The use and usefulness of geomorphology in river management

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Key Points
- River behaviour is different to river change. Understanding this distinction aids decision making on whether river management is required, and when to opt-out.
- Having a catchment-framed geomorphic understanding of river evolution, condition and recovery potential can be used to forecast future management options.
- Using geomorphic information is a critical for prioritisation and monitoring programs in river management.

Abstract
On the 20th anniversary of Australian Stream Management (ASM) Conferences, it is timely to reflect on the emergence of fluvial geomorphology as a key science in river management practice and to consider how it is used, and how it remains useful, in effective and proactive practice. I will consider how the emergence of fluvial geomorphology has provided critical landscape-based information with which to work. I will focus on three key principles and use case studies to demonstrate how geomorphology has been, and should be, used in process-based river management in the 21st Century.
1. How understanding river behaviour versus river change can be used to determine what is realistically achievable in conservation and management practice.
2. How knowing your catchment and understanding evolutionary trajectory provides context for making future forecasts on river condition and recovery potential.
3. How geomorphic information can be used to develop coherent, well integrated catchment action plans and a basis for prioritisation, decision making and monitoring.

Keywords
River behaviour, river change, river evolution, river condition, recovery potential, prioritisation, rehabilitation, monitoring

Introduction
In the 21st Century, fluvial geomorphologists are ideally placed to use their science in an applied manner, and provide guidance on environmental issues of concern. Understanding the impact of floods and droughts, landuse and climate change, water use etc. on river forms, processes and evolution requires that we understand interactions between water, sediment and vegetation, and how climate and anthropogenic impacts shape those interactions. More frequently, fluvial geomorphologists are asked to provide answers to a range of river issues, make forecasts about how systems might adjust in the future, and work with managers to implement strategies on-the-ground (Wohl et al., 2015; Fryirs, 2016). Questions such as: How will this river adjust? Where will this river change? What is the likelihood that future flooding will lead to river adjustment here? What impacts will mining, urbanisation, river rehabilitation have on this river? Can you predict for our catchment which rivers are fragile and which are not? If we undertake some activity in this part of a catchment will that impact elsewhere? Where in a catchment should we prioritise our activities? Should we undertake intervention or not? Almost all these questions can be answered with some degree of confidence with a coherent and sophisticated understanding of fluvial geomorphology at multiple scales (Gregory and Lewin, 2015; Wohl, 2013, 2014; Fryirs, 2016). However, in recent years there has been a severe erosion of

environmental science in management, and geomorphology has suffered a downward shift in the practice of 'doing' geomorphology and 'using' geomorphology (Lane, 2013).

Numerous researchers have highlighted the shortcomings of many management initiatives because of a lack of understanding about the geomorphology of the system under investigation (e.g. Bernhardt et al., 2005; Palmer et al., 2005; Tompkins and Kondolf, 2007). Effective use of geomorphology can guide management choices, change management activities or provide criteria to decide when to opt-out of management activities (i.e. adopt a precautionary or do-nothing approach). Here, I aim to highlight three key fluvial geomorphology principles that have, and should continue to, lie at the heart of all river management projects.

Principle 1) Understand the difference between river behaviour and river change

River reaches continually adjust to a range of flow, sediment and vegetation interactions and the associated balance of impelling and resisting forces along valley floors. The nature and rate of river adjustment vary from system to system, and over differing timeframes. In essence, however, river reaches can adjust in lateral, vertical and wholesale dimensions (sometimes called degrees of freedom). Vertical adjustment refers to the stability of the channel bed. Lateral adjustment refers to the ability of the channel to alter its banks. Wholesale adjustment refers to of the manner and rate of alterations to channel position on the valley floor. Different rivers adjust in different dimensions with varying degrees of ease.

