KEMANUSIAAN

KEMANUSIAAN 15 (2008), 13–26

Geomorphology and River Management

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Abstract. Engineering-dominated practices, visible in a "command and control" outlook on natural systems, have induced enormous damage to the environment. Biodiversity losses and declining provision of ecosystem services are testimony to the non-sustainable outcomes brought about by such practices. More environmentally friendly approaches that promote a harmonious relationship between human activities and nature are required. Moves towards an "ecosystem approach" to environmental management require coherent (integrative) scientific guidance. Geomorphology, the study of the form of the earth, provides a landscape template with which to ground this process. This way of thinking respects the inherent diversity and complexity of natural systems. Examples of the transition toward such views in environmental practice are demonstrated by the use of science to guide river management, emphasising applications of the River Styles framework.

Keywords and phrases: Biodiversity, Sustainability, Human impact, Ecosystem management, River health

INTRODUCTION

The Millennium Ecosystem Assessment (2005) presents strong insight into the extent and severity of damage that human activities have inflicted upon "natural" ecosystems across our planet. These impacts have been especially severe in river systems (e.g., Dudgeon et al. 2006). This reflects a combination of factors. Many river systems are inherently sensitive to human disturbance. The intensity of land use has been particularly pronounced upon valley floors, entailing a myriad of modifications for agricultural, industrial and urban purposes. Such land use has typically been accompanied by direct modification to river flows by dams, weirs and canals, among many factors. These practices not only impact natural systems; they also affect ecosystem services provided by these systems that are fundamental to human survival (e.g., provision of potable water, fish stocks, irrigation supply, etc.; Daily 1997). To address these concerns, a balanced approach to water resources management is required, one that promotes a harmonious relationship between humans and nature (Wang 2006). Humans are, by definition, a part of ecosystems (Leopold 1949). Our relationship to the natural world shapes our livelihood. This, in essence, is the basis of sustainability. We either believe in, and make genuine commitments to achieve sustainable practice, or we do not. We already live with the legacy of past impacts that humans have inflicted upon the environment. We now have a choice about the imprint that we leave for future generations.

In this article I contend that, in many parts of the world, a transition in our approach to water resources management is underway. Focussing primarily upon the management of river systems, I discuss the emergence of an "era of river repair" (Postel and Richter 2003; Brierley and Fryirs 2008). In this emerging era, increased emphasis is placed on biodiversity management and protection of ecosystem services, with the explicit recognition that past approaches to river management were not sustainable. Both scientific and management issues are discussed, with highlights including the imperative for new forms of research to guide the process of river repair and direct links provided between insights from scientific and social science perspectives. Of even greater importance, however, is the need for river practitioners to work directly with managers and politicians in an effort to improve river health and deliver genuinely sustainable programmes (Rogers 2006). The radical nature of this transition is highlighted by some of the language that has been used to describe these new practices, referred to by Funtowitz and Ravetz (1991) as "Post-Normal Science."

Inevitably, any contribution on such a topic reflects the experience and bias of its author. The perspectives conveyed here are those of a fluvial geomorphologist with an unashamedly conservationist outlook who has worked on management applications of river science for around two decades. My research has focussed largely upon human impacts on river systems associated with land use changes (especially vegetation clearance) and the use of insights from fluvial geomorphology as a biophysical platform for guiding efforts to improve river health. This culminated in my co-authoring a book entitled *Geomorphology and River Management* (Brierley and Fryirs 2005). In this book, river responses to human disturbance are reviewed, and an approach to the use of river science to guide management applications is developed. It is a fundamental premise of this work that a geomorphic template provides a coherent platform with which to integrate scientific understanding of river systems. A landscape platform can be used to describe and explain links between river forms and processes, water and sediment fluxes, ecosystem and biogeochemical relationships, etc. Such thinking prompts a move away from discipline-bound perspectives in the management of river systems, whether driven by geomorphologists, hydrologists, ecologists, biologists or water chemists. Fragmented science will yield only fragmented solutions. Such partial outcomes may compromise the biodiversity values and ecosystem services that we seek to protect. In a sense, the quest for integration represents a renewed call to develop the science of "potamology" as the study of running waters (Penck 1897). Although we have developed remarkable insights into the character and behaviour of most aspects of river science, we have been largely unsuccessful in our efforts to pull together this understanding to provide coherent, "whole of system" guidance to river managers. This shortcoming is considered in my recent co-edited book entitled *River Futures* (Brierley and Fryirs 2008), which examines the use of integrative river science to guide the process of river repair in various parts of the world.

