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Geomorphology in action: Linking policy with on-the-ground actions through applications of the River Styles framework

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ABSTRACT

Integrative approaches to natural resources management build upon scientifically informed policy frameworks. Landscape templates provide a physical platform with which to develop and enact coherent measures which balance concerns for ecosystem health and economic development. The River Styles framework (Brierley & Fryirs, 2000, 2005, p. 398) is a geomorphic tool that feeds scientific information into river management applications and prioritization, striving to ensure that actions reflect the values of a given place. Three recent developments in the use of the River Styles framework in New South Wales, Australia are reported here. First, the use of this cross-scalar, catchment-framed tool in the development and implementation of proactive and strategic management measures is outlined. Regional-scale conservation planning activities are applied using reference reaches for differing River Styles. Catchment-scale investigations into river character, behaviour and evolutionary trajectory frame site/reach considerations in their catchment context. Second, policy links to on-the-ground activities are explored, highlighting ways in which a physical landscape template provides an integrating platform for catchment action planning, water management planning, vegetation management, water quality assessment, conservation and rehabilitation planning and implementation, and monitoring programs. These applications build upon a fragility index that combines concerns for common values, system condition and risk. Third, extensions to the River Styles framework that support management of urban streams are outlined. The use of Geographic Information Systems as a cross-scalar spatial analysis tool with which to guide coherent management applications is highlighted.

Introduction

Across the world government agencies are striving to develop and enact integrative approaches to natural resources management that maintain and/or enhance ecosystem health while facilitating and supporting economic development and growth. Examples include the European Water Framework Directive (Piegay et al., 2008) and South African Water Law (Rowntree & Du Preez, 2008). In these cases, river management strategies and activities reflect policy directives. Effective management is adaptive, building upon scientifically informed policies that themselves are emergent. Unfortunately, however, single-issue management frameworks continue to pervade environmental management practice in many instances. Piecemeal management can only deliver fragmented outcomes, compromising our capacity to achieve sustainability goals.

It could be argued that the combined influence of factors such as population pressure, urbanization, climate change and land use impacts, among many considerations, are currently subjecting environmental systems to greater pressure than at any previous stage of human history. Although there is now greater appreciation of the values and multiple uses of rivers, and many management strategies openly strive to balance the drive for economic productivity with concerns for river health, some question whether an ecosystem approach to river management is yet to truly emerge (Hillman, 2009). Ill-conceived and conflicting exploitation of resources continues to undermine efforts at sustainable practice.

Integrative approaches to natural resources management frame assessments of human impacts upon sustainability values in their landscape context. Appraisal of these spatial relationships, and their changes over time, are innately geographic concerns. For example, practices undertaken on hillslopes (such as forestry management)

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affect activities on valley floors (such as agricultural land uses and fisheries management), and prospectively impact upon coastal environments. Geomorphic principles provide a landscape platform with which to link policy, planning and on-the-ground applications in a coherent, cross-scalar manner, ensuring that strategies reflect the values and attributes of a given place (Brierley, Hillman, & Fryirs, 2006; Fryirs & Brierley, 2009). For example, landscape platforms provide a critical basis with which to appraise habitat availability and viability in river systems (e.g. Petts & Amoros, 1996; Dorava, Montgomery, Palcsak, & Fitzpatrick, 2001). They can also be used to interpret riparian vegetation associations (e.g. Corenblit, Tabacchi, Steiger, & Gurnell, 2007), frame water quality guidelines (e.g. turbidity and contaminant levels; ANZECC, 2000) and develop and assess flow management rules NSW Office of Water 2010. Clearly, many non-geomorphic factors, such as biotic and chemical considerations, influence ecosystem integrity, and it should never be forgotten that the weakest link within an ecosystem determines its performance as a whole (Brierley & Fryirs, 2008). While geomorphic considerations provide the physical template upon which ecosystems operate, they may not be the ultimate determinant of ecosystem performance. However, ecosystem potential will NOT be met unless geomorphic river forms and processes are appropriate for a given setting.

The development of coherent catchment management plans requires agreement on what the key problems are, understanding how a river has achieved its current state (and its likely future condition if left alone), what needs to be done (if anything), where and when to intervene, and what treatments to use. Just as importantly, catchment-scale thinking is required to develop and implement strategic and cost-effective approaches to prioritize management activities. Actions undertaken in one part of a catchment or system often have off-site or lagged responses (either positive or negative) that must be forecast and understood. The River Styles framework provides a landscape platform with which to develop grounded knowledge on these issues (Brierley & Fryirs, 2000, 2005). Catchment-scale applications of this framework were reported earlier from the Bega Catchment in New South Wales, Australia (Brierley, Fryirs, Outhet, & Massey, 2002). Here we report on broader-scale policy developments that build upon this work. Following a brief overview of the River Styles framework, three applications are documented. First, cross-scalar applications of the River Styles framework are presented. Second, policy initiatives that link catchment actions to water planning are outlined. Third, urban extensions to the River Styles framework are discussed. The use of Geographic Information Science (GIS) as a spatial analysis tool with which to integrate and apply these applications is documented.

Table 1
Stages of analysis in the River Styles framework (Brierley & Fryirs, 2005).

Stage 1: Catchment-wide survey of river character and behaviour • River character is defined in terms of valley setting, channel planform, the assemblage of channel and floodplain geomorphic units, and bed material texture • River behaviour is assessed in relation to the process-form associations of the assemblage of geomorphic units • The pattern and connectivity of reaches of differing River Styles is interpreted at the catchment scale, based upon analyses of slope along longitudinal profiles, discharge, stream power, valley morphology and sediment attributes
Stage 2: Catchment-framed assessment of river evolution and geomorphic river condition • Reach condition is appraised relative to a reference condition (an intact or good condition reach of the same River Style) • Where reference reaches are not available, the 'expected' character and behaviour of the river is determined using a set of desirability criteria relevant to the type of river under investigation • Catchment scale patterns of river condition are compiled from reach-scale analyses • River evolution is analysed over timeframes of hundreds of years • The causes of current river condition and change are determined • Geomorphic river responses to human disturbance are compared to the 'natural range of variability' for each reach
Stage 3: Assessment of the future trajectory of change and geomorphic river recovery potential • Catchment scale analyses of river evolution are used to assess river recovery potential • Prospective river futures are interpreted in relation to reach sensitivity to human disturbance and the catchment-scale linkage of disturbance responses • Appraisal of whether reach adjustments constitute a change in River Style is used to determine the optimal condition that can be achieved in rehabilitation efforts • Pressures and processes that may compromise future geomorphic river condition are identified • A range of future scenarios is constructed to provide the target conditions for management practice
Stage 4: Catchment-based visioning, identification of target conditions and prioritization of management efforts • A catchment-scale physical vision of the best-attainable river structure and function is determined, based upon prevailing boundary conditions • Target conditions for river rehabilitation are assessed, framed in relation to the catchment-scale vision • Management applications are selected to enhance natural system recovery mechanisms • Management efforts are prioritized based on the condition and recovery potential of each reach. This approach recognizes the higher costs and lesser prospects for success in prioritizing the repair of poor condition reaches. • Catchment-framed rehabilitation plans emphasize the connectivity of the system, recognizing that reach condition is reliant upon the condition of surrounding reaches, and the potential for off-site treatment responses. • Short-term responses and longer-term system recovery are monitored in order to promote and sustain societal investment in the ongoing process of river repair.