In an attempt to provide guidance on how to analyse and interpret this complexity at the reach scale, and to clarify the terminology used, Brierley and Fryirs (2005) and Fryirs and Brierley (2013) make a clear distinction between river behaviour and river change (**Figure 1**). ***River behaviour*** is defined as "*adjustments to river morphology induced by a range of erosional and depositional mechanisms by which water moulds, reworks and reshapes fluvial landforms, producing characteristic assemblages of landforms at the reach scale*" (Brierley and Fryirs, 2005, p143). River behaviour reflects ongoing geomorphic adjustments over timeframes in which flux boundary conditions (i.e. flow and sediment regimes, and vegetation interactions) remain relatively uniform, such that a reach retains a characteristic set of process-form relationships. This concept should not be confused with that of attaining equilibrium. Rather the concept of river behaviour encapsulates the range of 'expected' or 'natural' processes and adjustments that occur along any given river type. The forms of adjustment and the resultant landforms are a vital and characteristic part of the behavioural regime of that river type. River behaviour can be measured as the '*capacity for adjustment*'. Different river types have different capacity for adjustment. The capacity for adjustment is a measure of the range and extent of geomorphic adjustments that can occur for that river type, and the ease with which a river is able to adjust its form in the vertical, lateral and wholesale dimensions (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013).

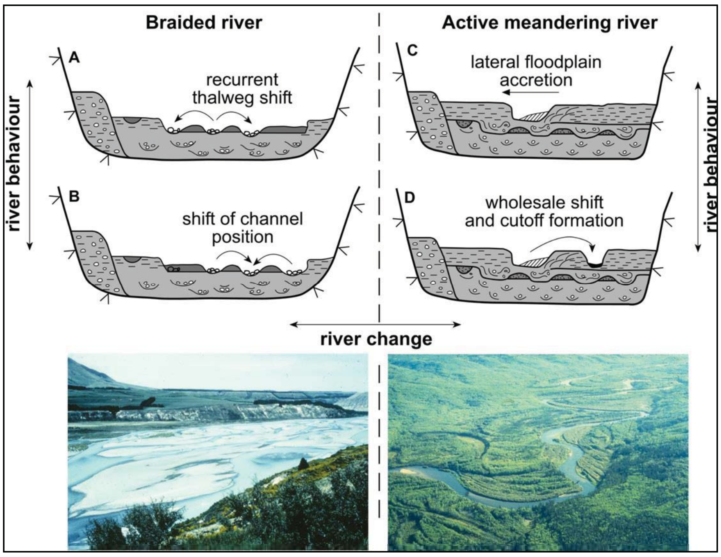

Figure 1. River behaviour versus river change

River behaviour – expected adjustments that occur for a particular river type (e.g. lateral migration and bank erosion and cutoff formation along the meandering river; thalweg shift for the braided river). **River change** – when a wholesale shift n river type (and behaviour) occurs (e.g. a change from braided to active meandering).

Modified from Fryirs and Brierley (2013)

Alteration to the balance between impelling and resisting forces may induce a shift in the behavioural regime of a river whereby the reach evolves to a different type of river with a different characteristic form. *This shift in process-form relationships along a reach is referred to as **river change***, whereby alterations to the assemblage of geomorphic units reflect a different river type with a different behavioural regime. River change can occur in response to natural and/or human disturbance. River change can take the form of progressive evolutionary adjustments, or dramatic, near-instantaneous changes in response to catastrophic events (Baker and Costa, 1977; Phillips, 2009). Alternatively, if the system lies close to a threshold condition, relatively small events can reconfigure the system to a different state (Schumm, 1979; Church, 2001).

The distinction between river behaviour and river change, and the ability to read this in the landscape provides a very useful indicator of whether a river is adjusting as expected or whether anomalous activity or threatening processes are occurring that may trigger a management response. In this context, processes that are expected to occur as part of the behavioural regime of a reach are not considered threatening processes and do not trigger a management response. For example, recognising that bank erosion is within the expected capacity for adjustment of some river types (e.g. meandering rivers) and occurs at certain rates gives an indication that the river is adjusting as it should and is fully functional. This river has the physical forms and processes that are likely supporting the ecological integrity of that reach (Brierley and Fryirs, 2008). Lateral migration of river bends (and erosion of concave banks) instigates pool development that provides habitat for aquatic fauna. Similarly, certain vegetation associations occur along these river bends and meander migration instigates woody debris recruitment along many rivers. If however, the rate of erosion is anomalous (e.g. occurring in unexpected places along a river bank) or is accelerated relative to expected rates for that part of the river system and river type, then the geomorphology of that river reach can be considered impaired to some degree and only then may bank erosion be considered a management issue.