This article has three sections. First, the emergence of an ecosystem approach to river science and management is outlined. Second, the use of principles from fluvial geomorphology as a platform for integrative river science and management is discussed. Third, applications of these issues are demonstrated through the use of the River Styles framework.

EMERGENCE OF AN ECOSYSTEM APPROACH TO RIVER SCIENCE AND MANAGEMENT

Flow regulation and channel modification have been core components of human endeavours to alter river courses to meet human needs, especially those associated with reliable supply of water and minimisation of flood hazards. However, such actions have been unsustainable on two accounts. First, no consideration has been given to ecosystem values. There has been no sense of humans living in harmony with nature. Rather, this has been an era of "command and control" (Holling and Meffe 1996; Hillman and Brierley 2005). Attempts by humans to assert their dominance over natural systems are elegantly captured as the quest to "make wetlands drier, and drylands wetter." Second, in all too many instances our efforts to modify natural systems to meet human needs have failed to achieve their intended goal, especially when viewed over the longer term of decades or centuries. Indeed, there are countless examples of immediate- to short-term disasters too, such as dams that infill rapidly during the process of construction and levee systems that fail or actually trap water behind them. The tragedy of such actions is the legacy that is left behind for future generations to clean up. All too often, the costs of repair greatly exceed those associated with construction that brought about environmental damage.

In large part, the era of river repair sets out to reverse the degradative tendencies brought about by human actions. Key examples of these attempts include increasing recognition of the importance of wetlands in retaining water during periods of drought and their role as environmental filters, prompting considerable investment in wetland reconstruction. Similarly, the short-term benefits of dams and flow regulation structures are often out-weighed by the long-term costs associated with dam removal. Maintenance costs for channelisation programmes greatly exceed the initial costs of implementation. The dilemma here is clear. Adoption of approaches that "work with nature" yields not only environmental benefits; it is also cheaper in the medium term. Such actions promote and/or enhance the viability of self-regulating river systems, for which the environmental benefits are ongoing and costs are minimised.

Table 1 contrasts scientific attributes of the traditional "command and control" approach to river management with those associated with the emerging "ecosystem" approach to it. Fundamental differences in goals and aspirations, and the nature and application of scientific insight are highlighted in this table. Typically, command and control perspectives are applied in order to deliver particular human needs (e.g., water supply) in a predictable and recurrent manner. Deterministic science, typically with an engineering focus that applies discipline-bound, reductionist principles, is tasked with imposing human values upon natural systems. Such thinking emphasises the quest for stability, negating the inherent diversity and variability of natural systems. In doing so, this thinking works against the very principles that generate and maintain ecosystems. Within an ecosystem approach to river management, due regard is given to the uncertainty and complexity of natural systems through the application of cross-disciplinary science framed within a probabilistic context. Concern is placed on long-term, sustainable outcomes, emphasising the need for coherent planning applications at the catchment scale. Such strategies present a stark contrast to "band-aid" engineering solutions applied on a site-specific or reach scale. All too often, these applications work against each other on broader scales, requiring extensive expenditure for ongoing maintenance.

Even more profound than these scientific considerations are the management issues that must be addressed if we are to achieve genuine engagement with the process of river repair. Several of these issues are highlighted in Table 2. First and foremost, river repair will not be achieved and sustained unless there is

Table 1. Scientific attributes of command and control and ecosystem approaches to river management (simplified from Hillman and Brierley 2005).

Command and Control	Ecosystem Approach
Discipline-bound, reductionist	Holistic, cross-disciplinary
Single-purpose, deterministic	Multi-purpose, probabilistic
Site-specific or reach-scale applications	Catchment (landscape)-framed approach
Quest for stability over decadal timeframes	Works with natural variability over centuries or millennia
Desire for certainty in outcomes	Recognises uncertainty and complexity

genuine societal commitment to the process. While top-down, politically driven perspectives may set the agenda, bottom-up, participatory practices are fundamental to the implementation and maintenance of sustainable practices. River management is not merely a technical task; it is inherently a socio-economic and cultural issue that reflects societal values (Higgs 2003). Having said this, it is also true that sustainability cannot be achieved unless due regard is given to ecological concerns. Critically, the collective assemblage of these values is specific to any given system. This highlights the importance of geographic relationships to place that lie at the heart of the process of river repair (Brierley et al. 2006). These are long-term commitments; by definition, sustainable practices never stop. Adoption of adaptive management principles provides the most appropriate framework with which to facilitate this process (Holling 1978). Such principles apply monitoring procedures to ensure that due commitment is given to a process of learning, ensuring that we adapt our practices by "learning as we go."