Overview of the River Styles framework

The River Styles framework provides baseline information and understanding of river forms, processes, evolution, condition and trajectory, working under the principle 'know your catchment' (Brierley & Fryirs, 2000, 2005). The framework has four stages, detailed in Table 1. The first stage examines the pattern and connectivity of reaches of different River Style within the context of catchment-scale controls. Stage Two analyses geomorphic river condition, in the context of river evolution and responses to human disturbance. Stage Three interprets river recovery potential at the catchment-scale based upon analyses of the key drivers and stressors that limit system functionality. Finally, management applications of the information generated in Stages 1–3 are identified in Stage 4, based on the prioritisation of reach rehabilitation activities within a catchment-scale vision.

Rather than presenting a prescriptive approach to the analysis of river systems (cf., the Rosgen approach; Simon et al., 2007; Lave, Doyle, & Robertson, 2010), the River Styles framework is an open-ended learning tool. The assessment of river character and behaviour in Stage 1 is based on analysis of the assemblage of geomorphic units (channel and floodplain landforms) along any reach. If new features or combinations of features are noted, a new river type is characterized. Similarly, Stage 2 of the framework uses a non-prescriptive approach to the determination of reach condition, whereby practitioners select (or develop) appropriate geomorphic criteria for the type of river that they are working upon (Fryirs, 2003). This enables the assessment of the 'natural' diversity and range of variability (i.e. the 'expected' behavioural regime) of a river and how far a reach has deviated from this condition. In Stage 3, a catchment perspective is critical in the analysis of reach sensitivity to disturbance, connectivity, the response gradient of evolutionary adjustments and appraisal of recovery potential (Brierley & Fryirs, 2009; Fryirs, Spink, & Brierley, 2009). Limiting factors and pressures to river recovery, whether natural or human induced, are assessed. In Stage 4, a vision of the optimal achievable state, and associated target conditions, are determined, and a prioritization framework for management actions is applied. Such guidance, based on the physical attributes of the system, may clash with social priorities and values, especially the quest for short-term, quick-fix solutions in areas of obvious disturbance and change (Eden & Tunstall, 2006). However, application of measures in these areas may be ineffective in both financial and environmental terms unless degradational influences are addressed elsewhere within the catchment. Caution is needed here, as lack of immediate or short-term success may reduce societal confidence in our capacity to promote and sustain river repair over the long term (Brierley et al., 2006).

The flexible and adaptive nature of the River Styles framework has facilitated a range of cross-scalar applications in the management of river systems in New South Wales.

Recent developments in cross-scalar applications of River Styles information

Ecoregion scale

An ecoregion is defined as an area that has relatively equivalent climatic, topographic and biogeographic conditions (Bailey, 1989). As biophysical diversity values often relate to particular ecoregions, they are most appropriately managed at this scale. Various types and patterns of rivers and their associated biodiversity are evident within each ecoregion. Identification and protection of unique and/or rare river types is a prerequisite for their management.

Systematic River Styles assessments have been applied across most of New South Wales to support the protection of river systems (over 60,000 km have been mapped). Some important lessons in relation to heritage protection have emerged. For example, Mulwaree Ponds in Wollondilly catchment is the last remaining large-scale chain-of-ponds systems in an intact physical condition in the Southern Highlands and Tablelands ecoregion of New South Wales. Ecoregion-scale applications can also be used to identify (sub) catchments that require conservation or those within which to develop and trial catchment-scale approaches to river rehabilitation planning and response (see Brierley et al., 2002). This approach allows agencies to concentrate efforts, monitor response and demonstrate what can be achieved across a system as a whole. Similarly, large-scale demonstration sites can be used to show what can be achieved through more focused and targeted efforts for particular types of river that are considered to be distinctive (or representative) within a given ecoregion.

Catchment scale

Working with geomorphic recovery promotes the best 'bang for the buck' for strategic planning efforts, minimizing waste of financial and human capital through (Brierley et al., 2002). Controls on river health often reflect process-interactions and controls at the catchment scale (Chessman, Fryirs, & Brierley, 2006). For example, the distribution of fish in catchments is often controlled by topography (location of barriers to passage), water quality and elevation. Explaining river health requires a multi-scalar approach to analysis and monitoring (Brierley, Reid, Fryirs, & Trahan, 2010). Most systems are responding to a legacy of multiple impacts of varying antiquity, such as land use changes and engineering structures such as dams, weirs, diversions and stopbanks. Some rivers are resilient and remain in good physical structure. Others show signs of recovery. In these instances, the do nothing option is appropriately justified so long as no other threatening processes located elsewhere in the system compromise environmental improvement. Targeting of fragile rivers for protection or improvement is a logical and strategic option in catchment-scale planning. Scientific insights that appraise 'what is physically achievable' should be viewed alongside local knowledge and values that frame 'what is socially acceptable' (Spink, Hillman, Fryirs, Brierley & Brown, 2010).

Reach scale

To date (February 2011), 57 River Styles have been identified in NSW by consultants, Catchment Management Authorities and the NSW Office of Water. They include river types in confined, partly confined and laterally-unconfined valley settings, along with tidal rivers and discontinuous water courses. Coastal catchments of NSW (east of the Great Divide) are dominated by confined and partly-confined rivers. New variants of river type with distinctive behavioural regimes have been characterized in the latter setting (Fryirs & Brierley, 2010). This state-wide template of reach-scale river character and behaviour provides baseline information for river management planning and policy in rural and urban areas (Outhet and Moore, 2008; Outhet & Young, 2004, 2007). Reference reaches for the spectrum of River Styles are being identified across NSW. The aim and challenge is to identify replicate reference reaches in each ecoregion so that the full range of natural behavioural variability can be established. In addition, each reference reach can be monitored over time to determine temporal variability. To date, reference reaches in good or intact physical condition have been identified using a rigorous set of procedures for 32 River Styles. Geomorphic condition indicators applicable to the River Style are assessed at each reference reach using rapid, objective, remote sensing and field methods developed by Outhet and Young (2002, 2004). Once established, this dataset significantly enhances the prospect for transferability of knowledge within ecoregions, requiring less reliance on expert knowledge or historical insights, enabling derivation of representative (bio)monitoring and auditing programmes tied to these reference reaches.

Working with river behaviour is a key attribute of effective rehabilitation design. Attempts to lock the river in a particular state, regardless of natural change, are destined to fail, and will cost much more to repair in the long term. In New South Wales, reach-scale rehabilitation strategies are designed and implemented that are specific to the types of river and their patterns in any given catchment. Rivers respond physically to variations in many natural factors such as flow and sediment input. Reference reaches can reveal the natural variability of each River Style. River rehabilitation designers can allow for this variability in the design of their projects.