In contrast, mass failure bank erosion is not part of the expected capacity for adjustment of a low sinuosity fine grained river type. Rather, if it occurs it suggests that anomalous processes such as bed instability may be operating that require further investigation. A threatening process (i.e. bed incision) may be occurring, impacting on geomorphic condition for that reach of that river type and may induce river change at some point. In this case a management 'alert' may be issued and a treatment response enacted.

Principle 2) Know your catchment and understand evolution as a basis for forecasting (condition and recovery potential)

Few practitioners and frameworks successfully recognise the need for separation of *condition* assessments from *river recovery* assessments (Fryirs, 2015; Fryirs and Brierley, 2016). Assessments of geomorphic river condition consider the state of the river as we see it today by comparing the geomorphic condition of river reaches – disturbed vs. 'expected' conditions – for reaches of the same river type. When placed in an evolutionary context, condition assessments allow practitioners to interpret WHY change and degradation may have occurred allowing targeted actions on causes of deterioration rather than just the visible symptoms (Fryirs, 2015). This is different from assessments of *river recovery potential* that place each reach in a catchment context and forecast future trajectories of adjustment and potential future states (or moving targets) (Brierley and Fryirs, 2016; Fryirs and Brierley, 2016). Assessments of river recovery potential examine the effect of various limiting factors and pressures operating in a catchment, and the impact they will have on each reach in that catchment (Fryirs, and Brierley, 2016). Pressures are external factors that impact from outside a catchment, e.g. climate change, or policy that produces landuse change. Limiting factors are internal to a catchment, e.g. sediment and water availability or vegetation-related fluxes (Fryirs and Brierley, 2001; Brierley and Fryirs, 2005). In this context, river recovery potential is defined as the capacity for improvement in geomorphic condition over the next 50-100 years (i.e. what is realistically achievable in management practice and for vision development). Both river condition and recovery analyses are framed in the context of 'Knowing Your Catchment' and having a solid understanding of river evolution.

Evolutionary analyses aim to identify the natural and human-induced disturbances that may have pushed the condition of the system beyond the bounds of expected behaviour, producing anomalous responses in the contemporary system (Fryirs, 2016). Examples include prolonged drought, or catastrophic flooding and/or flow regulation, landuse change, channelisation, riparian vegetation and wood removal etc. By examining past disturbance impacts that have regulated system structure and function over time, inhibitors to system recovery (i.e. improvement in condition) can be removed or targeted for remediation.

To adequately assess river condition and recovery potential requires that, first we understand the *past* trajectory of adjustment to understand why the river is in the condition that it is today; and second, use this to forecast potential future trajectories of adjustment, and determine the potential of the reach to recover along those trajectories (e.g. **Figures 2** and **3**). The former is determined using evolutionary analysis, while the latter is a forecasting or scenario-building exercise (Brierley and Fryirs, 2005; Fryirs and Brierley, 2016).

While developing evolutionary sequences may seem to be an exhausting, resource-rich and time-consuming exercise, as Montgomery (2008: 292) states “it pays to do the painstaking work of historical sleuthing” because evolutionary analyses provide many ‘golden’ geomorphic insights that can directly aid in river management practice, saving time, money and heartache when the wrong treatment response is used because the causes and threatening processes were not correctly identified and the condition and recovery potential of the reach compromised.

