Linking the physical form and processes of rivers with ecological response

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Abstract Fluvial eco-geomorphology seeks to link the physical form and processes of rivers with ecological responses by adopting an ecosystem perspective in research and management. It is recognized that the physical habitat is not static, and there are numerous and complex interconnections at various scales that determine fluvial form and processes. In turn, the physical environment exerts a strong control on river biota, but the effects can be indirect and mediated through complex interactions. As a consequence, there are considerable uncertainties in manipulating fluvial systems; hence an adaptive approach to management is required. Contributions from papers presented from the session on eco-geomorphology in the IAHS–ICCE–UNESCO International Symposium on the Structure, Function and Management Implications of Fluvial Sedimentary Systems are discussed in the context of two major themes of ecosystem management: physical habitat improvement and restoration of flow regimes. Challenges and opportunities for fluvial eco-geomorphology are outlined.

Key words eco-geomorphology; ecosystem management; river corridor; habitat rehabilitation; habitat restoration; instream flow; environmental flow

INTRODUCTION

The IAHS–ICCE–UNESCO International Symposium on the Structure, Function and Management Implications of Fluvial Sedimentary Systems addresses four themes: eco-geomorphology, flood plains, variability, and new techniques. This paper explores several facets of the first theme: "Eco-geomorphology: linking the physical form of fluvial sedimentary systems with ecological response". Specifically:

– What is "eco-geomorphology"?
– Why is an "eco" perspective required?
– Application of an eco-geomorphic approach.
– Challenges for ecosystem management—eco-geomorphology.

ECO-GEOMORPHOLOGY

Bauer (1996) defines geomorphology as the area of study that leads to an understanding of and appreciation for landforms and landscapes including their geometry, structure (internal and external), coexistence with other forms (biotic and otherwise), and dynamics (mode of evolution and processes integral to their existence and evolution).

This symposium considers a subset of geomorphology—fluvial sedimentary systems—and recognizes that the management of the abiotic aspects of these systems is integral to the overall health of river ecosystems. In this context, eco-geomorphology can be defined as linking the physical form and processes of rivers with ecological response by adopting an ecosystem perspective. The ultimate purpose is to make management decisions based on the best available information, and to systematically learn from these management decisions.

AN ECOSYSTEM PERSPECTIVE

Fundamentally, an ecosystem approach is a perspective, a way of looking at, understanding, and managing a problem (Day & Hudson, 2001). The integration of an ecosystem perspective and fluvial geomorphology to address river system issues reflects the following:

1. Overall, there are considerable signs that the capacity of ecosystems to continue to produce many of the goods and services we depend on is declining (WRI, 2000).
2. The biodiversity crisis involves more than the endangerment and extinction of individual species. It also involves the loss and degradation of habitats, species assemblages, and natural processes (Christensen *et al.*, 1996).
3. There is recent widespread recognition of the importance of ecosystem complexity and the vast array of interconnections that underlie ecosystem function (Peterson, 1993), at various scales (Thoms & Parsons, 2002).
4. There is recognition of the dynamic nature of physical environments, indeterminate hydraulics, and equifinality (e.g. Kondolf & Downs, 1996); and the importance of the connection between the physical system and ecological responses (e.g. Walker *et al.*, 1995; Ward & Stanford, 1995).
5. Geomorphological knowledge is central to successful enhancement, rehabilitation, and restoration of physical habitat and flow regimes (e.g. Brookes & Shields, 1996; Graf, 1996).
6. Sustainability has become an explicitly stated, or legislatively mandated, goal for many agencies and jurisdictions (e.g. New Zealand's Resource Management Act 1991—Day & Hudson, 2001; and Denmark's legislation for water course restoration—Nielsen, 1996).

The Ecological Society of America (ESA) Committee on the Scientific Basis for Ecosystem Management outlines the components/concepts to implement "Ecosystem Management", which they define as management driven by explicit goals, executed by policies, protocols, and practices, and made adaptable by monitoring and research based on the best understanding of the ecological interactions and processes necessary to sustain ecosystem structure and function (Christensen *et al.*, 1996):

1. Intergenerational sustainability of ecosystem function.
2. Clearly defined and operational management goals.
3. Management based on the best available science and models.
4. Recognition of the complexity and interconnections of ecological systems.
5. Recognition that ecosystems are constantly changing.
6. Acknowledging that ecosystem processes operate at multiple temporal and spatial scales that transcend management scales.
7. The need to consider humans as integral parts of ecosystems.
8. Adaptability and accountability in management.

A key aspect is that "sustainability" is applied not to specific goods or services that ecosystems provide, but rather to the capacity of ecological processes and structures that produce these goods and services (Christensen *et al.*, 1996; WRI, 2000).

