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Review

What are we monitoring and why? Using geomorphic principles to frame eco-hydrological assessments of river condition

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ABSTRACT

Monitoring and assessment are integral components in adaptive management programmes that strive to improve the condition of river systems. Unfortunately, these procedures are generally applied with an emphasis upon biotic attributes and water quality, with limited regard for the geomorphic structure, function and evolutionary trajectory of a river system. Geomorphic principles convey an understanding of the landscape context within which ecohydrologic processes interact. Collectively, geo-eco-hydrologic understanding presents a coherent biophysical template that can be used to frame spatially and temporally rigorous approaches to monitoring that respect the inherent diversity, variability and complexity of any given river system. This understanding aids the development of management programmes that 'work with nature.' Unless an integrative perspective is used to monitor river condition, conservation and rehabilitation plans are unlikely to reach their true potential.

Contents

1. Introduction

Despite various concerns about its application in practice, few would argue about the premise and aspirations of adaptive management (Allan and Curtis, 2005; Gunderson, 1999; Lee, 1999; McLain and Lee, 1996; Pahl-Wostl, 2007; Walters, 1997). This supposition is especially apparent in the field of river rehabilitation, where recent assessments have found a dismal record of its use (Bernhardt et al., 2005). Shortcomings include a lack of clear statements regarding the intent, aims and vision of rehabilitation projects, poor records of monitoring and documentation of the effectiveness of management actions, and inappropriate collection, processing and archiving of pre-treatment data with which to make post-project appraisals (or audits) in a rigorous and effective manner (e.g. Bernhardt et al., 2005, 2007; Buijse et al., 2002; Downs and Kondolf, 2002; Kondolf, 2006a; Kondolf

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and Micheli, 1995; Ormerod, 2004; Woolsey et al., 2007). In addition, rehabilitation efforts are unlikely to achieve their intended outcomes unless they build upon an appropriate understanding of the functioning of the system under investigation (e.g. Clarke et al., 2003; Committee on River Science at the U.S. Geological Survey, 2007; Jansson et al., 2005; Kondolf et al., 2006; Lake et al., 2007; Mika et al., 2008; Wohl et al., 2005). The effectiveness of management actions cannot be evaluated without ongoing monitoring and evaluation of outcomes. Regardless of the limitations of current practice, it is incumbent upon river researchers and practitioners to collectively develop appropriate tools with which to develop and apply more comprehensive monitoring procedures.

In this paper we adopt the term *river condition* to highlight the biophysical approach explored herein, as opposed to notions of *river health* that include societal perceptions of a river's status and its values (Karr, 1999). Auditing, assessment and monitoring of river condition must go hand in hand. A clear distinction should be made between audits and assessments. An audit, such as the Australian Sustainable Rivers Audit (NLWRA, 2001), provides information on the current situation or status of a river. Essentially these exercises generate databases that can be used to monitor compliance, or track change in status over time. Compliance indicators are useful for ensuring that certain predetermined conditions (e.g. a stream discharge or water quality target) have been achieved, or if not, how much deviation has occurred from the 'compliance' level. However, this paper advocates that compliance indicators on their own are not sufficient to gauge river condition.

Condition assessments measure both 'pressure' and 'response' variables (indicators) and provide the means to develop a clear understanding of pressure-response (i.e. cause–effect) relationships that regulate the observed changes in system condition. Condition assessments place much greater emphasis on integration of diverse indicators and interpretation of response variables to examine causes rather than simply recording the symptoms of contemporary river condition. Procedures used to monitor river condition should be based upon these assessments.

For monitoring data to be successful, comprehensive baseline data are required from audits to compare subsequent performance and determine the relative condition of a system (whether it is improving or deteriorating). Management effectiveness can then be assessed. When used effectively, assessment and monitoring inform the gaps between 'what was there,' 'what is there now' and 'what is expected.' Most importantly assessment determines 'why' a transition has taken place. This aids the capacity to achieve management goals or 'what is envisioned.' This information provides critical insight into the effectiveness of management actions, guiding revisions to management practice. Interpretation of data derived from such exercises should also provide empirical evidence to support (or refute) theoretical advances that describe and explain inherent system characteristics and change. These considerations are fundamental principles of adaptive management.