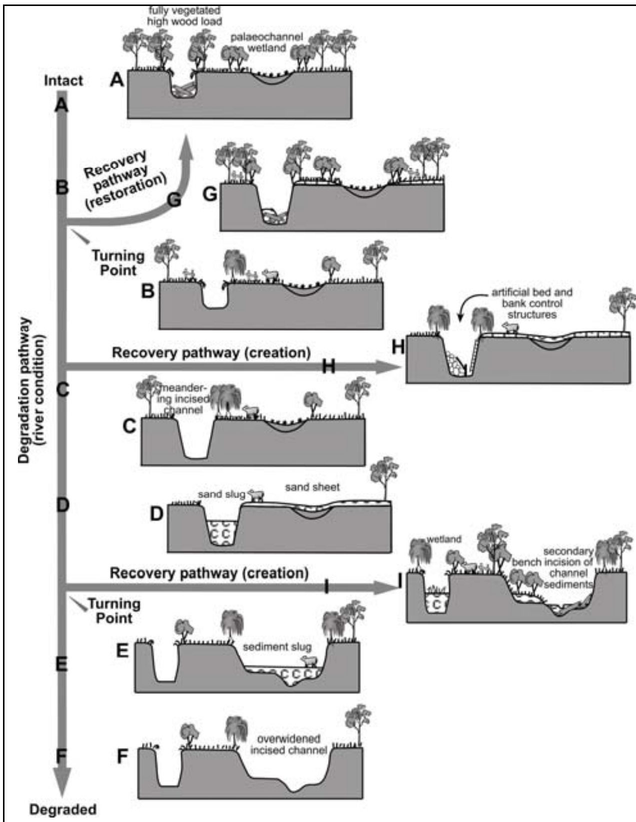

Figure 2. Trajectories of geomorphic adjustment for a meandering planform-controlled river in Wollombi Brook (see Brierley and Fryirs, 2016; Fryirs et al., 2012; Fryirs and Brierley, 2016). The degradation pathway depicts river condition based on analysis of river evolution using ergodic reasoning, and the restoration and creation pathways depict river recovery options.

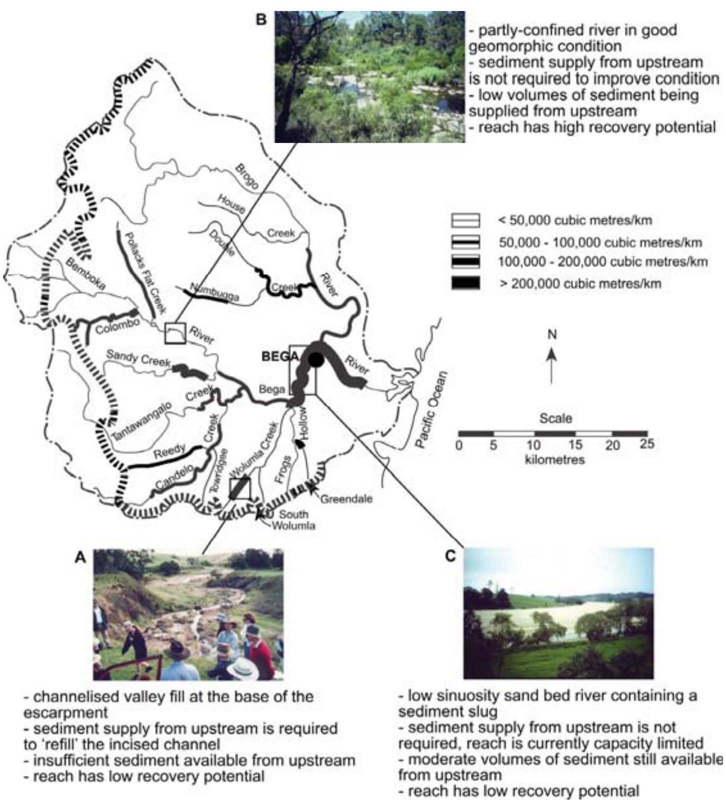

Figure 3 Example from the Bega catchment of how to assess river recovery potential for three reaches in different geomorphic condition (from Fryirs and Brierley, 2016 and based on Fryirs and Brierley, 2001).

Principle 3) Using geomorphology in river management (prioritisation, decision making and monitoring)

At the start of the 21st Century it is time to move the industry from the inertia of 'developing more toolboxes', 'reinventing the wheel', and 'collecting more of the same data' towards data ***integration*** and ***use***. By investing in development of geomorphologically-based analysis of river systems and catchments (river behaviour, evolution, condition and recovery potential), practitioners have a powerful basis with which to undertake river conservation, management and rehabilitation practice.