Underlying this transition in approach to river management is a fundamental shift in our perception of the natural world. Learning to live with variability and complexity requires that we accept and embrace uncertainty (e.g., Hillman and Brierley 2008; Darby and Sear 2008). It is impossible to "know" what the future will bring, but whatever happens we will have to deal with it. Thinking that we can conquer nature to meet our needs is naive indeed, but it has not stopped us from trying to do so in the past. Among the many complications faced is the ever-changing nature of biophysical interactions and outcomes. Evolution is a fact, but it does not always follow a smooth, uninterrupted and predictable path. Awareness of the potential for surprising outcomes is an integral component of precautionary and proactive management.

Table 2. Managerial attributes of command and control and ecosystem approaches to river management (simplified from Hillman and Brierley 2005).

Command and Control	Ecosystem Approach
Top-down, politically driven	Bottom-up, participatory
Technical (engineering) focus	Integrates social and ecological considerations
Construction focus	Continuum of interventions – including the "do nothing" option
Short-term focus	Long-term commitment
Limited monitoring	Adaptive management

A further irony that underlies the traditional, engineering-dominated approach to river management is the way in which we respond to the negative consequences of these actions, thinking that technological solutions provide the most appropriate way to address concerns brought about by applications of technology. All too often, this merely adds a further layer of engineering-based modifications, failing to address the underlying causes of environmental degradation. This recurrent application of measures with a construction focus is termed "technofix" by Higgs (2003). A stark contrast is presented by some contemporary approaches to river rehabilitation that strive to "leave the river alone" (e.g., Simon and Darby 2002; Piegay et al. 2005). Such perspectives view rivers as dynamic, living systems (Everard and Powell 2002) and allow them to support aquatic ecosystems while they consume their own energy as they self-adjust.

Finally, it should never be forgotten that prevention is better, and cheaper, than cure. Prospects for success in the process of river repair are markedly enhanced when conservation values and threatening pressures/processes are recognised at the outset, enabling the development and implementation of precautionary and strategic practices. The use of geomorphic principles can greatly aid river management practices in this regard.

THE USE OF GEOMORPHOLOGY AS A BIOPHYSICAL TEMPLATE

Geomorphology is the study of the form of the earth. In explaining the character, behaviour and distribution of landforms, emphasis is placed upon the processes that generate and modify the earth's surface and the evolutionary changes that have been experienced at any given place. As river geomorphic processes shape the diversity of features along valley floors, they act as a key determinant of habitat diversity in river systems (e.g., Petts and Amoros 1996; Dorava et al. 2001). For example, a range of habitats is associated with differing substrate sizes and their arrangement on the channel bed. The interaction of these materials with flow, and the importance of these relationships as determinants of habitat availability, has prompted the rapid growth of subdisciplines such as ecohydraulics and ecohydrology (e.g., Palmer and Bernhardt 2006). These developments are indicative of steps to revisit notions of potamology mentioned earlier. Geomorphic principles lie at the heart of these notions. The character and distribution of pools, riffles and runs along river courses are determined by geomorphic processes. Similarly, some floodplains are characterised by geomorphic features such as backswamps and wetlands. These channel and floodplain features are key determinants of the diversity of habitat along any given river.

Geomorphic considerations are also key determinants of vegetation associations along valley floors, thereby influencing a suite of biophysical interactions that mutually adjust to fashion river forms and processes (see Corenblit et al. 2007). Differing geomorphic surfaces comprise different sediment sizes and are inundated by flows of differing magnitude and recurrence interval, influencing the type of vegetation found on these surfaces. These differing vegetation communities, in turn, affect the operation of geomorphic processes in channel and floodplain compartments, acting as resistance elements that often promote deposition. In addition, vegetation interactions fashion the input of organic matter into river systems and affect the thermal regime by influencing shade. Channel size and instream roughness affect the passage of flow and the dissipation of flow energy. These impacts upon sediment reworking, in turn, affect the turbidity of flow and water quality. It is the operation of these processes as a whole that fashions ecosystem potential.