Recent literature has highlighted the importance of integrative scientific tools with which to guide theoretical advances in river science and associated river management applications (e.g. Brierley and Fryirs, 2008; Paola et al., 2006; Petts et al., 2006; Rodriguez-Iturbe et al., 2009; Vaughan et al., 2009). This is especially evident in the rapid (re)emergence of ecohydrology or hydroecology (e.g. Palmer and Bernhardt, 2006). However, genuine advancement in monitoring and management applications will only occur when ecohydrologic principles are related directly to their landscape and evolutionary context (see Clarke et al., 2003; Cullum et al., 2008; Newson and Large, 2006; Newson and Newson, 2000; Sear and Newson, 2003; Sear et al., 2008; Ward et al., 2001, 2002; Wiens, 2002). Insights gained into a river's evolutionary trajectory and responses to natural and/or human-induced disturbance events are needed to describe and explain its contemporary physical state and identify causes of adjustment. Placing this information in a catchment context allows assessment of off-site limiting factors and pressures on future trajectories of change and recovery potential (Brierley and Fryirs, 2005).

In this paper, we demonstrate how geomorphic considerations can be used as a template atop which existing ecological and water quality based approaches can be placed so that more integrative monitoring programmes are used to assess river condition. This manuscript has two primary aims:

a) To show how geomorphological principles underpin notions of ecohydrology, and how this provides a physical template with which to analyze river systems; and
b) to demonstrate how this template can be used to monitor river condition in a spatially and temporally rigorous manner.

Finally, the discussion highlights how an integrative approach to assessment and monitoring of river condition enhances prospects for river rehabilitation in emerging ecosystem-based approaches to river management.

2. Reframing ecohydrology within a geomorphic context

The aim of river management and rehabilitation is to improve the ecological integrity of the system (Palmer et al., 2005). Within this context, ecohydrology is being promoted as the best approach for understanding and solving many riverine problems such as biodiversity loss and altered hydraulic regimes (Palmer and Bernhardt, 2006; Zalewski, 2000). The field of ecohydrology aims to take a more holistic view of river systems, focusing on the integration of the abiotic processes of hydrology with the biological processes of ecology (Palmer and Bernhardt, 2006). Whilst this perspective provides a rationale for rehabilitation, it does not necessarily provide the best approach for monitoring the level of degradation. Ecohydrology in its own right ignores the extent to which geomorphic processes influence both hydrological and ecological relationships. All too often, approaches to river analysis have emphasized concerns for water quality and ecological relationships without acknowledging inherent linkages to the physical attributes of aquatic systems (Karr and Chu, 2000; Newson et al., 1998). This is somewhat ironic, as most rehabilitation activities manipulate the physical structure of a river (its geomorphology) in attempts to improve water quality and enhance ecological values.

Deterioration in river condition from good to moderate to poor can be conceptualized in terms of transitions in condition across both abiotic and biotic thresholds (Hobbs and Harris, 2001). Fig. 1 highlights a pressure-state-response approach for examining how biotic and abiotic components of a river system interact to dictate its biophysical condition. States 1 and 2 represent a river that is fully functional in

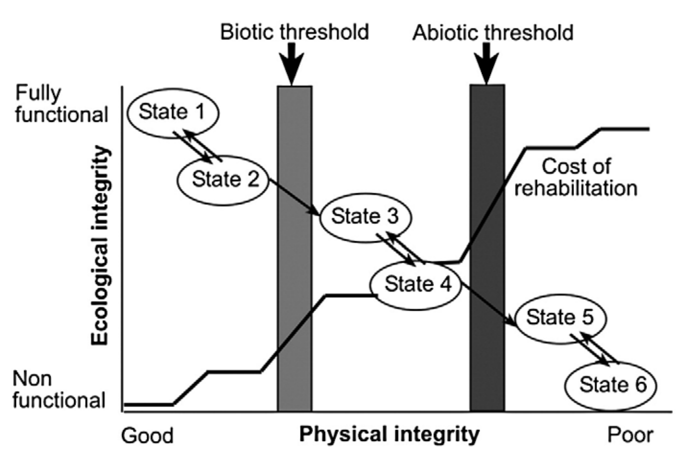

Fig. 1. A conceptual model for system transitions across biotic and abiotic thresholds in assessments of river condition.
Modified from Hobbs and Harris (2001) and reproduced from Fryirs et al. (2008).

biophysical terms. The slight deterioration in condition indicated by the two states merely reflects the natural physical adjustments occurring after disturbances such as flood events or dry periods (i.e. the natural range of seasonal or inter-annual variation or response to natural abiotic extremes). In this conceptualization, such disturbances do not severely threaten the natural ecological functioning of the system. Indeed, ecosystems and their biotic components are adapted to these disturbance events (Baron et al., 2002; Bunn and Arthington, 2002; Poff et al., 1997). However, once a biotic threshold is breached, the ecological integrity of the river deteriorates, as reflected in the transition from Zone A to Zone B in Fig. 1. The potential for recovery (and improvement in river condition) towards States 1 and 2 is constrained until the limiting biotic factor is addressed. Example may include eradication of exotic species and reintroduction of native species. However, once an abiotic threshold is breached, and a shift to States 5 and 6 occurs, the river is considered to be in poor physical and ecological condition. The physical integrity of the river has been compromised and a range of abiotic limiting factors severely constrain the potential for recovery and improvement in condition. In such instances, breaching of a threshold may result in irreversible shifts in river structure, function and condition (Brierley and Fryirs, 2005). Elsewhere, changes may be reversible, such that biotic structure and ecological processes are able to recover. This framework demonstrates that if monitoring is focused simply on biotic variables and ecohydrology, then underlying (and potentially more costly) abiotic causes of deterioration in river condition will not be detected. This highlights the importance of adding the '*geo*' to '*ecohydrology*' in assessments of river condition.