In the following section concepts, management measures, contributions from this symposium, and lessons learned are discussed in terms of improvements of physical habitat structures and restoration of flow regimes.

APPLICATION OF AN ECO-GEOMORPHIC APPROACH

Concepts

1. *Physical habitats and processes continue to be lost or degraded.* There is no question that there is a worldwide need to conserve and improve aquatic habitats (Revenga *et al.*, 2000). For example, in the United States Kauffman *et al.* (1997) note the most important factor contributing to the decline of aquatic biodiversity is the loss or degradation of habitats. Impacts are related to a broad range of activities from the watershed scale (e.g. deforestation); to the river segment scale (e.g. flow regulation); to the reach scale (e.g. river training works); down to the local scale (e.g. removal of large woody debris).
2. *Restoration of water quality, physical habitat structures and abiotic processes is a prerequisite for re-establishment of biodiversity* (NRC, 1992, 1996). The structure, operation and other aspects of the organization and development of stream communities are largely determined by the organization, structure, and processes of the physical stream habitat (e.g. Frissell *et al.*, 1986) together with the pool of species available for colonization (Wevers & Warren, 1986).
3. *Realistic goals and objectives are required.* The goal of ecosystem management must be intergenerational sustainability (Christensen *et al.*, 1996), but objectives are conditioned by political, scientific, and economic realities (Graf, 1996), which often differ significantly from natural or reference conditions. This frequently precludes restoration (Duel *et al.*, 1996), but there are a number of options for improvements:
   Enhancement: "any improvement of a structural or functional attribute" (NRC, 1992), but the endpoint of that improvement is not to resemble the original state.
   Rehabilitation: "… improvements of a visual nature to a natural resource; putting back into good condition or working order." (NRC, 1992). The direction of change is toward the original state.
   Restoration: "return of an ecosystem to a close approximation of its condition prior to disturbance … ensuring that ecosystem structure and function are recreated or repaired, and that natural dynamic ecosystem processes are operating effectively again." (NRC, 1992).
4. *River corridor improvements are usually based on physical templates* (e.g. Petersen *et al.*, 1992), *and processes* (e.g. Walker *et al.*, 1995). Structures and processes can be compared with similar reference reaches (e.g. Kondolf & Downs, 1996; Rosgen, 1996; Florentin *et al.*, 1997).

5. *Structural habitat improvements and restoration of flow regimes are necessary but not necessarily sufficient to restore particular species, because external factors may be equally, or even more, important* (e.g. climate and ocean conditions for salmon—Beamish, 1993; Rothschild, 1995; Anderson, 1998).

Management measures

River enhancement projects often use instream structures to enhance aspects of the habitat for selected river reaches. For example, Miles (1998) describes the performance of spurs, boulders, boulder groups, weirs, and woody debris, to mitigate the effects of highway construction along the Coquihalla and Coldstream rivers in British Columbia.

Ideally, a restoration project (and the direction of change for rehabilitation projects) aims to achieve five objectives, by restoring or reintroducing the:

1. natural range of water quality;
2. natural streamflow and sediment regimes;
3. natural river corridor morphology;
4. natural river corridor plant communities; and
5. aquatic and terrestrial animals.

In many cases, only the first few steps are required. Larsen (1994) for example, describes the selective removal of stopbanks and bank protection, re-establishment of old river channels and islands, and construction of drop structures to control erosion of diversion channels, in the rehabilitation of 160 km of the Danube River. The objective was not to restore the original state but rather construct several of the more important features of the original state, recognizing fundamental changes to the sediment and flow regimes. In the Kissimmee River system in Florida, the initial objective was to restore the rivers historic geomorphic and hydrological characteristics. Toth (1996) describes restoration of ~100 km of river–flood plain ecosystem, including 70 km of river channel and 11 000 ha of wetlands.

In terms of flow and sediment regimes, the terms "enhancement", "rehabilitation", and "restoration" equate with the concept of "minimum flow", "instream flow", and "environmental flow" (cf. Dunbar & Acreman, 2001, who use the latter terms interchangeably). Minimum flows are often a subjectively determined water level or flow, retained for the purpose of survival of a particular fish species. Instream flows are an objective balance of the flow regime needs of in-channel uses (e.g. fish and water sports) and off-channel uses (e.g. irrigation). Environmental flows provide a flow regime for the river corridor (i.e. the channel itself as well as the flood plain, and the transitional upland fringe) and receiving waters (e.g. lake, coastal zone), for the purpose of maintaining ecosystem structure (e.g. wetlands, oxbow lakes) and processes (e.g. nutrient cycling; sediment flux) in their own right.