At the same time, the viability of habitat is influenced by a wide range of non-geomorphic factors, such as biotic and chemical considerations. It should never be forgotten that the weakest link within an ecosystem determines its performance. If an element is missing or the chain is broken, the system may be compromised. While geomorphic considerations provide the biophysical template upon or within which ecosystems operate, these considerations 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.

In considering the application of river science to guiding management practice, it is important to frame our thinking in terms of "whole of system" perspectives at the catchment-scale. It is only at this broader scale that off-site and lagged consequences of disturbance elsewhere within a river system can be appraised. In many instances, the legacy of these impacts may be felt for hundreds or thousands of years. To appreciate these concerns, an evolutionary approach to inquiry is required, framing landscape responses to human disturbance in relation to the "natural" variability and evolutionary trajectory of any given system. It is only in this light that prospective river futures can be meaningfully appraised. These various threads of geomorphic enquiry are integrated within the River Styles framework, thus providing a coherent biophysical template for river management.

THE RIVER STYLES FRAMEWORK

The River Styles framework comprises four stages (Brierley and Fryirs 2005). The first stage entails determination of the reach-scale character and behaviour of rivers. The landforms that make up any given reach provide a basis for interpreting the processes that form and rework each feature. These features are termed geomorphic units. Characteristic assemblages of erosional and depositional geomorphic units can be found in either channel or floodplain compartments. Critically, explanation of the downstream pattern of River Styles along the longitudinal profile for any given catchment provides an insight into the connectivity of that system and the associated operation of flow and sediment fluxes.

Rather than presenting a prescriptive approach to the analysis of river systems, the River Styles framework provides an open-ended learning tool (cf. Simon et al. 2007). Nature is not pigeon-holed into particular types. Rather, the assemblage of geomorphic units along any reach is the key determinant of the type of river. If new features or combinations of features are noted, the river is characterised as a new type. Examples of differing River Styles are shown in Figure 1. Among the key attributes that differentiate the examples shown are the influence of bedrock as a determinant of river form/process associations (e.g., gorge versus alluvial rivers), variants of channel planform (braided, wandering, meandering and anastamosing), and the presence of discontinuous watercourses (e.g., wetlands, swamps).

Stage Two of the River Styles framework analyses geomorphic river condition. This appraises the present condition of a reach of a given River Style relative to a reference condition (ideally an intact reach of the same River Style). The criteria used to assess geomorphic condition must be relevant to the type of river under investigation. Once more, a non-prescriptive approach is used. A set of principles is documented, whereby practitioners select (or develop) appropriate criteria for the type of river that they are working on. These reach-scale procedures are then combined to analyse patterns of river condition at the catchment scale, identifying the distribution of remaining good condition reaches and patterns of river response to disturbance.

While analysis of geomorphic river conditions provides a measure of the contemporary attributes of a reach, effective management strategies require an appreciation of evolutionary trajectory to determine what is achievable in rehabilitation terms. In the River Styles framework, the determination of river recovery potential is based upon analyses of river evolution at the catchment-scale, applied over timescales of hundred or thousands of years. This enables assessment of the "natural" range of variability (the behavioural regime of a river), along with geomorphic river responses to human disturbance. From these insights, differentiation can be made between those reaches that continue to operate in the same River Style despite human disturbance, relative to those that have experienced a fundamental change in process-form relationships (i.e.,