The need to include geomorphology as a central component of monitoring is recognized implicitly by the emerging concept of hydromorphology, as used within the European Water Framework Directive (Griffiths, 2002; Kallis and Butler, 2001; Oberdorff et al., 2002; Orr et al., 2008; Skinner and Bruce-Burgess, 2007; Vaughan et al., 2009). Implicitly, hydromorphic perspectives assess flow-sediment interactions at a particular time and place. This provides useful insight into spatial variability in hydraulic process relationships at that time. However, such assessments provide a static snapshot of a system, seldom capturing the full behavioural regime of a river reach. Typically, they are not performed under formative flow stages at which river morphology is created and/or reworked (Brierley and Fryirs, 2005). Ideally, monitoring procedures frame assessments of geomorphic condition in an appropriate spatial and temporal context, directly linking geomorphic considerations to eco-hydrological assessments of river condition.

3. Spatial (scalar) considerations in programmes to monitor river condition

River networks can be viewed as gravitationally-induced sets of (dis) connected, multi-dimensional, and multi-scalar attributes framed within a catchment context, within which differing process relationships operate over variable timescales (e.g. Benda et al., 2004; Brierley and Fryirs, 2005; Montgomery, 1999; Thorp et al., 2006). Catchment-scale monitoring frameworks are required to capture the inherent variability and connectivity of a given river system. This is required to assess system responses to prevailing fluxes and trajectories of river adjustment. Cross-scalar (nested-hierarchical) approaches place the range of processes operating at hydraulic unit, geomorphic unit and reach scales in a catchment context, assessing spatial linkages between these components (Brierley and Fryirs, 2005; Frissell et al., 1986; Griffiths, 2002; Newson and Large, 2006; Wohl et al., 2005).

3.1. Catchment-scale considerations

Each catchment has its own history, its own boundary conditions, and is subject to a system-specific set of disturbance events. As such, rehabilitation planning should be a catchment-specific exercise (e.g. Allan and Johnson, 1997; Bohn and Kershner, 2002; Brierley and Fryirs, 2005; Gregory and Downs, 2008; Sear et al., 1995; Wissmar and Beschta, 1998; Wohl et al., 2005). Monitoring programmes should be framed at the catchment scale, to contextualize and capture the diversity and pattern of river character and behaviour across the system. Catchment-scale investigations are also more likely to identify and treat the causes, rather than the symptoms, of degradational processes, determining whether degradational influences are site-specific or reflect off-site impacts induced by disturbance events elsewhere in the catchment (Brierley and Fryirs, 2009; Skinner and Bruce-Burgess, 2007). Connectivity and catchment position are key determinants of the influence and persistence of off-site impacts upon geomorphic river condition for any given site. Due regard should be given to appraisal of the nature of discontinuities in patterns and process relationships in determining representative reaches within which to structure sampling frameworks. Some boundaries may be gradual; others are abrupt (e.g. Poole, 2002). Concern for connectivity should extend beyond longitudinal notions to include lateral and vertical dimensions: Channel and floodplain compartments should be considered, as should surface–subsurface interactions (Ward, 1989). As noted by Michaelides and Wainright (2002), Fryirs et al. (2007), Jungwirth et al. (2002), Wilby and Gilbert (1996) and many others, there is often significant disconnectivity in water, sediment, nutrient and ecological associations along rivers. This further emphasizes the importance of catchment-specific considerations in the analysis and interpretation of off-site impacts on river condition.