In places where catchment-wide (or region-wide), coherent and scientifically-rigorous datasets exist, well-integrated, cost-effective and proactive catchment-action (or regional) plans have been developed that are ready for implementation. Such plans can be used to develop visions, monitoring programs and decision-making structures that ensure 'best bang for buck' resource allocation. **Figure 4** shows a decision making tree (used in the River Styles framework; Brierley and Fryirs, 2005) for prioritising river conservation and rehabilitation based on geomorphic assessments of river condition and recovery potential. In general, the further down the decision making tree a reach sits, the lower its priority and the higher the cost of rehabilitation and maintenance (except strategic reaches).

In an era of conservation-first prioritisation, geomorpholgical datasets can/do provide an essential ingredient in precautionary and effective river management practice. This approach is not necessarily new and has been around for at least 15 years (Rutherfurd et al., 1999, 2001). However, for this approach to be successful, analyses of river behaviour, evolution, condition and recovery potential must be undertaken using a coherent, scaffolded approach so that layers of information can be appropriately embedded and archived. Such information datasets provide a transparent evidence base upon which prioritisation and decision-making can take place. **Figure 5** shows an example of how this has occurred across the Hunter region (and NSW) by the Department of Primary Industries, Water (formerly NSW Office of Water) using the River Styles Framework (Brierley et al., 2011; Fryirs and Brierley, 2016).

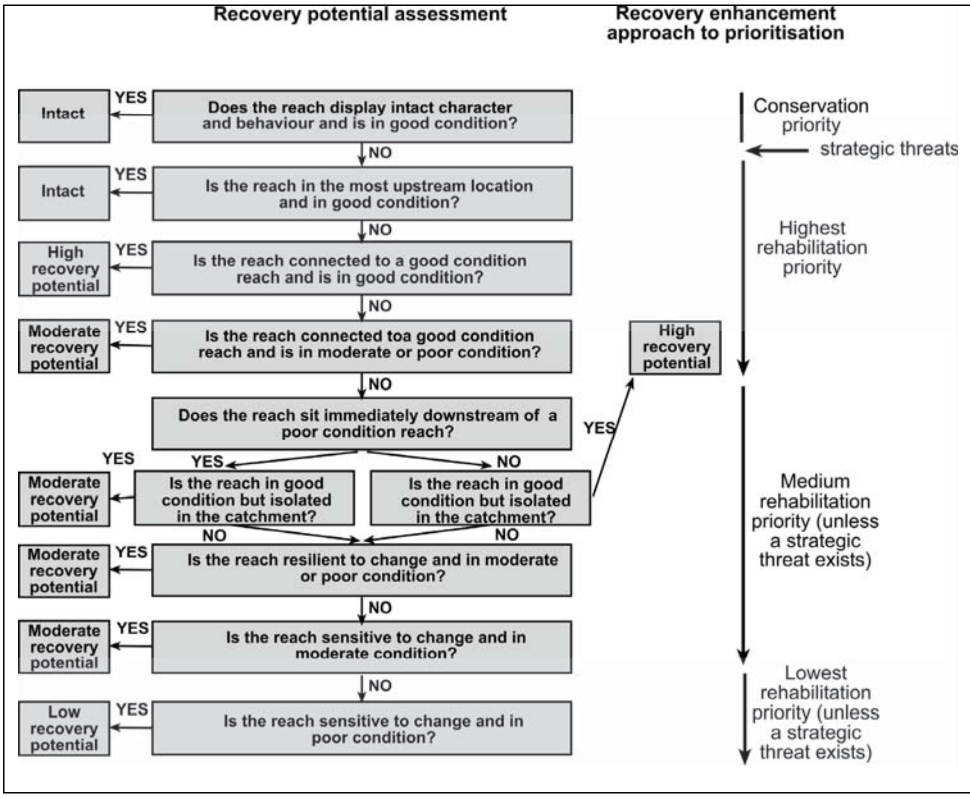

Figure 4. The River Styles decision making tree for assessing river recovery potential based on river condition, and associated priority placed in conservation and rehabilitation. Based on Brierley and Fryirs (2005) and Fryirs and Brierley (2016).