Understanding process-based behaviour sits at the core of the River Styles framework. The framework is based on the geomorphic principle that "form follows function". That is, the observed and categorised geomorphic character, behaviour and condition integrate all the geomorphic processes operating at all scales. This enables practitioners to interpret cause and effect relationships for each reach. River Styles are often subjected to characteristic degradational tendencies and response gradients (Fryirs et al., 2009). Reach-scale responses to disturbance are framed in relation to the expected behaviour of a reach given its catchment setting and prevailing boundary conditions. These insights guide determination of appropriate types of intervention and consider alternative rehabilitation strategies that are specific to the River Style under investigation, providing scientific justification for prevention of inappropriate strategies whilst not assuming that there is 'only one way' to fix a problem. Appraisal of the effectiveness of rehabilitation works for particular problems in certain types of river enables transferability of knowledge to different reaches of the same River Style. Critically, such applications must be framed in relation to prevailing biophysical fluxes at the catchment scale. In NSW, rehabilitation strategies have been designed specifically for the river type. This ensures that the plan works with the natural processes occurring along the reach and the 'right' structures are installed, the 'right' vegetation established and the 'right' range of dynamic/behaviour encouraged. Rehabilitation strategies are adapted to suit local conditions rather than imported from elsewhere (e.g. Brooks, 2006).

Site-specific scale

The site-specific scale includes the landform and habitat scales of analysis. As landforms (termed geomorphic units in the River Styles framework) represent particular process-form associations, appraisals of their assemblage in any given reach provide insight into river evolution. From this, likely sensitivity to disturbance and trajectory of river adjustment can be assessed. These process considerations are vital components of rehabilitation design. Just as important, however, are the habitat considerations that are manifest at this scale (whether for macroinvertebrates, fish, platypus, etc). Similarly, appraisal of appropriate vegetation associations for differing channel and floodplain geomorphic units is a critical component of rehabilitation plans. Concerns for ecohydraulics and ecohydrology have major implications for the management of flow, sediment and nutrient fluxes and the availability/viability of microhabitat. Environmental flow allocations must link these concerns to the assemblage of instream geomorphic units along a given reach (e.g. pools, runs, riffles, etc).

River Styles and policy developments in New South Wales

Linking catchment action with water planning

Contemporary natural resource management in Australia is undertaken within a cycle of planning, implementation, monitoring, evaluation, and reporting. Ultimately, decisions reflect the policy or legislative context in which they are set. Hence, prospects to maximize economic and environmental benefits are constrained by the over-arching policy framework or legislation that guides or enacts decision-making. Recent initiatives in New South Wales apply the River Styles framework directly within a policy context.

Most Australian jurisdictions (states and territories) have separate planning processes for the development of water management plans (WMP) and catchment action plans (CAP). The former process focuses on sharing water between the needs of the environment and extractive users within a legislative context, while the latter focuses on investment in on-the-ground natural resource rehabilitation works within an incentive-based context. Intergovernmental agreements within Australia (for example the National Water Initiative) require jurisdictions to link the two planning processes so that a more integrative approach is achieved, bringing about greater efficiency and improved alignment in efforts to maintain or improve the condition of freshwater ecosystems, including rivers, aquifers and wetlands. To do this requires the development of a shared approach to analyse condition, values and risks, with separate spatial layers being developed for each. In NSW shared spatial products have been developed as a platform to guide common investment. Setting objectives and strategies based on these products will lead to improved alignment of activity, and better targeting and coordination of management and investment. Mapping of areas for protection and rehabilitation, tagged by priority, also includes within-region prioritisation. A program logic approach links investment decisions to long-term goals and objectives using a hierarchical approach. Fig. 1 provides a conceptual model of how water management plan (WMP) and catchment action plan (CAP) processes can be aligned through the utilization of a program logic model based upon a common, agreed set of spatial layers that highlight shared priorities for investment (Hamstead, 2010). Geomorphic considerations using the River Styles approach have been at the forefront of the spatial approach. It forms the foundation of the shared spatial layers used in aligning the two planning frameworks, explicitly relating to the River Condition Index that underpins these processes.

Using River Styles condition information to analyze riverine value

Defining instream "value" has been a common tool utilised in the WMP and CAP process to determine areas of conservation or protection priority. The common *riverine value layer* that has been developed to align the plans separates the value associated with extraction of water from those associated with leaving the water in the river. The value layer is based on the following datasets:

- River Styles Geomorphic Condition
- Biodiversity Forecaster – Conservation Priority (or surrogate using threatened species).
- Community identified assets/values
- Macro Water Sharing Plan – Instream Values
- Macro Water Sharing Plan – Community Dependence on Extraction

The *conservation priority* uses the Biodiversity Forecaster tool developed by Turak et al. (2010). When appropriate data are not available to apply these procedures, the threatened species databases managed by NSW Department of Industry and Investment and the Department of Environment, Climate Change and Water are used to identify water sources containing those species that are water dependent. River Styles maps are then used to identify reaches that are in good geomorphic condition within that catchment. Geomorphic condition assessments are used to determine which water courses provide the habitat requirements that ensure the protection or survival of the identified threatened species, population or community. These reaches are then identified/valued as a priority for conservation. This is based on findings that deterioration from good to moderate condition instigates a greater loss of species diversity and habitats than if the condition deteriorates further from moderate to poor condition (Chessman et al., 2006). Once deterioration from 'good' has begun, the integrity of the system is compromised. The following rules are applied in this assessment:

> Rule 1: Poor condition streams exhibit a lack of geomorphic complexity and are generally associated with large over-widened homogeneous channels that lack pools that provide drought refuge in times of low flow.
> Rule 2: Fine-grained streams have a High Stress Vulnerability Score because these streams generally lack geomorphic diversity regardless of their condition. Therefore this makes any pools or other geomorphic units particularly susceptible to reduced low flow regimes and their ability to provide drought refuge.