An example that highlights subcatchment variability in river condition in response to geomorphic considerations is shown in Fig. 2. Adjacent subcatchments in Twin Streams catchment in west Auckland, New Zealand have quite different downstream patterns and connectivity of rivers (Fig. 2). The headwater regions across much of the Huruhuru subcatchment are relatively low slope and are characterized by the confined, low sinuosity, fine bed river (Fig. 2). Before European settlement these streams mostly comprised intact valley fill which has since become channelized (Fig. 2; Reid et al., 2009). Today, these disconnected reaches only remain in localized areas of the upper catchment. In contrast, the adjacent Oratia-Opanuku subcatchment is comprised of a longitudinally well connected pattern of rivers, characterized predominately by gravel bed systems that transport sediment more readily (Fig. 2). The nature of human impacts and strength of connectivity determine the degree to which a system responds to disturbance events and the prospects for recovery. Streams in Huruhuru catchment are more sensitive to increased intensity of peak flows, and headcuts have incised many valley fills, degrading condition and changing river style. In contrast, streams are far more resilient and are able to recover more quickly in Opanuku/Oratia subcatchment (Gregory et al., 2008).

3.2. Reach-scale considerations

Most monitoring applications are performed at the reach scale, whereby data collected at a given site or a range of sites are considered to be representative of a length of river that has a consistent (similar) character and behaviour. Meaningful analysis of river condition frames analyses of 'what is expected' at the reach scale (i.e. the range of behaviour for that type of river) in relation to the downstream pattern of reaches. The ways in which rivers adjust to a range of disturbances determines the geoindicators that can be used to measure the condition of rivers and what 'expected' condition these measurements are to be compared against (see Fryirs, 2003; Brierley and Fryirs, 2005). Clearly, attributes that are measured must be relevant to the behavioural regime for that type of river, providing a meaningful basis to compare like with like (Fryirs, 2003; Fryirs et al., 2008; Fryirs and Brierley, 2009). For example, it is pointless comparing the geomorphic condition of a forested meandering gravel bed river to a channelized urban stream (Whittier et al., 2007). As the natural range of variability