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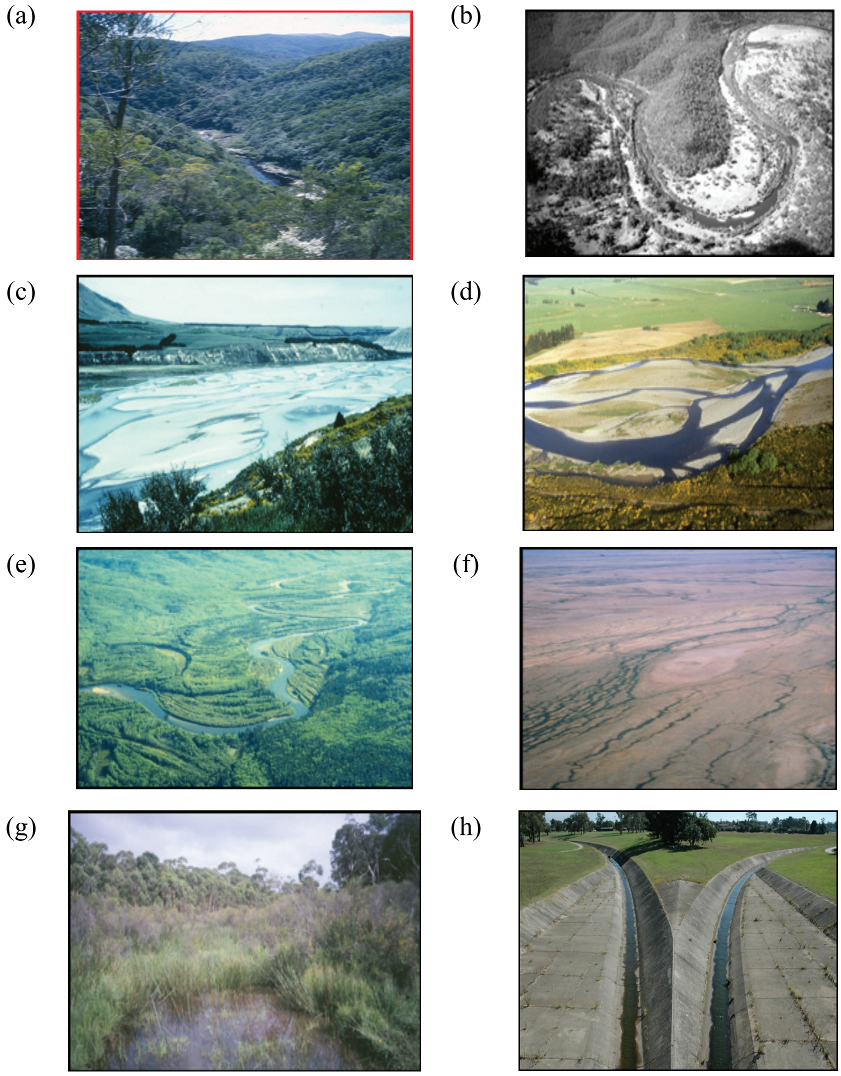

Figure 1. The inherent diversity of river character and behaviour. Rather than manage rivers to some "norm," approaches to sustainable rivers embrace the variability and complexity of river systems, reflected here as a gorge (a), bedrock-controlled discontinuous floodplain (b), braided river (c), wandering gravel-bed river (d), meandering river (e), anastamosing river (f) and a discontinuous watercourse (g). The "human river style" (h) is testimony to the creativity of engineering perspectives that view rivers as stormwater drains with little or no ecosystem value.

metamorphosis, as marked by a different set of geomorphic units). The appraisal of whether adjustments have been reversible or irreversible, over management timeframes of 50–100 years, determines the optimal condition that can be achieved through rehabilitation practice. Once more, it is the application of these investigations on the catchment-scale that enables threatening processes that may compromise future geomorphic river condition to be identified (e.g., downstream passage of sediment slugs, headward extension of incisional processes). Identification of recovery potential is vital if strategic management actions are to "work with" prevailing river dynamics, targeting degradative influences before they get out of hand.