The riverine value spatial layer also includes community identified values (using a consultative process similar to procedures identified by Pannell et al., 2009), instream values (NSW Office of Water, 2010), and community dependence on extraction (NSW Office of Water, 2010). Community based aquatic assets refer to water dependent assets that are valued by the community for environmental, economic and social reasons. Identified assets are

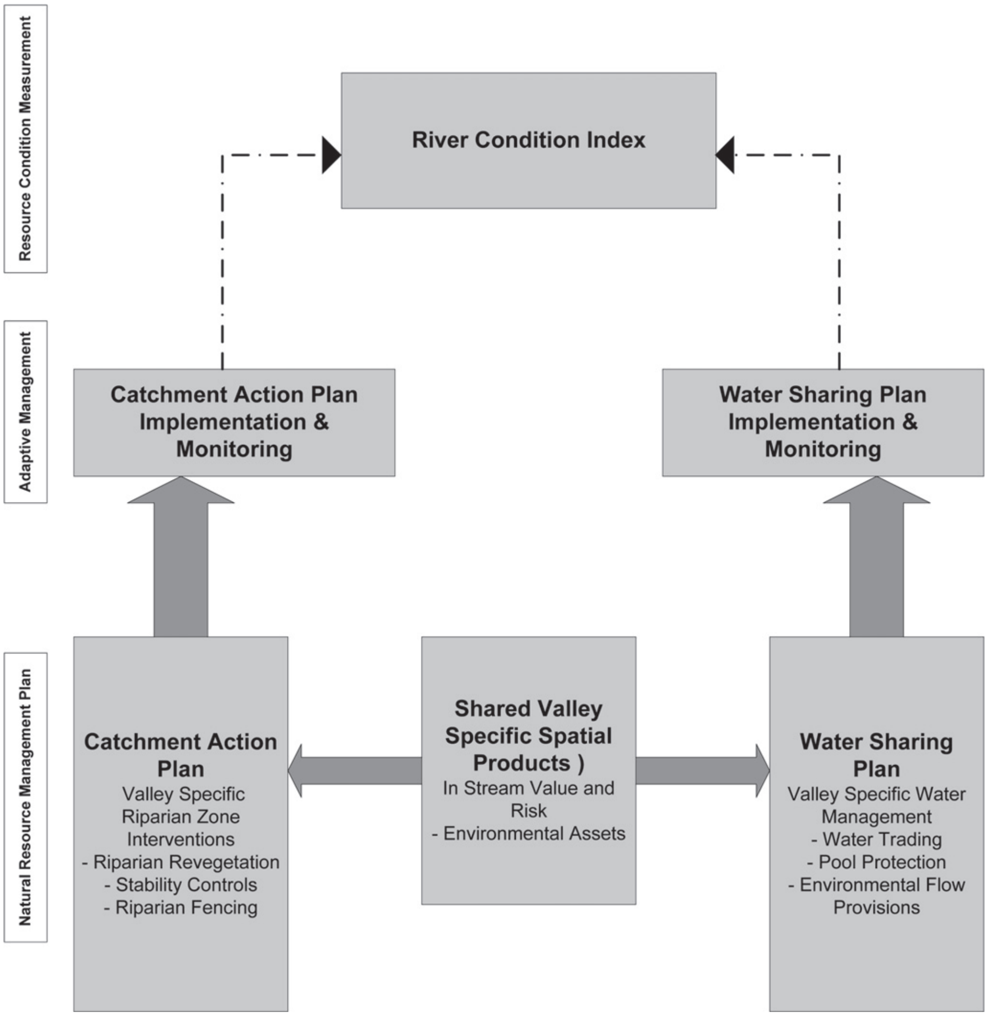


Fig. 1. A conceptual causal relationship diagram based on the Program Logic Model for the Alignment of Water and Catchment Management Plans (Hamstead, 2010). Nested behind this diagram is a series of hierarchical conceptual models that highlight key knowledge gaps that require further investigation. However, it is the River Styles information that provides the fundamental layer upon which other biological information is tagged. This therefore implicitly recognizes the contribution of physical character and behaviour through the objective setting, planning and investment processes for two completely distinct natural resource plans.

incorporated as spatial data layers within the value assessments, integrating a shared approach to community engagement and input that incorporates local knowledge while promoting greater public support and enhanced community respect for process.

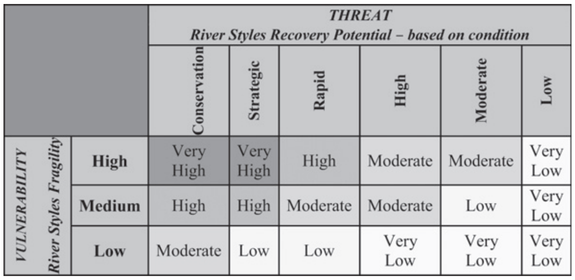
River value is also used in the WMP process to define water trading rules. For example, an area with a high riverine value may have rules which allow the trade of water out of such an area, but do not allow water trading back in. This achieves the long-term objective of reducing water entitlement within high value areas and therefore reducing one of the pressures impacting upon the aquatic health of the system.

Analyzing risk based on River Styles recovery potential and fragility: developing a risk to riverine value layer

In New South Wales, risk assessments form a foundation for investment priorities for conservation and rehabilitation through a CAP and investment in water access rules in a WMP. For example, reaches that contain important pool refugia that are sensitive to physical disturbance would be the target of CAP investment in stock-fencing and revegetation and WMP investment in a low flow cease-to-pump rule that ensures critical low flows and pool water levels are protected from extraction to maintain refugia habitat. Prior to the adoption of a common spatial layer for both types of plans, risk assessments were undertaken using differing approaches. Without the common spatial framework for investment based on risk, an investment by one type of plan had the potential to be negated by a lack of investment by another.

The *risk to riverine value* spatial layer links the risk to riverine value from extraction with the risk to riverine value from physical disturbance. The method for defining risk to instream value from extraction is detailed in NSW Office of Water (2010). Risk is defined by *likelihood* (from Table 2) assessed against the *consequence* as defined by the instream value spatial layer (described above). Risk assessments for extraction and physical form are then combined by averaging these scores. In this process, River Styles information is used to determine the measure of *likelihood* of change. It combines Recovery Potential assessments and Stream Fragility classifications. *Fragility* is a measure of susceptibility to change in character and behaviour for a particular river type, while *recovery potential* provides a measure of the capacity of a reach to return to good condition or to a realistic rehabilitated condition, given the limiting factors impacting on the reach (e.g. riparian vegetation condition such as weed succession, land use such as livestock grazing and trampling impacts, presence of infrastructure such as dams and the rate/degree of physical pressures acting on the reach). The fragility

Table 2
Reach-based measurement of risk (resilience) based on vulnerability and threat.



		THREAT River Styles Recovery Potential – based on condition					
		Conservation	Strategic	Rapid	High	Moderate	Low
VULNERABILITY River Styles Fragility	High	Very High	Very High	High	Moderate	Moderate	Very Low
	Medium	High	High	Moderate	Moderate	Low	Very Low
	Low	Moderate	Low	Low	Very Low	Very Low	Very Low

classification is based on the ease of adjustment of bed material, channel geometry, and channel planform when subjected to degradation or certain threatening activities (Cook & Schneider, 2006). Significant change is more often seen along river types that have higher levels of fragility (i.e. rivers that are not robust or have lower resilience). Significant adjustment may result in a change to a different type of river, if a certain threshold (level of disturbance) is exceeded (Brierley, Fryirs, Boulton, & Cullum, 2008). Three categories are derived based on this definition:

- Low fragility: Resilient ('unbreakable'). Minimal or no adjustment potential. Only minor changes occur such as bedform alteration and the likelihood of river change is minimal, regardless of the level of damaging impact.
- Medium fragility: Local adjustment potential. The reach may adjust over short sections within the vicinity of the threatening process. Major changes to river character can occur, but only when a high threshold of damaging impact is exceeded. For example, a catastrophic flood, sediment slug or clearing of all vegetation from bed, banks and floodplain may be required to induce change.
- High fragility: Significant adjustment potential and sensitive to change. The reach may be dramatically altered or degraded over long sections. Major character changes can occur when a low threshold of damaging impact is exceeded (e.g. clearing of bank toe vegetation alone).