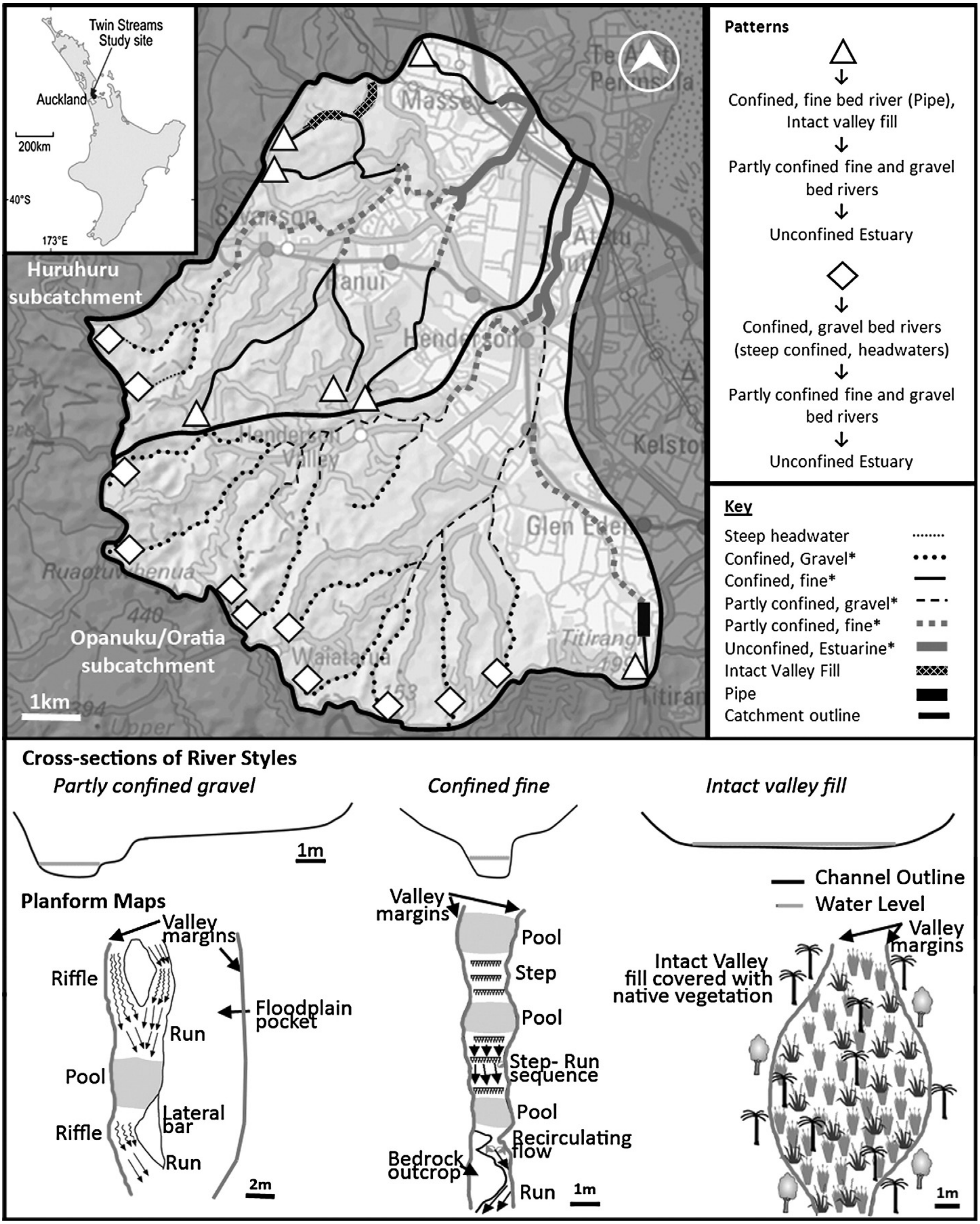

Fig. 2. Geomorphic considerations in assessment of river condition in Twin Streams catchment, New Zealand. This shows the distribution and patterns of geomorphic river types (Δ identifies disconnected subcatchments and ◊ denotes well connected subcatchments; for more detailed maps see Reid et al., 2008a,b and 2009). These river styles can be related to the cross-sections and planform maps below. *Rivers that are low sinuosity.

of these rivers is quite different, the 'expected' outcome of attribute measurement should vary dependent upon river type. For example, bank erosion is expected along the concave bank of a meandering river bend, but is an inappropriate measure to consider in analyzing a gorge. Appropriate standards, reference reaches or guiding images are required to frame assessments of the pattern, extent and rate of bank erosion for any given type of river. Table 1 highlights appropriate geoindicators with which to assess the geomorphic condition of three types of river shown in Fig. 2.

3.3. Geomorphic/hydraulic unit

Field sampling of river condition is performed at sites that are considered to be representative of a given reach, whereby samples are collected from specific habitats or geomorphic units (e.g. pool, run, riffle). It is at this scale that physical habitat availability is a function of the range of textural associations and flow interactions that occur along any given river type. Condition assessments must ask: What associations of hydraulic units are expected for this type of river? What level of heterogeneity is expected at different flow stages? In a gravel bed system, heterogeneity is shaped by complex sediment and flow interactions, whereas heterogeneity in sand bed systems is far more dependent upon riparian vegetation associations and the loading of wood.

Unfortunately, many monitoring programmes that assess river condition fail to give appropriate concern to the representativeness of data collected. All too often there has been a preoccupation with sampling particular units as a basis for notionally representative programmes. Undue emphasis upon pool and riffle features is similar to a seeming aesthetic preference for smoothly meandering rivers in rehabilitation design (Kondolf, 2006a,b). Truly representative monitoring programmes analyze the range of habitat along a reach, systematically assessing the suite of geomorphic/hydraulic units and vegetation/wood functional habitats in channel and floodplain compartments, rather than selecting any particular feature and considering it to be representative of the site as a whole. Seemingly, the quest for comparability as part of statistical rigour in experimental design has taken the place of common sense in representative sampling of features that are more meaningfully associated with any particular type of river, given that a range of habitat is required for species to complete ecological life cycles. Monitoring programmes should strive to assess all habitat needs; their availability, fragmentation, and viability.

Table 1
Relevant geoindicators to assess geomorphic river condition for three types of river in Twin Streams catchment. For details on how to measure these geoindicators, see Brierley and Fryirs (2005).
Modified from Reid et al., 2008a,b.

Geoindicator	Intact valley fill	Confined, low sinuosity, fine bed river	Partly confined, low sinuosity, gravel bed river
Channel attributes			
Size	No	No	Yes
Shape	No	No	Yes
Bank morphology	No	No	Yes
Instream vegetation structure	Yes	Yes	Yes
Woody debris loading	Yes	Yes	Yes
River planform			
Number of channels	No	No	Yes
Sinuosity of channels	No	No	Yes
Lateral stability	Yes	No	Yes
Geomorphic unit assemblage	No	Yes	Yes
Riparian vegetation	Yes	Yes	Yes
Bed character			
Grain size and sorting	Yes	Yes	Yes
Bed stability	Yes	Yes	Yes
Hydraulic diversity	Yes	Yes	Yes
Sediment regime	Yes	Yes	Yes

4. Temporal considerations in the design of river monitoring programmes

Unraveling underlying causes of river condition decline is not always easy or straightforward. However, success in these applications is unlikely to be achieved through static check-list or tick-box approaches that systematically assess structural attributes of river systems, without giving due regard to functional attributes (see Gordon et al., 2004; Fryirs et al., 2008). Unless measures of system structure are tied directly to process controls, underlying causes of system degradation cannot be addressed (Clarke et al., 2003; Fryirs et al., 2008; Jansson et al., 2005; Wohl et al., 2005). Interpretation of temporal variability in processes and trends is vital.