In the river corridor flow regimes are required to maintain lateral (riverine–riparian–flood plain), longitudinal (headwater–riverine–estuary) and vertical (riverine–groundwater) processes (e.g. nutrient dynamics and energy flow) (Vannote *et al.*, 1980; Junk *et al.*, 1989; Ward & Stanford, 1989, 1995). In this regard, Hill *et al.* (1991) argue that multiple flow regimes are needed to maintain biotic and abiotic resources: (a) flood flows that form flood plain and valley features; (b) overbank flows that maintain surrounding riparian habitats, adjacent upland habitats, water tables, and soil saturation zones; (c) in-channel flows that keep immediate stream banks and channels functioning; and (d) in-channel flows that meet critical fish requirements. Hill *et al*. (1991) add there is a need to determine how altered streamflows affect channels, transport sediments, and influence vegetation.

Downstream effects must be explicitly considered. For example, flow manipulations can modify water quality in deltas, estuaries and adjacent wetlands (e.g. salt wedge position, California Water Plan 1994; Abam, 2001), and can limit fish passage (e.g. river mouth closure—McDowall, 1992), and habitat availability (e.g. Oyebande, 2001); and can significantly modify productivity (Yin *et al.*, 1997), morphology and hydrodynamics of the coastal zone (Kirk, 1991; Abam, 2001).

Contributions from this symposium

In this symposium a range of issues related to habitat description, habitat improvement, and flow regime alteration, are described at a number of scales. Improvements have focused on enhancing highly modified rivers (e.g. removing sections of bed and bank protection in concrete lined channels—Kurashige, 2002), rehabilitating structural elements (e.g. placement of large woody debris—Hughes & Thoms, 2002), or restoring structure by restoring processes (e.g. breaching levees to create splay deposits and flood plain complexity—Mount *et al*., 2002; restoring flow regimes—Thoms & Parsons, 2002).

Highly engineered rivers constructed for optimum flood and erosion protection control have few redeeming aesthetic or ecological features. Kurashige (2002) examined changes following habitat improvement measures in a concrete-lined reach of the Pankenai River, Japan. Concrete was removed to expose the soft mudstone bed in mid channel, drop structures were installed, and a meander pattern was constructed by narrowing the channel. Concrete was retained on the banks. Seven months after the channel enhancement, a pool–riffle sequence developed, the channel continued to evolve, and fish-species diversity increased. In other studies, highly modified rivers have been improved for aesthetic reasons, with little consideration to ecology (e.g. Brookes, 1995, cited in Brookes & Sear, 1996). The positive biological response of the Pankenai River case study is encouraging.

Creation of low sinuosity single channel rivers through lowland flood plains has provided significant benefits (e.g. supporting agriculture, navigation and flood control), but at the expense of the processes and functions of the natural flood plain (e.g. Alexander & Mariott, 1999). Mount *et al*. (2002) describe deliberate large-scale levee breaching on the Cosumnes River of central California to rehabilitate flood plains by re-establishing the hydraulic connectivity and promoting the erosion and deposition processes that create and sustain flood plain and wetland ecosystems. Field studies indicate that flows through the breaches are broadly mimicking historical processes associated with avulsion and crevasse splay formation. Large woody debris transported through the levee breaches is accumulating in the sand splay complex and increasing topographic complexity by creating localized scour. These controlled levee breaches have successfully rehabilitated key habitats with development of patches of typical riparian forests—willows and cottonwoods. Native species, including Chinook salmon, utilize the flood plain for spawning and rearing, and seasonally flooded habitats support as many as 22 species of native and exotic fish. Also, downstream flood flows are attenuated (Florsheim & Mount, 2002). This study demonstrates that by restoring processes, complex bio-physical landscapes can be restored to significant ecological benefit.

Snags and large woody debris (LWD) are the sticks, branches, trunks and whole trees that fall into rivers and become lodged in the bed or banks. Removal of downed trees from the river bed was undertaken to develop and maintain navigation channels, to mitigate flood levels and bank erosion, and to remove obstacles to fish passage (Sedell *et al.*, 1990). However, the reduction in delivery, or removal, of large woody debris from channels has significant adverse effects in North American streams (e.g. Hicks *et al.*, 1991; NRC, 1996). Hughes & Thoms (2002) point out the ecological importance of large woody debris (LWD) in rivers in Australia, and discuss the influence of LWD on channel form. Over a 95-km reach of the lowland River Murray, Australia, LWD was greatly under-represented in straight sections of channel, and the limited debris present was distributed relatively evenly across the channel. Large woody debris was mainly associated with eroding bends. Distribution patterns at the sub reach scale (0.5–1.5 km) suggest that LWD is mainly recruited by bank erosion and falls into the river perpendicular to the flow. It subsequently remains close to where it falls and is realigned rather than actively moved by the river. For the very low gradient ($<0.000\ 17\ \mathrm{m\,km^{-1}}$) lowland River Murray the association of LWD with higher velocity zones in eroding bends suggests the debris is relatively immobile. In headwater streams in North America LWD has a dominating structural role (Beechie & Sibley, 1997); and in mid-sized streams large wood was important in debris-scour pool formation (Bilby & Ward, 1989). Debris scour pools are also developed in high-energy gravel–cobble–boulder rivers in New Zealand. In contrast, Piegay (1993) and Piegay & Gurnell (1997) found that in relatively high-energy European upland rivers (slopes typically >0.005) LWD was predominantly located in depositional sites and hence thought to be highly mobile.