Stage Four of the River Styles framework involves management applications. These are separated into three components. First, a vision of what is achievable (or desirable) is determined. This catchment-scale analysis integrates insight into the diversity of rivers; the identification of unique, rare or remnant river types; appraisal of reach condition; and recovery prospects. In this process, a balanced approach to determining conservation and rehabilitation priorities should be adopted, clearly specifying what we are trying to achieve and why. Second, target conditions for any given reach are framed in relation to the catchment-scale vision. Rehabilitation practices that address the underlying causes of degradative processes, rather than the symptoms of river adjustment, can be determined for differing River Styles. Finally, a prioritisation framework for management actions is applied (Fig. 2). The premise adopted here is that conservation priorities must be addressed at the outset. Degradative influences that may threaten the inherent value of these reaches are addressed as strategic priorities. Unless these values are protected, recovery may be compromised or require inordinate expenditure to rehabilitate the river, with uncertain prospects for success. Indeed, a precautionary and proactive approach to river management is required, as costs for environmental repair are likely to become excessive if fundamental adjustments occur to geomorphic river structure. In many instances, strategic measures that are applied in order to protect conservation values address threatening processes in reaches adjacent to high conservation value reaches. Beyond these considerations, more emphasis is placed on those reaches that have inherent recovery potential (helping the river to help itself) than on poor condition reaches with low recovery potential, where the application of extensive and expensive rehabilitation techniques may yield limited success. Rather than applying band-aid "solutions" that require recurrent, invasive maintenance with limited prospects for achieving substantive environmental benefits, low-cost measures in reaches with high recovery potential are more likely to result in sustainable approaches to river management. Such applications improve the capacity of a river system to "self-fix." Improvements to river conditions in these reaches will enhance prospects for addressing concerns in reaches in poor condition, over the longer term. While such scientific guidance may clash with social perspectives, especially in the face of the quest for short-term, quick-fix solutions, attention should be drawn to the ineffectiveness of such measures, in both financial and environmental terms. In addition, lack of success may reduce societal confidence in our capacity to promote river repair. As a fall-back option, our choices should always be guided by the goal of achieving sustainable outcomes. Ultimately, the adoption of sustainability principles relative to development options or other priorities represents the choice that we must make as a society (or that politicians must make, notionally on our behalf). Future generations will be left to consider the effectiveness of the choices we make and the actions we make today.

CONCLUSIONS

The prospects for river repair are contingent upon our efforts to merge scientific and managerial concerns of river health and rehabilitation with social considerations in the design and application of sustainability programmes. This requires that due regard is given to both product and process. This sentiment is

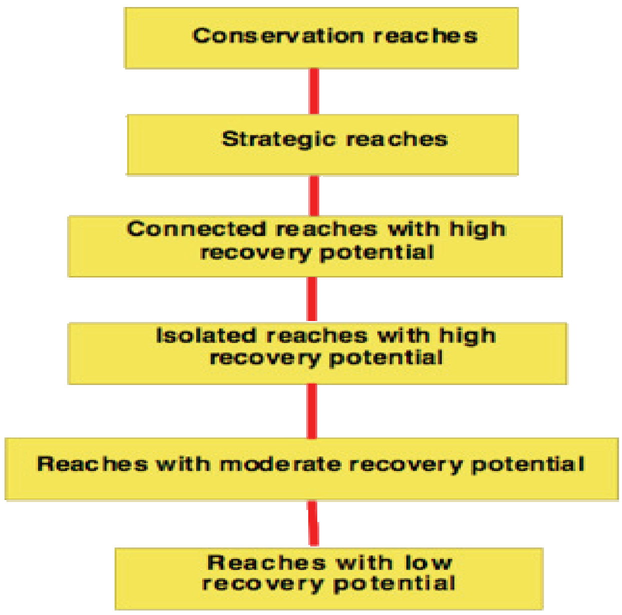

Figure 2. Prioritisation framework for catchment-scale river conservation and rehabilitation practices used in the River Styles framework (Brierley and Fryirs 2005).

captured in a quote by Robert Bea, a civil engineer charged with the design and implementation of levees along the lower Mississippi River near New Orleans following damage induced by Hurricane Katrina in August 2005: "If I had $10 to spend on a levee, I would put $8 on people and $2 on dirt" (*New Scientist* 28.04.07, p.10). In a similar vein, we cannot afford to view environmental repair as a multitude of minor issues and dilemmas. Rather, we must focus our efforts on the major questions that confront biodiversity management and sustainability programmes. In terms of river management, channel and floodplain compartments must be viewed in relation to land use pressures on the catchment/ landscape scale. Such thinking emphasises linkages and feedback mechanisms that promote self-sustaining systems. Piecemeal and fragmented programmes will not achieve sustainable success. After all, there are too many species to save them one at a time.

Comprehensive, coherent information is required to guide the process of river repair. A geomorphic template provides a critical platform upon which to integrate cross-disciplinary information in a meaningful manner. Just as importantly, tools such as the River Styles framework provide a genuine link to place, enabling community values to be tied directly to specific systems, rather than over-generalised applications. Such is the inherent value of geographic discourse. Ultimately, healthy rivers are the product of healthy societies.

ACKNOWLEDGEMENTS

Sincere thanks to Universiti Sains Malaysia, especially Wan Ruslan Ismail, for the opportunity to run a workshop on "The Role of Geomorphology in River Management" (12.12.07) and a wonderful field trip.

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