In this assessment, the likelihood of change (or resilience to change) is indicated by the vulnerability or susceptibility (stream fragility) to physical disturbance threats (recovery potential):

$$\text{Likelihood} = \text{Fragility} \times \text{Recovery Potential}$$

Table 2 shows how likelihood was calculated for different levels of recovery potential and fragility.

Using River Styles information in monitoring and evaluation of the WMP and CAP

In New South Wales, the River Condition Index (RCI) provides an overall measure of aquatic ecosystem condition. With recurrent monitoring and evaluation, this index is used to track change over time for both CAP and WMP. This is the primary evaluation tool used to gauge the effectiveness of all natural resources management activities associated with rivers and riparian zones over the long-term. The value and risk spatial layers are used at the beginning of the planning process for both WMPs and CAPs. The value layer is used to guide the development of trading rules in a WMP and areas for conservation priority in a CAP. The risk layer is used to guide water access rules in a WMP and strategic priorities for on-ground investment and incentives in a CAP. Alignment of investment in aquatic NRM can be achieved as the spatial layers provide an easily interpreted multi-disciplinary spatial appraisal of the key environmental assets and their vulnerability at water source or reach scale.

Each plan also has its own performance monitoring program. The development of the RCI is based on the Framework for the Assessment of River and Wetland Health (FARWH), building upon a referential condition assessment to generate an overall picture of river health (Norris et al., 2007a, b). The NSW RCI uses four of the six possible input indices:

- Geomorphic (River Styles) Condition Index (GCI) – input under FARWH "Physical Form" category to generate the geomorphic condition index.
- Native Riparian Vegetation Cover index (native woody vegetation; NRVI) – input under FARWH "Fringing Zone" category to create the native riparian vegetation index (Lovett & Price, 2007).
- Hydrologic Stress Index (rating; HSI) – input under FARWH "Hydrological Change" category to create the hydrologic stress index.
- River Biodiversity Condition Index (RBCI) – input under FARWH "Aquatic Biota" category using the Biodiversity Forecaster.

The RCI uses a standardised Euclidean distance formula to integrate input indices. The standardised Euclidean distance formula was chosen in accordance with the recommended FARWH approach (Norris et al., 2007a):

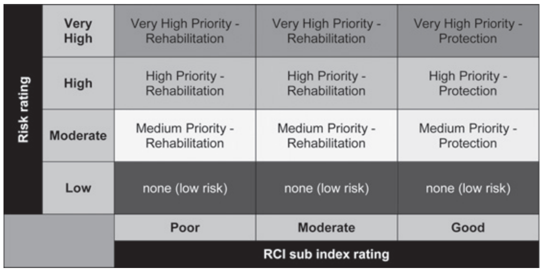
$$\text{RCI} = 1 - \frac{\sqrt{(1-\text{GCI})^2 + (1-\text{NRVI})^2 + (1-\text{HSI})^2 + (1-\text{RBCI})^2}}{\sqrt{4}}$$

This approach enables data collected from disparate methods to be combined into a single score of overall condition. Application of the method produces a score (range 0–1), where a higher score indicates better condition, such that:

0.8–1 = Very Good (equivalent to FARWH "Largely Unmodified")
0.6–0.8 = Good (equivalent to FARWH "Slightly Modified")
0.4–0.6 = Moderate (equivalent to FARWH "Moderately Modified")
0.2–0.4 = Poor (equivalent to FARWH "Substantially Modified")
0–0.2 = Very Poor (equivalent to FARWH "Severely modified")

Table 3 provides an example of the reach-scale prioritization framework that is applied using this information. Based on these criteria, consistent approaches to assessment of river condition integrate concerns for riparian vegetation, geomorphology, hydrology and biodiversity values (see example in Fig. 2). Fig. 3 shows how these data inform management action priorities for the

Table 3
Reach-scale prioritization framework.



Risk rating				
	Very High	Very High Priority - Rehabilitation	Very High Priority - Rehabilitation	Very High Priority - Protection
	High	High Priority - Rehabilitation	High Priority - Rehabilitation	High Priority - Protection
	Moderate	Medium Priority - Rehabilitation	Medium Priority - Rehabilitation	Medium Priority - Protection
	Low	none (low risk)	none (low risk)	none (low risk)
		Poor	Moderate	Good
		RCI sub index rating		

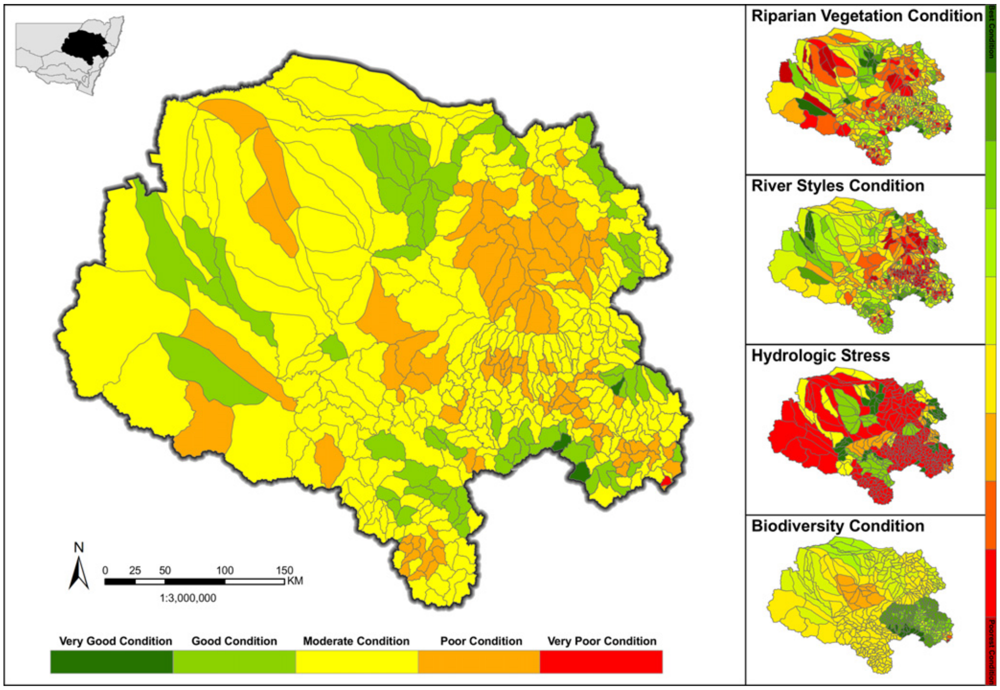


Fig. 2. NSW Office of Water River Condition Index for the Central West, Namoi and Hunter Catchments. This diagram includes each of the indices used to develop the overall condition index for this portion of NSW.