The research of Hughes & Thoms (2002) has important implications for the re-introduction of LWD as a river management tool, particularly for large, low gradient rivers. Results suggest that in lowland rivers similar to the Murray, large woody debris reintroduction needs to be managed at the scale of individual meander bends.

In channel and bank edge vegetation plays a significant morphological, water quality and ecological role (Wade, 1994; Newall, 1995; Harper *et al.*, 1995). The removal of vegetation ("weeds") causes significant adverse effects (e.g. Penczak, 1995; Monahan & Caffrey, 1996), but is routinely undertaken in channel maintenance. While there are examples of the benefits of retaining different patterns and types of channel and bank vegetation in streams (e.g. Purseglove, 1988; DEPA, 1995), there is little information on the hydraulic and sediment effects. However, the problem is complex. Plant form varies enormously and attempts have been made to analyse, both physically and theoretically, the simpler types (e.g. vertical stems), and the flow-transition stages through which they pass (citation in Pitlo & Dawson, 1990). James *et al*. (2002) describe flow–sediment–vegetation interactions in a flume-based study. Their investigations show that conventional sediment dynamics modelling approaches are not well suited to accounting for vegetation interactions, and new approaches are being developed. These advances will be required to predict more complex situations where plants vary in size, shape and flexibility, and their response varies with the location and extent of plants, plant density and season, and water depth and velocity.

In planning the restoration of channel structures an adequate understanding of channel geometry at the reach scale is needed and this must be in the context of catchment influences. This must account for actual conditions at the restoration site, as opposed to generic approaches based on presumed attributes of the channel (Kondolf, 1998). Factors to be considered include changes in channel form, hydraulics, and sediment flux. Young *et al.* (2002) used topographic data and hydrological regionalizations to develop statistical models of channel type groupings, median bed surface grain size, and the occurrence of sand slugs in rivers in the 30 000 km^2 Murrumbidgee River. The pre- and post-disturbance stream condition was modelled across the river network and reaches that are currently degraded by sand deposition that are candidates for restoration were identified.

Kondolf & Downs (1996) note that geomorphologically-based channel classification schemes (e.g. Rosgen, 1996, in western North America) have been used as a means to incorporate geomorphological information and, ultimately, to communicate reach-specific information to restoration design. However, habitat-unit-based approaches to restoration must be used with caution because of uncertainty related to indeterminate hydraulics (i.e. width, depth etc. can adjust in a variety of ways to imposed changes in flow and sediment load—Maddock, 1970), and the fact that a given channel form may be the result of different channel process histories (equifinality). It is not always possible to infer correctly the causes of a given channel conditions from its morphological expression alone (Kondolf & Downs, 1996). For example, are increased flows from deforestation causing channel degradation, or is channel erosion accelerated by removal of riparian vegetation? Rehabilitation must address the underlying causes to succeed.

Fine sediment is as an important element of stream condition (e.g. Harper *et al.*, 1995). Vogt & Symader (2002) examine the role of the structure of the river bed in controlling the composition of macro benthos as an indicator of the health of small rivers in southwest Germany. Substrate composition, water quality, and diversity and abundance of macro benthos in all habitats were measured at numerous sites. Differences in biological integrity were identified at the land-use scale, and between substrate classes within habitat types. It was found that sampling only the habitats dominated by fine material underestimates the biological quality of a river. In areas of good water quality, river beds with large amounts of fine sediment have poor biological index scores. Sources of contamination were differentiated and identified, which is an important step in planning remediation (e.g. rehabilitating a riparian buffer to control sediment flux from agricultural areas into streams). Thus, Vogt & Symader (2002) seek to remedy the underlying cause of habitat degradation.

Knowledge of important features to use to typify habitats in terms of refuge availability (and thus susceptibility to disturbance) of primary producers and secondary producers is still in its infancy (Biggs *et al.*, 2001). Franks *et al.* (2002) describe the spatial and temporal variability of hydraulic parameters and the distribution of macroinvertebrates and substrate at the Wood and Burleigh Brook confluence, east Midlands, UK. They report that with the exception of the shear zone, hydraulics for each flow zone did not significantly change from low to medium flows. Substrate was more important in determining macroinvertebrate composition than hydraulics. Recent research in New Zealand also shows distinct faunal assemblages can be associated with different substrate types (Death, 2000); but other reviews suggests most benthic taxa are substrate generalists (Giller & Malmqvist, 1998). The lack of change in macroinvertebrates over the flow range examined has important implications for determining flow requirements for instream food production in streams.