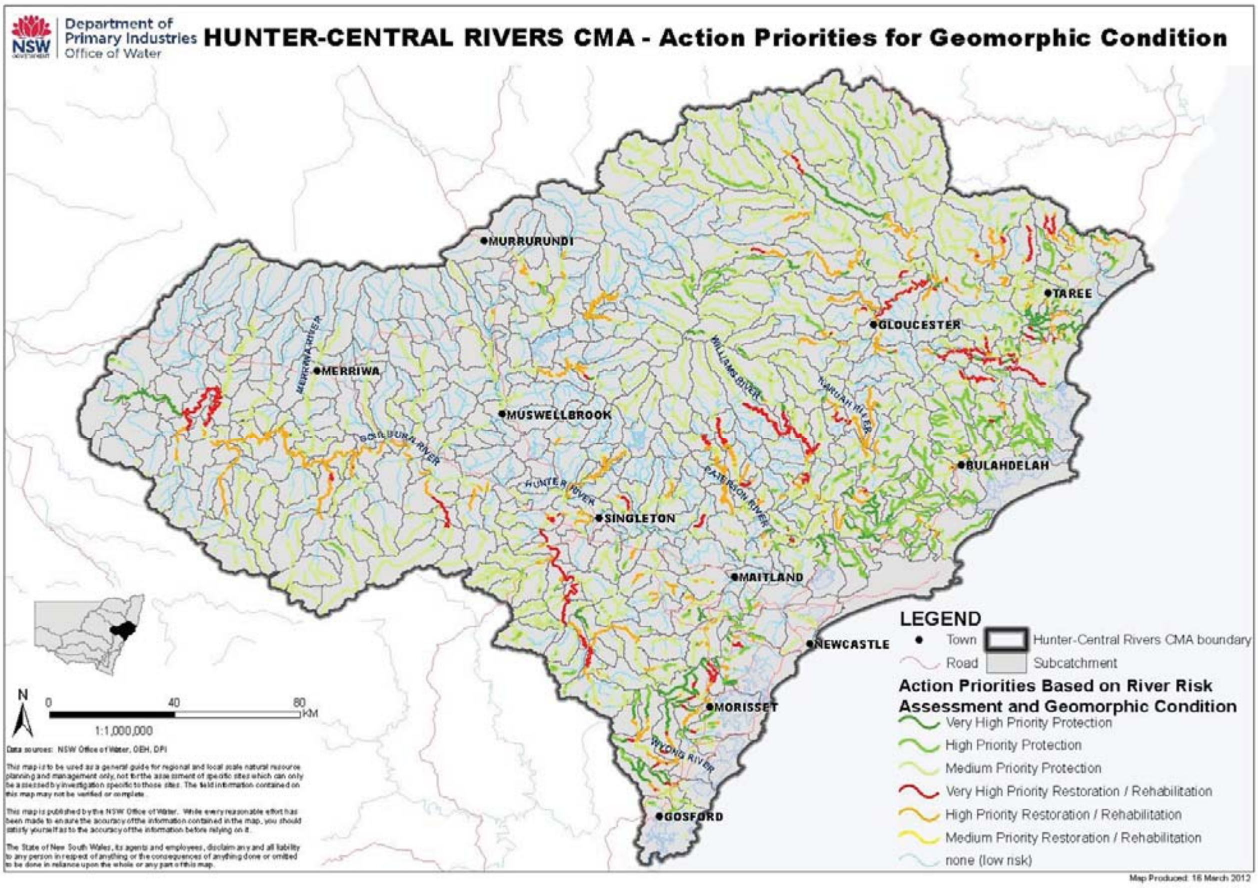

Figure 5. Example of a geomorphology action priority plan based on assessment of geomorphic river condition and recovery potential using the River Styles framework. This example is for the Hunter Valley, a 22,000 km^2 catchment on the central coast of NSW. This type of work has now been completed across NSW for regional river management planning and assessment. Image © NSW Department of Primary Industries (Office of Water) and reproduced with permission.