Central West catchments in NSW. In this way, scientifically informed datasets provide a platform for proactive decision-making. Critically, these spatial analysis layers facilitate the application of management strategies in a coherent, cross-scalar manner.

Applications of the River Styles framework in urban settings

Human activities have modified most streams in the world. Impacts are especially pronounced in urban environments (Paul & Meyer, 2001). Management of urban streams requires special consideration because of their limited capacity and space for adjustment, the high cost of space, the threats to life and property during flooding, and their high visibility/profile. Although modified, urban streams still have a wide range of biophysical values. Environmental setting exerts a primary control upon the type and patterns of rivers around which a city is built and operates (Davenport, Gurnell, & Armitage, 2001). For example, much of northern Sydney is constructed around dissected sandstone gorges, while Melbourne lies atop the lowland floodplain of the Yarra River.

Extensions to the River Styles framework incorporate the identification of modifications and their impacts upon different types of river in urban settings (e.g. Gregory, Reid, & Brierley, 2008; Reid, Gregory, & Brierley, 2008; Reid, Brierley and Boothroyd, 2010). From this, the choice and application of appropriate management strategies can be guided through comparison of modified and unmodified rivers of the same type.

Point, linear or areal modifications to urban and regulated streams can be differentiated. Examples include stormwater outlets, bank protection works and carparks respectively. These modifications must be viewed in their geomorphological context, envisaging the processes they interact with, the way in which they change them, and their possible indirect effects on streams. The anthropophysical layer developed here attempts to remove modifications from their human context (i.e. their name and purpose) and use their structural characteristics to interpret their geomorphological influences. Interpretations can then be made of the combined effects of modifications rather than the individual impact of each type of modification. As a result, modifications that have the same direct or indirect geomorphic impact on streams are characterized in the same group. From this, types of geomorphic response are generated. Different forms of modification, such as a causeway and a dam, can have similar impacts on streams. The same modification can also have different influences depending upon the type of stream and conditions that are experienced at various stages of flow. For example, bridges may induce scour or aggradation, depending upon circumstance. Alternatively, while a single bed control structure may impact on flow and sediment continuity at low flow stages, these effects are reduced as flow stage rises, until at peak flow the stream may behave in a very similar way to its pre-modified state.

Direct geomorphic impacts are assessed in terms of changes to river planform, roughness, grain size distribution, geomorphic unit assemblage and channel capacity. Indirect geomorphic impacts are considered in terms of off-site impacts on flow, sediment transport and vegetation associations. With regard to flow, it is important to consider how modifications affect flow quantity, depth and width, velocity, turbulence, and the position of the thalweg and slack water areas (Table 4). When considering sediment transport, it is important to consider how modifications affect the transport rate, quantity and calibre of sediment, and also the locations of erosional and depositional areas (Table 5). With regard to both sediment and water transport, it is also important to consider the stage that modifications begin to interact with the geomorphology of streams. For vegetation associations, it is important to include the impact of modification on the coverage and composition of vegetation in the channel and on the floodplain (Table 6).

The anthropophysical layer for urban streams allows the practitioner to acquire detailed information within a relatively short period of time after Stage One of the River Styles framework has been completed. This information is then compiled to explain the extent of modification and interpret geomorphic responses to

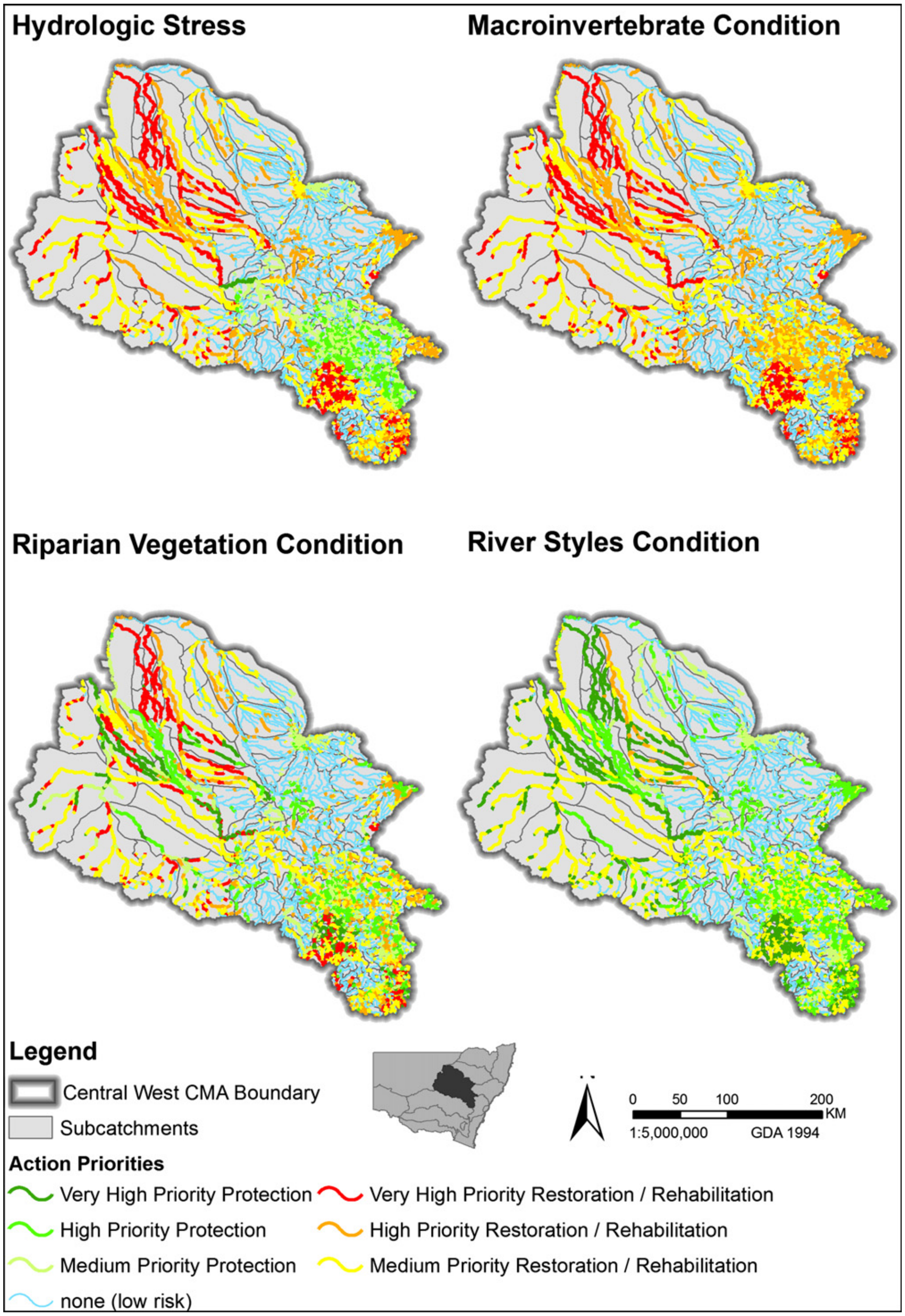


Fig. 3. Catchment Action priorities for the River Condition Index Indices. These individual risk assessments were developed by the NSW Office of Water's as part of Agency's involvement in development of the Draft Central West Catchment Management Authority Catchment Action Plan. This provides an example of how the spatial data can be used to deal with specific issues for priority setting within a Natural Resource Planning process.