Bartley & Rutherfurd (2002) recognize that adequate descriptions of habitat diversity are a prerequisite for predicting biodiversity of a stream. They use descriptive properties of the thalweg bed elevation to represent physical diversity and suggest that wiggliness, fractual dimension, and standard deviations of depths provide appropriate measures. They conclude that these tools can be used to assess if habitat diversity correlates with biological diversity, but this has to be demonstrated. It is unclear how single indices of habitat heterogeneity can explain spatial aspects of habitat use. For instance, flow fields are usually complex (e.g. Crowder & Diplas, 2000; Kondolf *et al.*, 2000; Franks *et al.*, 2002), and habitat utilization by fish is not well described by simple measures such as mean depth, mean water column velocity and some measure of substrate (e.g. Scott & Shirvell, 1987; Shirvell, 1989; Gordon *et al.*, 1992; Geist & Dauble, 1998; Freeman *et al.*, 1997). Fishermen are well aware that the juxtaposition of habitat features—such as shear zones and holding pockets—are important determinants of the locations of fish in streams. This has important implications for the development of habitat suitability indices (e.g. in PHABSIM modelling; Milhous, 1999).

Thoms & Parsons (2002) use the example of environmental flows to demonstrate the utility of an eco-geomorphological approach for identification of characteristic scales of hydrological, geomorphological and ecological influences in the Condamine–Balonne River, Queensland. They also discuss problems of integrating science, and developing appropriate biological indicators in spatially and temporally complex river systems. The central thrust of this paper is identical to this overview paper—an ecosystem perspective approach is required, and this requires paradigm shifts in thinking, science, and management.

Recent work has indicated that fine suspended particulate organic matter (FSPOM) is the most important form of carbon for riverine aquatic food webs (Thorp *et al.*, 1998). Olley (2002) uses stable carbon isotope and C/N ratios to distinguish the sources of carbon to the FSPOM in the Murrumbidgee River, Australia. The proportion of organic matter derived from catchment soils, catchment vegetation and in-channel primary production varied along the 1000-km length of main channel. Olley (2002) found catchment soil sources dominate during flood events. During non-flood periods riparian vegetation and catchment soil sources in the tributary catchments were important in the upper reaches of the main channel. As this material metabolizes and enters the dissolved phase downstream, in-channel primary producers incorporate this material back into the FSPOM. There are significant stores and delays in the system. In-channel primary producers are on average using terrestrial material photosynthesized from the atmosphere 40–50 years ago. Olley's (2002) findings suggest it may be decades before the full implications of land-use change are experienced in downstream aquatic food webs. Further, it may be decades before the full benefits of watershed and riparian vegetation restoration are experienced.

McGinness *et al.* (2002) discuss the implications of fragmentation of riverine and flood plain habitats on carbon, which is an important food source and forms the base of the food web in the Macintyre River—a large flood plain river in the headwaters of the Barwon–Darling River system, Australia. Dissolved organic carbon budgets were calculated for "natural" and "current" flow scenarios, which provides an insight into the potential impact of water resource development upon flood plain river connections and the exchanges that they facilitate.

The importance of river corridor morphology and position in the catchment are illustrated by the contrast in the significance of flood plain sources of carbon discussed by Olley (2002) and McGinness *et al*. (2002). Olley (2002) revealed the importance of in-channel carbon cycling of terrestrial organic matter and in-channel primary production. Olley (2002) suggested that the lowland flood plain is not a significant source of carbon and illustrates the importance of longitudinal processing of carbon. McGinness *et al*. (2002) found anabranch channels contained significant pools of carbon in comparison to the main river channel in the lower Macintyre River. Dissolved organic carbon and phytoplankton concentrations in the anabranch billabongs were particularly high, and may be concentrated sources of labile food energy when flushed into the river.

The work of McGinness *et al*. (2002), Olley (2002), and Thoms & Parsons (2002) (and associated work such as Walker *et al*., 1995; and Thoms & Sheldon, 2002) are exemplars of the approach required to develop environmental flow objectives. In their own right they are excellent research, but are not isolated fragments of excellence—rather they are part of a much "bigger picture" approach to the development of science, river restoration, and integrated watershed management.