Using this framework, reaches in good condition with high recovery potential are considered worthy of conservation on geomorphological, ecological and societal grounds as they provide a range of ecosystem services. Those reaches with good and moderate recovery potential are then considered high priorities for management. These are often reaches in moderate geomorphic condition. The intervention strategy for these reaches tends to be minimalist because the cost:benefit is high and success is more likely. Only then are reaches in poor condition considered worthy of intervention as the cost:benefit of treatment is low, as is the likelihood of success without ongoing and persistent maintenance and intervention (c.f. Moore and Rutherfurd, 2014). In these cases it is often considered prudent to leave these reaches until they show natural signs of improvement before intervening.

As noted by Fryirs et al. (2013) and at many ASM conferences, monitoring and evaluation in Australian river management practice is poor. Rigorous and well-planned monitoring programs are essential to best management practice. In particular, geomorphologically based monitoring programs framed around assessments of river behaviour, evolution condition and recovery potential across catchment (or regions) are required. These programs will then be robust enough to detect whether a system is behaving as 'expected', and whether improvements (or deterioration) in condition and recovery potential is occurring (Brierley et al., 2010; Fryirs, 2015, Fryirs and Brierley, 2016). These programs need to be conducted over timeframes that will allow the detection of these geomorphic processes and adjustments. The monitoring should comprise an archive of consistent pre- and post-treatment information so that improvements (or otherwise) over time can be tracked. More importantly, the monitoring program needs to be tailored to the timeframes over which the geomorphic processes operate. Some processes will adjust readily (e.g. local reorganisation of sediment on the channel bed) whereas others will adjust over longer timeframes (e.g. the establishment of benches). Realistic timeframes of process activity (and detection) need to drive the recurrence of monitoring, the overall timeframe for monitoring and the identification of measures of success (e.g. Bernhardt et al., 2005; Palmer et al., 2005).

Rigorous and well-planned monitoring programs have the power to generate data which helps decide when enough has been done and when to opt-out of the river rehabilitation process and allow the system to self-adjust. Monitoring that allows informed decisions to be made about opt-in and opt-out strategies is a critical and vital part of precautionary, process-based, recovery enhancement river management (Fryirs, 2015). Rigorous geomorphic interpretations (diagnoses) of system attributes and functions can tell practitioners when a recovery response has been triggered and when to leave the reach alone. Knowing when to opt-out can reduce the need for long term maintenance and what has been termed 'restoration persistence' (Moore and Rutherfurd, 2014).

Conclusion

In process-based and recovery enhancement approaches to river management, the intent is to work with natural processes to improve geomorphic condition and enhance river recovery rather than simply treating the visible symptoms. However, for this to occur requires that we have a geomorphic understanding of river behaviour, evolution, condition and recovery potential at reach, catchment and possibly regional scales. River rehabilitation strategies can then be implemented that are proactive, cost-effective and more likely to achieve their intended goal – improved river condition. As such, geomorphology has been, should be, and continues to be useful in river management practice in the 21st Century.

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References

Baker VR, & Costa JE. (1987). Flood power. In Mayer L, Nash D (eds). *Catastrophic Flooding*, Allen and Unwin, Boston, 1-21.

Bernhardt, E.S., Palmer, M.A., Allan, J.D., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J. *et al*. (2005). Synthesizing U.S. river restoration efforts. *Science*, 308:636-637.

Brierley, G.J. & Fryirs, K.A. (2005). *Geomorphology and River Management: Applications of the River Styles Framework*. Blackwell Publications: Oxford, UK.

Brierley, G.J. & Fryirs, K.A. (Eds.) (2008). *River Futures: An Integrative Scientific Approach to River Repair*. Island Press, Washington DC.

Brierley, G.J. & Fryirs, K.A. (2016). The use of evolutionary trajectories to guide 'moving targets' in the management of river futures. *River Research and Applications* DOI: 10.1002/rra.2930

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, 1132-1143.