Table 4
Urban impacts upon geomorphic attributes of the flow regime.

Flow Attributes	Modification Attributes
Volume	Impoundment, permeability, diversion
Width and Depth	Cross-sectional shape and size
Velocity	Planform, roughness, bed slope
Turbulence	Roughness
Position of Thalweg and Slack Water areas	Flow obstruction and deflection; orientation
Stage Effect	Channel and/or floodplain processes

Table 5
Urban impacts upon geomorphic attributes of sediment flux.

Sediment Load Attributes	Modification Attributes
Rate	Sediment protection/loosening/exposure
Volume, Calibre and Sorting	Impacts on flow characteristics, especially velocity and power
Distribution of erosion and deposition	Flow obstruction and deflection; orientation
Stage Effect	Channel and/or floodplain processes

Table 6
Urban impacts upon geomorphic attributes of riparian vegetation associations.

Vegetation associations Attributes	Modification Attributes
Coverage	Flow obstruction and deflection; orientation. Impacts on flow characteristics, especially velocity and power
Composition	Impacts on water quality and ecological attributes.
Stage Effect	Channel and/or floodplain processes

modification within a reach, between reaches, along river courses and across a catchment. The following modifications and sequence of procedures are recommended for identification of River Styles in urban settings (Fig. 4):

1) Those River Styles that can be fully identified and contain no direct urban modifications are recorded as per conventional River Styles.
2) For other sections of river, the River Styles procedural tree is used, as far as possible, to identify the physical characteristics of each River Style.
3) Those River Styles that can be fully identified, but contain point modifications or modifications along a localised section, are recorded as 'Modified' and a (M) is noted at the end of the River Style name.
4) Given the nature of some urban modifications, it may not be possible to identify a River Style down to its geomorphic unit level or finer. If movement through the River Styles tree is terminated (i.e. direct modification prohibits the identification of a 'full' or 'natural' River Style), the name given to the modified River Style reflects the truncation of the process of identification and the type of modification. For example, it may not be possible to appraise attributes beyond the planform scale for an alluvial river. Therefore, if bed material texture and geomorphic units are obscured, the river may simply be noted as 'Piped meandering (M)'.

Adoption of these procedures enables the development of catchment-wide management plans that are sympathetic to the natural values of the rivers under consideration.

Discussion

Generating, using and archiving useful scientific knowledge for river management

Adaptive management is an iterative process in which baseline understandings gained from tested theories, and lessons learnt from applications, promote knowledge advancement that enhances scientific and management applications in a positive feedback cycle. Such a perspective implicitly frames actions in relation to research developments, systematically reinforming policy, planning and on-the-ground efforts to improve river health. Coherent management applications that strive to protect and rehabilitate river systems build upon grounded (authentic) insights into the character, behaviour, patterns and evolutionary trajectory of rivers within any given catchment. Undue reliance upon modelled data limits prospects for local understanding and/or engagement in the process of river repair, and associated ownership of environmental outcomes. Geomorphic understanding provides the landscape context for such endeavours, recognizing that if the physical structure of a river changes, so does everything else.

The River Styles framework provides a generic set of desktop and field procedures that can be applied to construct the cross-scalar landscape template for any catchment. Geospatial analysis using a Geographic Information System can be applied to store, integrate and interrogate information datasets for this spatially explicit physical template (see Table 7). Appropriately framed relational databases provide not only data storage and access facilities, they also support data collection, organization,

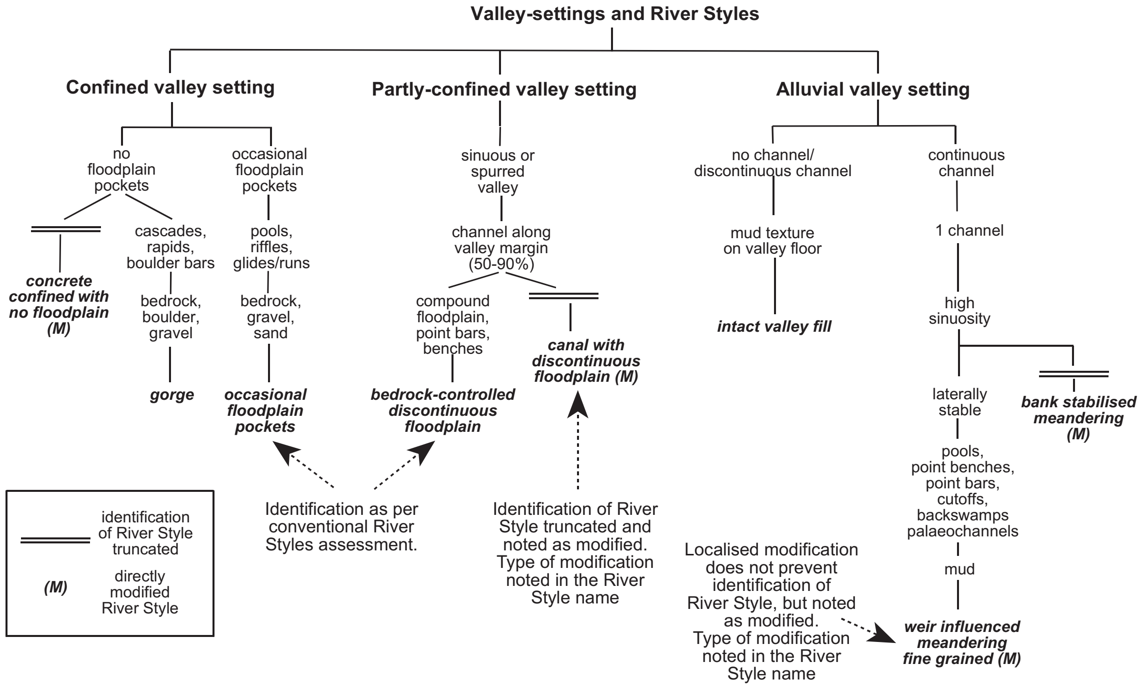


Fig. 4. Example of a catchment-specific River Styles tree including modified River Styles.

Table 7
Overview of GIS functionality to support River Styles applications.