Each reach has a natural range of variability, as process-form relationships adjust at differing flow stages and in response to disturbance events that occur over a range of timescales. Assessment of river condition must be framed in relation to this behavioural regime (Benda et al., 2004; Hughes et al., 2005; Poole, 2002; Ward et al., 2001, 2002). Increasingly, inherent dangers of guiding image (leitbild) approaches to river rehabilitation are being recognized, as such approaches fail to consider the potential effect that prevailing pressures and/or threatening processes that operate elsewhere in the catchment have upon the reach under investigation (Skinner and Bruce-Burgess, 2007). Hence, referential approaches should be used with caution (Skinner et al., 2008), framing leitbilds as moving targets rather than a specific condition (or endpoint), as 'nature' is not fixed and is continually adjusting (Newson and Clark, 2008; Stoddard et al., 2006). Insights into system dynamics should be placed in context of the evolutionary trajectory of each reach, framing system responses to human disturbance in light of the 'natural' range of behaviour and evolutionary trajectory of the river (Brierley and Fryirs, 2005).

Assessment of river condition is especially problematic in those instances where river change has occurred. Should assessments be framed in relation to the contemporary or the former type of river? In many instances, comparing contemporary system attributes relative to past river conditions may not be relevant or appropriate, as the contemporary river type may have a different behavioural regime. The key issue here is whether the river has been transformed into a different type of river, or whether the range of behaviour has been altered but the river continues to operate as the same type of river (Brierley et al., 2008).

Proactive rehabilitation plans seek to apply strategic measures before degradational influences take hold (positive feedback loops surely prompt adherence to the ditty "a stitch in time …"). To do this, monitoring programmes are used to assess contemporary river character and behaviour, interpreting responses to human disturbance in relation to 'natural' variability and the evolutionary trajectory of the system (Gregory and Downs, 2008; Montgomery, 2008; Sear et al., 2008; Wohl et al., 2005). Understanding of the underlying causes of system degradation then provides a basis to determine what is achievable in rehabilitation terms and how river condition can be improved (or preserved). Ultimately, it is hard to envisage how strategic and cost-effective river management plans will be achieved unless due regard is given to appropriate baseline data and monitoring programmes that build upon such geomorphic principles.

The timeframe over which monitoring programmes are implemented should capture the natural range of behaviour of the river, thereby reflecting the timeframe over which geomorphological adjustments occur (e.g. Skinner and Bruce-Burgess, 2007). Marked differences in 'state' are expected over differing timescales in, say, tropical, temperate, arid and Mediterranean rivers. Regardless of locality, 'expectations' of river character and behaviour will vary with flow stage, significantly affecting assessments of river condition.

Hence, consideration must be given to the distribution and rate of process activity in framing condition assessment procedures. In addition, sufficient flexibility should be built into programmes to measure system responses to disturbance events. For example, post-flood analyses will inevitably generate different results than measurements collected after sustained periods of low flow. Longer-term monitoring programmes are required to assess system variability and adjustment at a range of scales, moving beyond programmes that view river systems as static and unidirectional (Skinner and Bruce-Burgess, 2007). Particular emphasis should be placed upon determination of formative flow stages. Process–form relationships along some rivers are driven primarily by extreme events. Elsewhere, rivers may demonstrate pronounced seasonal and/or inter-annual variability. The key message here is the imperative to frame monitoring programmes in relation to the behavioural regime of the river under investigation, rather than a predetermined sampling regime imported uncritically from elsewhere.

5. Discussion

Integrative approaches to analysis of river condition provide critical insights with which management efforts are able to address the underlying causes of system degradation. Effective monitoring and assessment programmes set out to capture this information. To achieve this, emphasis must be placed upon measures of the functionality of the system under consideration, rather than check-list appraisals that focus upon attributes of river form. In other words, how a system works is far more important than how it looks in geo-eco-hydrological terms. It is increasingly recognized that efforts to 'work with nature' are a key consideration in the design and implementation of sustainable and cost-effective river rehabilitation measures (e.g. Beechie and Bolton, 1999; Brierley and Fryirs, 2009; Downs and Gregory, 2004; Hildén, 2000; Montgomery and Bolton, 2003). Clearly, appropriate understanding of system dynamics is required to inform this process. Responsive and proactive management builds upon coherent baseline data tied to substantive monitoring data.

Building upon the primary messages from this paper, a summary of principles to be considered in developing a monitoring programme to assess river condition is presented in Table 2. This list is not intended to be exhaustive. Rather, its intention is indicative, aiming to provide a platform against which existing monitoring programmes can be compared and prospectively improved, and new programmes can be developed.