Black *et al*. (2002) describe a protocol for the assessment of anthropogenic impacts of hydrological regime changes on Scotland's rivers, lakes, and their riparian zones. The protocol builds on the indicators of hydrologic alteration (IHA) methodology (Richter *et al*., 1996) in which the degrees of alteration of a range of hydrological variables, that are thought to be significant to biota, are estimated. This new initiative is required to comply with the European Water Framework Directive which aims to limit anthropogenic impacts to a level insufficient to cause significant loss of ecological quality (measured primarily in terms of the species complement of aquatic communities). A major challenge for this research will be the calibration of these flow regimes in terms of ecological impacts. For example, the authors report that macroinvertebrate and biotic indices of ecosystem health, such as RIVPACS, which is widely used in the UK, were insensitive to flow regime alteration, even for rivers with major flow alterations. This finding is not inconsistent with Franks *et al*. (2002) who report that with the exception of the shear zone, hydraulics for each flow zone at a confluence did not significantly change from low to medium flows. The need to integrate hydraulics is clearly evident, and Black *et al*. (2002) propose further research.

Bogen & Bønsnes (2002) illustrate how downstream fluvial systems can change as the result of flow manipulations. They evaluated the impact of changes in water level regimes since 1861 on the deltaic depositional processes of a Norwegian lake with high sediment transport rates. Decreased water level fluctuations created a large delta plain and lagoons, producing more favourable conditions for aquatic vegetation and fish. These results will be applied in the development of operational directives for the power stations. This work provides a good example of why downstream effects of flow manipulations must be explicitly considered, however they are rarely undertaken.

Lessons learned

A multi-level approach of enhancement, rehabilitation and restoration is often required to remedy degraded riverine ecosystems (based largely on Reeves *et al*., 1991; Frissell & Nawa, 1992; Beschta *et al*., 1996; Spence *et al*., 1996; Kauffman *et al.*, 1997; Day & Hudson, 2001):

1. Undertake a watershed assessment to identify critical habitats, and habitat bottlenecks.
2. Critical habitats should be protected (e.g. controlling livestock access to prevent trampling of spawning areas), and reconnected (e.g. resetting or removing culverts that block fish passage).
3. Loss of river corridor habitat diversity can be remedied with instream structures (e.g. large woody debris placement; boulder clusters) and structural changes (e.g. creating off-channel pools and backwaters; breaching levees), even in highly engineered systems.
4. Structural improvements often fail if watershed improvements are not undertaken simultaneously (e.g. control excessive sediment inputs). Structural improvements should be self-sustaining (e.g. a wetland replenished by groundwater inputs and periodic flooding rather than weirs and water pumping).
5. The ultimate objective is the restoration of processes at the reach and watershed scale. Restoration of processes can be undertaken quickly (e.g. levee breaching) or may be long term (e.g. growth of riparian forests to provide instream large woody debris through bank erosion).
6. However, it must be cautioned that ecological success does not automatically follow morphological success.

An ecosystem approach to flow regime management involves at least the following steps (expanding largely on Hill *et al*., 1991; Thoms & Sheldon, 2002):

1. Determine the physical nature of the entire riverine ecosystem, and receiving waters, at multiple scales (segments of similar discharge and sediment regimes; reaches; habitat structures and communities; and microhabitats).
2. Identify the significant ecological requirements and processes associated with the significant physical structures and flow characteristics (in-channel flow; riparian flows, flood plain and upland fringe forming flows; estuary flows; nearshore zone).
3. Identify the key hydrological and geomorphological drivers, and the implications of change (e.g. impoundments reducing flow and sediment) on physical habitat structure and processes.
4. Derive key management goals and objectives for each of the significant structures and processes for each segment of the river and receiving waters.
5. Evaluate and implement management options.
6. Critically evaluate outcomes and enhance the science, goals and policies.

These approaches can establish the context within which management decisions are taken and research agendas are set. The expert panel (e.g. Thoms & Swirepik, 1998) and building block methodologies (King & Louw, 1998; Arthington, 1998) provide implementation guidance.

CHALLENGES FOR ECOSYSTEM MANAGEMENT—ECO-GEOMORPHOLOGY

Habitat improvements and environmental flows, two central themes of eco-geomorphology, have a number of common challenges. Ten major challenges are briefly outlined. Each probably warrants a session in its own right. The objective here is to promote further discussion.