Data storage

- Efficient large file storage to support various data types including vector, raster, image, 3d, time series, tabular, hyperlinks, etc
- Qualitative and quantitative attributes linked to spatial features supporting spatial and temporal queries
- Spatially explicit relational database that supports the development of conceptual models
- Supports data import and export, and associated metadata, with appropriate regard for data standards
- Capacity to embed finer-scale data (e.g. merging finer-scale digital elevation model data with air photograph and satellite imagery)

Spatial analysis: iterative process

- Data input: digitizing, gps and raster import, creation via other datasets, interpolation, etc.
- Data processing: raw data preparation such as coordinate systems, cell size resampling, data format conversion, etc
- Data display to support spatial analysis via live map based visualization: data overlay, symbolization, record selection, diagrams, etc. representing attribute values and/or statistical summaries to support spatial analysis
- Data query:
  - Within and between spatial datasets and standalone tables
  - Data preparation for input to statistical/modelling analyses (e.g. spatial summaries such as drainage area, mean slope, etc)
  - Tools to generate new data to address questions relating to analysis (i.e. spatial data representing query results) such as data extraction, interpolation, hydrological and geomorphic data extrapolation from DEM, extrapolation of land use, soils, etc. thematic data from imagery, etc
- Analysis of spatial relationships in landscapes
  - Catchment morphometrics
  - Longitudinal profiles
  - Reach boundaries
  - Landscape connectivity
  - Sediment transport, etc

Temporal considerations

- Incorporates temporal relationships via time series hydrological data, ongoing monitoring, data overlay, etc, enabling assessment of system dynamics in relation to changing boundary conditions (e.g. land use changes, climate change, etc)
- Platform for representative sampling and monitoring, framed in relation to landscape connectivity (e.g. repeat surveys as a platform for analysis of sediment budgets)

Management applications

- Generic geodatabase that records catchment specific information
- Decision support system via live maps supporting analysis, ongoing data development, etc
- Platform for watershed modeling (e.g. prediction of treatment responses)
- Presentation of results and knowledge transfer, including static maps, diagrams, tables, etc as deliverables for publication, presentation, education, etc
- Platform for data sharing, promoting communication among researchers, managers and stakeholders
- Common language based on visualization

integration, analysis and presentation, providing a common platform for enhanced communication among researchers, managers and stakeholders (see Brierley, 2009). Living databases that support a context-based operating system must be flexible, adaptive and cross scalar. Coherent monitoring applications can build upon such databases, giving due regard for representative site selection, ensuring that catchment-wide similarity, diversity and variability are appropriately captured, thereby aiding transferability of insights from one system to another (Brierley et al., 2010).

Collection and use of catchment-specific information requires appropriately skilled and trained personnel (Newson, 2002; Newson & Large, 2006). It is a time consuming exercise. Expectations that this is a simple process are naïve, and undervalue the importance that people place upon the values of any given system and their knowledge of that system. Scientific understanding is best viewed as a learning tool, rather than a generator of prescriptive, categorical insights (see Lave et al., 2010). Situated knowledge enables and supports monitoring applications that facilitate reflexive and responsive approaches to strategic adaptive management. It is only with appropriate information in hand that management strategies can 'hold the line', maintaining a coherent approach to integrative natural resources management in the face of inherent change and uncertainty (e.g. Hillman & Brierley, 2008). These are critical considerations in promoting resilience thinking as a platform for natural resources management.

Undertaking best management practice processes

Enabling and supportive governance frameworks are required to develop and implement more integrative policy frameworks for natural resources management (Gregory, Brierley, & Le Heron). Effective programmes merge strategic top-down policy and planning instruments with coordinated bottom-up (participatory) practices that promote and enhance environmental stewardship. Inevitably, however, these contested spaces are beset by challenges of divergent aspirations, values and mindsets. There is not necessarily a 'right' way that defines a prescriptive pathway to success. Rather, the biophysical, social and institutional setting within a given catchment will forge the most appropriate pathway.

Building upon applications of the River Styles framework outlined in this manuscript, the following attributes are considered to be important components of best management practice in natural resources management:

1) Develop scientifically informed and community owned policy and planning frameworks that are visionary and realistic. Environmental strategies must merge what is biophysically possible with what is socially and politically desirable/acceptable.
2) Make effective use of catchment-specific cross-disciplinary information that builds upon a geomorphic (landscape) template. No two areas or situations are exactly the same, so caution should be applied in appraising the transferability of data from one catchment to another. However, reach-scale appraisals of river character, behaviour and condition can be rigorously specified for any given River Style.
3) Appraise controls upon system dynamics and evolutionary traits, identifying key stressors and pressures that impact upon environmental values. What are the problems? What do we need to do to 'fix' them (or learn to live with them more effectively)?
4) Catchment based prioritisation of management actions provides a tool to assist in protection of assets, enabling more strategic targeting of investment and efficient allocation of resources. Although pressure is always exerted to do things quickly, a carefully constructed and rational plan of actions supports the implementation of more cost-effective measures and allows plans to operate on different planning cycles. Rational plans of action are well reasoned, clearly communicated, and effectively documented. They express a clear sense of what we are trying to achieve, how we are going to go about it, and why. Short, medium and long-term goals should be framed within a strategic plan that is owned and appropriately situated. Rational prioritization frameworks provide appropriate justifications for actions.
5) Purposeful approaches to management are proactive but flexible, responding effectively to new or threatening situations (i.e. holding steady when appropriate, rather than over-reacting to immediate pressures or 'emergencies'). Although consensus-based management practices are preferred, they may not always be achievable. However, caution should be

heeded in the application of compromise outcomes, as they may represent the worst of all possible worlds (half a habitat is scarcely a viable option).

6) Appropriate governance frameworks are enabling and supportive and must be appropriately resourced. New types of institution and career structures may be required to respond to emerging realities, accommodating divergent approaches and making effective use of new technologies.
7) Success must be measured and appreciated on the ground if benefits are to be sustained into the future. Learning environments use systematic and coherent monitoring and reporting procedures, striving to ensure that we meaningfully respond to lessons learnt.
8) Be patient. Translating applied research into practice is hard, but researchers have a social responsibility to be involved and 'hold the line' with conviction. Few would argue that our actions in river management best reflect what we know. Useful geomorphology is geomorphology in action!

Conclusion

Effective and coherent management actions in natural resources management build upon an appropriately informed, insightful and responsive policy framework. Effective policies, in turn, build upon scientific understanding of the diversity and variability/dynamics of any given system. The geomorphic template generated by the River Styles framework provides a cross-scalar, landscape platform for a host of policy, planning and on-the-ground applications. Applications in New South Wales now extend well beyond its use as a tool for river conservation and rehabilitation planning reported a decade ago (Brierley et al., 2002) to include:

a) Integrated management applications at ecoregion, catchment, reach and site-specific scales,
b) Meaningful integration into policy frameworks that link catchment action plans and water management plans that incorporate appraisals of river fragility and vulnerability alongside community values and associated assets, and
c) Targeted management actions for urban streams.

As noted by Rogers (2006), meaningful applications of scientific practice must build upon direct collaboration between researchers, stakeholders and decision-makers. In this way, geomorphic insights can be merged in an appropriate policy and planning context, enhancing prospects for success in the process of river repair.

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