Table 2
Principles to be considered in developing a monitoring programme to assess river condition.

Principles
1. Integrate cross-disciplinary linkages among geomorphic, biotic and water quality considerations within a holistic (whole of system) perspective.
2. Measure the right things in the right place at the right time.
3. Ensure that due regard is given to rigour, reliability, replicability and representativeness.
4. Apply spatially nested, representative procedures within a catchment framework, recognizing explicitly how controls upon process activity vary over differing spatial and temporal scales.
5. Appreciate the natural diversity in river character and behaviour for any given system, ensuring that procedures assess the inherent range of behaviour for each reach, framing analysis of short-term (event-driven) disturbance responses within a longer-term evolutionary context.
6. Analyze process-based criteria to assess underlying causes of system degradation, rather than merely working upon a form-based (check-list) referential basis, measuring attributes that are appropriate for that type of river.
7. Apply predictive (foresighting) tools to appraise prospective treatment responses in relation to the evolutionary/recovery trajectory of a system.
8. Adopt a heuristic, learning approach to management, responding to lessons learnt from monitoring programmes.

Unless monitoring programmes to assess river condition are appropriately framed, they are likely to overlook key factors that may cause system degradation (Principle 1). Geomorphic considerations provide a coherent landscape platform with which to ground eco-hydrological and water quality concerns, guiding the design of systematic, representative and comprehensive river monitoring programmes.

Self-evidently, monitoring programmes cannot measure everything. Monitoring programmes to assess river condition must take account of who is going to use the information and for what purpose. Strategic and informed choices must be made regarding what to measure, where, by whom, how often and for how long (Principle 2). Determination of appropriate responses to these issues is a mutually interactive process, as data are required to guide how monitoring procedures should be performed. A precautionary approach gathers a large body of data in the first instance, filtering this information to guide more targeted approaches to monitoring in the future. Implicitly, this process recognizes that various pressures or limiting factors that may impact upon river condition may be overlooked. Such is the basis of adaptive management, wherein learning from experience is the key to addressing such shortcomings. This is one of the many forms of uncertainty that underpin river management practice.

Although time restrictions may limit in depth quantitative analyses, this is no excuse for lack of rigour (Principle 3). Inevitably, any environmental assessment is only as good as the quality of its input data. Due regard must be given to reliability and replicability of scientific practice. Unless procedures are applied in an appropriate manner, the data may be worthless, prospectively resulting in misguided management applications that could impact negatively upon the very biodiversity values we seek to protect. Concerns for representativeness are a critical consideration in monitoring and/or sampling design. A clear statement should be provided on the rationale for site selection, indicating explicitly the representativeness of measurements used at each site (i.e. the hydraulic/geomorphic unit that is sampled, the reach in which these features are located, or the catchment as a whole). Efforts to meaningfully capture the diversity and variability of a reach will systematically assess biophysical attributes and process relationships for a representative array of features (geomorphic units). Undue emphasis upon a particular feature for reasons of notional comparability, such as systematic sampling of a pool or a riffle regardless of river type, does not provide a meaningful basis with which to analyze the functional interactions that fashion the behavioural regime of the reach under consideration (i.e. these features may be unrepresentative of that particular type of river; e.g. they are not found within a swamp).

It has long been recognized that application of nested-hierarchical principles presents a rigorous and systematic spatial platform with which to frame monitoring programmes (Principle 4; Frissell et al., 1986; Petts and Amoros, 1996; Rogers and O'Keefe, 2003; Brierley and Fryirs, 2005). Such principles recognize the imperative to work at the catchment scale, identifying biophysically meaningful reaches such that downstream patterns and trends can be interpreted. Within any given reach, systematic analysis of representative geomorphic/hydraulic units can be selected for measurement.

Meaningful monitoring programmes recognize that there may be considerable variability in the natural range of behaviour of any given reach/system (Principle 5). Appropriate measurement/sampling regimes should be applied to capture this inherent variability including formative events that fashion the character and behaviour of the reach/system. Once more, a trial and error approach may be required to develop this understanding. Inevitably, errors may be made, misjudgments will occur, and critical events will be missed. The key consideration here is to learn from these experiences through appropriate documentation and the application of adaptive management principles.

Ideally, longer-term process-based understanding provides contextual insights with which to capture inherent variability and adjustment across a range of scales. A good monitoring programme generates information that provides reliable signals about improvements or deterioration in condition, thereby informing management applications. Effective approaches to river management are no longer framed in relation to static reference conditions and notional endpoints. Meaningful efforts to enhance natural recovery mechanisms frame the contemporary dynamics of any given site in context of reach- and catchment-scale considerations and the broader evolutionary context (Brierley and Fryirs, 2005; Kondolf and Downs, 1996; Newson and Large, 2006; Wohl et al., 2005). In this way, 'dynamic' (uncertain) perspectives are tied to the evolutionary trajectory of any given system.

