophysical Monograph 194: 29-43.

Montgomery DR. 2008. Dreams of natural streams. *Science* 319(5861): 291-292.

Rutherfurd I. 2000. Some human impacts on Australian stream channel morphology. In River Management: The Australasian Experience, Brizga S, Finlayson B (eds). John Wiley & Sons: Chichester; 11-49.

Rutherfurd I, Jerie K, Walker M, Marsh N. 1999. Don't raise the titanic: How to set priorities for stream rehabilitation. In *Proceedings of the 2nd Australian Stream Management Conferen*ce. Adelaide, South Australia; 527-532.