1. **An ecosystem perspective is required**: This entails a paradigm shift. Sustainability is applied not to specific goods or services that ecosystems provide, but rather to the capacity of ecological processes and structures that produce these goods and services (Christensen *et al*., 1996; WRI, 2001).
2. **Addressing organizational inertia**: There is often a fragmentation of science into disciplinary lines, even in recently established organizations that operate under an ecosystem management legislative framework (e.g. New Zealand—Day & Hudson, 2001). Multi jurisdictional, ecosystem management based approaches are required (e.g. interior Columbia River basin ecosystem management plan—Quigley & Arbelbide, 1997).
3. **Establish management direction and accountability**: Christensen *et al.* (1996) suggest it must be recognized that current knowledge and paradigms of ecosystem function are provisional, incomplete, and subject to change; that the system itself is variable in time and space; and system, management and political time frames are invariably different. Management objectives and expectations must be explicitly stated and based on the best available knowledge; management approaches must be viewed as hypotheses to be tested by research and monitoring; management must also be able to adapt to new information and understanding; and public understanding and involvement are required.
4. **Uncertainties do not justify inaction**: Fluvial ecosystems are extremely complex. There will probably always be uncertainty in predicting river channel form and processes, and these uncertainties are compounded when predicting biological interactions that are only partially dependent on fluvial forms and processes. Consequently, it will not be possible to predict with certainty river channel or biological responses to specific alterations. However, there is a foundation for action. We are reasonably certain that fluvial geomorphic processes are critical in sustaining ecosystem structure and function; we have a reasonable understanding of the circumstances under which systems fail; and we have a conceptual and scientific underpinning, and case studies, upon which to base improvements.
5. **Uncertainty demands an adaptive management approach**: Adaptive management has two essential attributes: (i) it is a response to uncertainty about the system being managed, and (ii) actions are designed, at least in part, to provide new information about the system (Williams, 1998). To make informed decisions, managers require measures of confidence on scientific recommendations (e.g. flow regimes). They need to accept the existence of uncertainty and make decisions that will both protect resources and allow development of knowledge that will reduce the uncertainty (Castleberry *et al*., 1996). Comprehensive monitoring and assessment is required, and both success and failure of habitat improvements, and flow regime recommendations, must be reported, in order to learn and provide better advice to managers.

6. **Science and management must be integrated**: There is a need to integrate existing scientific knowledge into the decision-making process, for scientists to focus research on management questions, for scientists to participate in the policy-management arena, and for scientists to engage the public (Cullen, 1990; Cullen *et al.*, 1996; Christensen *et al.*, 1996; Day & Hudson, 2001; Link, 2002a,b).
7. **Setting realistic goals and objectives**: The goal of ecosystem management must be intergenerational sustainability (Christensen *et al.*, 1996), but objectives are conditioned by perceptual, political, scientific, and economic realities (Duel *et al.*, 1996; Graf, 1996). Pragmatic approaches, underpinned by an ecosystem perspective, are described by Graf (1996) for flow regimes below impoundments, and NRC (1992, 1996), Brookes & Shields (1996), FISRWG (1998), and Rutherfurd *et al.* (2000) for physical habitat improvements.
8. **A gradation of research needs exist**: Link (2002a,b) proposes that for fishery management a gradation of research needs exists, ranging from single species research (e.g. demographics, density-dependent effects, stock–recruitment relations) to ecosystem approaches (e.g. effects of predation, competition, environmental regime shifts, and habitat alteration on population dynamics, abundance, and community composition). I suggest that a gradation of research needs also exists for geomorphology. Examples are given for a few points along this gradation.
   (a) *Disciplinary science is still required*: Link (2002b) notes that despite notable advancement of technologies, methodologies, and theory over the past 150 years, many basic ecological questions remain. One end of the ecological research gradient is single species research. Schrader-Frechette & McCoy (1994) suggest (and Jewitt *et al.*, 2001; and Link, 2002b, concur), that it might be more pressing and achievable to apply practical and precise knowledge of particular species than to attempt complex ecosystem modelling for fisheries management. For example, Willson (1997) discusses the relevance of evolutionary processes to harvest management of salmonids. Hicks & Reeves (1994) discuss "bottlenecks" for fish and note the success of any habitat improvement is dependent to a large extent on the identification of the factor or factors that currently limit fish production. In terms of geomorphology, ecological disturbance research is highly dependent on prediction of flow fields (e.g. Crowder & Diplas, 2000; Waddle *et al.*, 2000) and motion of the bed (e.g. Laronne *et al.*, 2001). These works have significant research and management implications, but developments are from single discipline science.
   (b) *There is a need for additive integration*: Additive integration (Thoms & Parsons, 2002) is required in many areas. For example, MacDonald *et al.* (1991) and Kondolf, (2000) note that numerous researchers have shown that streambed gravels can limit spawning success of salmonids, but there are problems in determining the quality of the substrate because of inconsistencies in how the bed material is sampled, and how the samples are classed, and described. Kondolf (2000) notes that although many of the fundamental questions are essentially sedimentological and geomorphological, these disciplines have not been involved in many spawning gravel assessment; instead such assessments are typically conducted by biologists. Kondolf

(2000) cogently argues that grain-size distributions are better indicators for determining the quality of gravel spawning. There are different requirements for redd construction (limited by maximum movable size), incubation (limited by permeability, hence very fine interstitial sediment), and emergence (alevins live in the gravel and require connected intergravel pore spaces, which is limited by coarser interstitial sediment). By reviewing the fisheries literature, and applying size distribution data within this life stage perspective, Kondolf, a geomorphologists was able to unify disparate laboratory and field survey data of spawning success.