All too often, the quest for systematic monitoring programmes is misconstrued through broad-ranging check-list applications that fail to ask appropriate questions and measure inappropriate (or irrelevant) attributes for the particular reach/system under investigation (Principle 6). Such practices are exceptionally wasteful, prospectively compromising the opportunity for meaningful analyses to be performed. Meaningful monitoring programmes move beyond check-list monitoring programmes that give undue emphasis to state-based considerations (see Fryirs et al., 2008). In these programmes, lessons from past experiences and previous scientific analyses are used to ensure that appropriate data are collected that reflect the character and behaviour of each given reach (Fryirs, 2003). Such analyses recognize explicitly that the behavioural regime of the river may change over time.

Efforts to learn from monitoring and assessment programmes are markedly enhanced when we progressively test our understanding through predictive modeling exercises (Principle 7). Such exercises can be applied in a retrodictive manner using past data. However, the true value of these applications comes in predicting system responses to management treatments (Schmidt et al., 1998). Pre-treatment data are critical for such procedures, and appropriate statistical designs are essential (see Downes et al., 2002) Considerable benefits are likely to be gained through testing theoretical understanding, and using revised insight to reframe monitoring and management efforts.

Appropriate institutional arrangements and governance structures are critical to the effectiveness of monitoring and assessment programmes (Principle 8). Once initiated, the key to effective monitoring is to continue measuring to establish a continuous, living database. Having said this, there are inherent dangers in becoming locked into a particular framework that may not be entirely appropriate or suitable for management needs, especially when mandated responsibilities relate to biodiversity management. It is argued here that we have reached a critical transition point in the scientific guidance given to river managers to apply monitoring programmes. Integrative frameworks place ecological and water quality considerations in their landscape context. It is only in this light that we can 'inform the future' in a meaningful manner, hopefully applying appropriate measures to improve river condition. Unless management agencies appreciate the need for coherent scientific guidance, our efforts to 'learn as we go' will not achieve their full potential. This is not a matter of 'revolutionizing' or 'overthrowing' existing monitoring programmes. Rather, we are advocating the reframing, recontextualizing and extension of these programmes to generate more coherent, proactive and effective insight with which to guide management practices. When performed effectively, such strategies will not only help to improve river condition, their costs will also be less in the medium–long term.

Effective procedures recognize and 'work with' uncertainty (Hillman et al., 2008), viewing each system as an opportunity for further learning, while remembering that for every rule/principle there is an exception. Appropriate institutional arrangements are required to establish and update information archives. Information must be accessible, with uncertainties and limitations highlighted explicitly. Rigorous training programmes are a prerequisite for coherent understanding and consistent application (Newson and Large, 2006). When used effectively, monitoring data provide a common platform for knowledge transfer among river practitioners. Development of this collective understanding is a critical step in efforts to promote broader societal commitment, engagement and ownership in the process of river repair (Brierley and Fryirs, 2008).

6. Conclusion

River monitoring and assessment go hand in hand whereby monitoring data are collated and translated from multiple spatial and temporal scales into assessments of river condition and forecasts of future risks. This is an integral part of rehabilitation plans that apply adaptive management principles to assess whether treatments meet their intended goal in a timely and cost-effective manner. Hopefully, we learn from these experiences and enhance management practices in the future.

Monitoring data assist strategic decision-making by guiding what is likely to work where. It is only with this understanding in-hand that appropriate legal and policy guidance can be developed and implemented. Just as importantly, these data provide a rational basis with which to justify and prioritize management actions, informing which conservation and/or rehabilitation measures are to be applied where and at what expense. Appraisals of the effectiveness of management actions and lessons learnt from past experiences enable new strategies to be designed and implemented in a more effective manner.

Monitoring programmes must be appropriately framed in order to ground visioning and assessment processes that support an ecosystem approach to river management. Principles from fluvial geomorphology provide a landscape platform with which to link ecological and water quality components of river systems to physical structure and process. Framing monitoring programmes in relation to geomorphic considerations ensures that appropriate data are collected to appraise catchment-scale variability in river character and behaviour. From this, underlying controls of system degradation can be detected and this understanding can be incorporated within rehabilitation plans. Hence, an integrative framework presents a coherent basis for river monitoring and assessment programmes. Unless catchment-framed geomorphic principles underpin monitoring programmes to assess river condition, are we really measuring the right things in the right places at the right time?

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