Brierley, G.J., Reid, H., Fryirs, K. & Trahan, N. (2010). What are we monitoring and why? Using geomorphic principles to frame eco-hydrological assessments of river condition. *Science of the Total Environment,* 408, 2025-2033.

Church, M. (2001). Geomorphic thresholds in riverine landscapes. *Freshwater Biology*, 47, 541-557.

Fryirs, K. (2015). Developing and using geomorphic condition assessments for river rehabilitation planning, implementation and monitoring. *WIREs Water*, 2(6), 649-667. DOI: 10.1002/wat2.1100.

Fryirs, K. (2016). River sensitivity: A lost foundation concept in fluvial geomorphology. *Earth Surface Processes and Landforms: State of Science Series*. DOI: 10.1002/esp.3940.

Fryirs, K. & Brierley, G.J. (2001). Variability in sediment delivery and storage along river courses in Bega catchment, NSW, Australia: implications for geomorphic river recovery. *Geomorphology,* 38, 237-265.

Fryirs, K.A. & Brierley, G.J. (2013). *Geomorphic Analysis of River Systems: An approach to Reading the Landscape*. Chichester: John Wiley and Sons, Chichester, UK.

Fryirs, K. & Brierley, G.J. (2016). A geomorphic approach for assessing the recovery potential of rivers: Forecasting future trajectories of adjustment for use in river management. *WIREsWater.* In press.

Fryirs, K., Brierley, G.J. & Erskine, W.D. (2012). Use of ergodic reasoning to reconstruct the historical range of variability and evolutionary trajectory of rivers. *Earth Surface Processes and Landforms,* 37, 763-773.

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

Gregory, K.J. & Lewin, J. (2015). Making concepts more explicit for geomorphology. *Progress in Physical Geography* DOI: 10.1177/0309133315571208.

Lane, S.N. (2013). 21st century climate change: Where has all the geomorphology gone? *Earth Surface Processes and Landforms,* 38, 106–110.

Montgomery, D.R. (2008). Dreams of natural streams. *Science,* 319, 291-292.

Moore, H.E. & Rutherfurd, I.D. (2014). The problem of river restoration persistence. In Vietz, G. & Rutherfurd, I.D, Hughes R (eds). *The 7th Australian Stream Management Conference*. River Basin Management Society, Melbourne: Townsville, Queensland, 490-57.

Palmer, M.A., Bernhardt, E.S., Allan, J.D., Lake, P.S., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahm, C.N., Follstad Shah. J, *et al*. (2005). Standards for ecologically successful river restoration. *Journal of Applied Ecology,* 42:208-217.

Phillips, J.D. (2009). Changes, perturbations and responses in geomorphic systems. *Progress in Physical Geography*, 33, 17-30.

Rutherfurd, I., Jerie, K., Walker, M. & Marsh, N. (1999). Don't raise the titanic: How to set priorities for stream rehabilitation*. Proceedings of the Second Australian Stream Management Conference*. Vol. 2, 527-532.

Rutherfurd, I., Jerie, K. & Marsh, N. (2001). Planning for stream rehabilitation: Some help in turning the tide*. Water: Journal of the Australian Water and Wastewater Association*, 28, 25-27.

Schumm, S.A. (1979). Geomorphic thresholds: the concept and its applications. *Transactions of the Institute of British Geographers,* 54, 485-515.

Tompkins, M.R. & Kondolf, G.M. 2007. Systematic post project appraisals to maximize lessons learned from river restoration projects: case study of compound channel restoration projects in northern California. *Restoration Ecology*, 15(3), 524-537.

Wohl, E. (2013). The complexity of the real world in the context of the field tradition in geomorphology. *Geomorphology,* 200, 50-58.

Wohl, E. (2014). Time and the rivers flowing: Fluvial geomorphology since 1960. *Geomorphology,* 216, 263-282.

Wohl, E., Lane, S.N. & Wilcox, A.C. (2015). The science and practice of river restoration. *Water Resources Research,* 51, 5974–5997.