(c) *There is a need to merge disciplinary research*: For example, disturbance regimes are a major topic of biological research (e.g. Biggs *et al.*, 2001, refugia for macroinvertebrates; Power, 2001, on trophic dynamics; and De Vries, 1997, on salmonid egg survival). In a direct geomorphological contribution to disturbance ecology, Lapointe *et al.* (2000) developed empirical models to quantify the probability of salmonid egg pocket scour and fill during floods. They could predict how the expected losses vary with flood strength and reach characteristics. Similarly the work of Laronne *et al.* (2001) on the mobility of sediment patches in gravel bed rivers is directly applicable to disturbance ecology, which underlies flow regime requirements. More sophisticated hydraulic–geomorphic models are required to describe river channel dynamics at scales and with metrics appropriate to ecological needs for in-channel and environmental flows (e.g. Bult *et al.*, 1998; Railsback, 1999; Crowder & Diplas, 2001).

(d) *Interdisciplinary science is required*: A broad range of expertise is required to implement an ecosystem approach, including biology, chemistry, ecology, geomorphology, hydrology, and hydraulics; and social science and economics. However, work done under the rubric of "interdisciplinary teams" often provides nothing more than simultaneous mono-disciplinary work that deteriorates into nothing more than loosely related disciplinary studies without functional connection (citations in Jewitt *et al.*, 2001). In some cases integrated research is demanded by funding agencies, and is becoming a requirement for disciplinary survival, but there are perceptual, social, and institutional constraints on this integration (Bauer, 1996).

(e) *Major advances have been made in integrated research projects, at various time and space scales*: For example, Anderson (1998) reviews the role of oceanic and climatic fluctuations on the natural variation of the North Pacific ecosystem, and discusses natural and anthropogenic interactions and the implications to salmon management and hydro operations. Spence *et al.* (1996) and Quigley & Arbelbide (1997) take an ecosystem approach to the management of lands and waters of the Pacific Northwest and northern California. In the Sabie River, South Africa, innovative methods and techniques were explored to generate an integrated suite of models to estimate the responses of fish and riparian vegetation to changing hydrology, sedimentation and geomorphology (Jewitt *et al.*, 2001).

9. **Research designs and analytical options require a rethink and upgrading**: Lack of control, insufficient replication, and unplanned treatments are not

necessarily insurmountable. A broad mix of appropriate research approaches and analytical tools is required (e.g. Richards, 1996; Michener, 1997). Some new approaches are described in this session (e.g. Bartley & Rutherfurd, 2002; Black *et al*., 2002; Thoms & Parsons, 2002) and others in the new techniques session of this symposium (and this volume).

10. **The paradigm shift to an ecosystem perspectives requires better conceptual and analytical models**: A significant shift in conceptual models is required to implement ecosystem management. A large number of case studies are testament to this shift gaining momentum in physical habitat structural improvements. The research of Mount *et al*. (2002) in restoring processes to reconstruct bio-physical features is notable. However, there are few examples of linking "eco" and geomorphology with respect to flow regimes in river corridors. I contend that there is a paradigm shift between single species instream flow assessments for the purpose of setting a minimum in-stream, and environmental flow assessments. The research of Olley (2002), McGinness *et al*. (2002), and Thoms & Parsons (2002) are notable examples of an eco-geomorphological approach to environmental flow assessment.

    In-channel ("instream") flow allocations are very contentious, and the underlying models are questionable. Castleberry *et al*. (1996) concluded: "… there is now no scientifically defensible method for defining flow standards." They recommended abandonment, or at least significant modification and careful use, of PHABSIM, a widely used tool. Clearly, more sophisticated models are required to address in-channel flow needs (e.g. Guay *et al*. 2000; Waddle *et al*., 2000; Bartholow *et al*., 1993); and to support the conceptual leap to river corridor flows (e.g. Thoms & Sheldon, 2002).

    A major problem is the inherent difficulty of ever elucidating, particularly to the point of predicting, the multiple complex dynamics of ecosystems (Link, 2002b) at multiple scales (e.g. phytoplankton–nutrient cycling to fish passage from the river mouth to headwater spawning areas). Conceptual issues underlying development of new modelling approaches are discussed by Waide & Kennedy (1998). These issues are addressed in practical terms in the Sabie River, South Africa (Jewitt *et al*., 2001), and North America (Bartholow, 1998; Hardy & Addley, 2001).

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