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Review

Geomorphology within the interdisciplinary science of environmental flows

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ABSTRACT

The field tradition in geomorphology informs beyond studying landforms by also providing a stage for understanding how geomorphic elements influence the ecology of biota. The intersection between fluvial geomorphology and riverine ecology represents an ideal confluence to examine the contribution of the geomorphic field tradition to environmental flows, and show this area of riverine management as a research frontier for applied geomorphology. *Environmental flows* have consisted of a set of ecological-based stream flow guidelines designed to inform sustainable water resource management that supports healthy riverine habitats and provides sufficient water supply for society. Geomorphological understanding is central to environmental flows because it is the interaction between flow, form, and substrate that influences habitat type, condition, availability and biotic use across space and time. This relationship varies longitudinally, laterally, vertically, overtime, and across macro- to mesoscale morphologies within the riverine environment. The geomorphic template is, therefore, as integral as the flow. We reviewed studies where field evidence indicated that geomorphology impacts the effectiveness of environmental flow strategies and we make the case for the need to increase geomorphic considerations in environmental flows. Although flow is commonly referred to as the master variable in environmental flows, geomorphology mediates the effects of flow regime on ecological processes. Concepts and applications from this perspective on the role of geomorphology in riverine ecosystem research will inform the practice, policy, and implementation of environmental flows.

1. Introduction

The geomorphology, hydrology, and ecology of river systems interact through complex processes occurring across a range of spatial and temporal scales. The interface among these processes and the desire to manage river systems for natural and human benefit attract researchers from many disciplines. Several professional meetings have focused on the interdisciplinary advancement of river system sciences (cf. Table 1), including two previous Binghamton geomorphology symposia. Collectively, these meetings have increased engagement in collaborative, interdisciplinary studies of rivers and deepened our understanding of the structural and functional interactions that influence the physical, ecological, and chemical dynamics of riverine ecosystems. In the context of the 2012 Binghamton geomorphology symposium on *The Field Tradition in Geomorphology*, we examined the contributions of field geomorphology to the interdisciplinary river science of environmental flows; and we present this area of applied science as a research frontier for geomorphology.

Managing ecological water allocations — including the quantity, timing, frequency, duration, and quality of river flows for freshwater ecosystems, herein referred to as environmental flows — are increasingly being required to sustain an agreed-upon level of ecological condition for riverine biota and provide sufficient water supply for societal needs (Petts, 1996; Tharme, 2003; Newson and Large, 2006; Richter et al., 2006; Poff et al., 2010). Flow regulation downstream of dams and water withdrawals and returns are primary sources of flow alteration and are direct means to control or influence stream flows. This is precisely where environmental flow management can be used as a soft engineering tool to prevent further riverine degradation, protect extant resources, and/or restore ecological function. Geomorphology occupies a key realm in this arena because it is the process-based interactions among river flow, sediment, morphology, and organic materials that influence the ecological condition of habitat type, quality, and availability for biotic use across space and time (Poff and Ward, 1990; Thoms and Parsons, 2002; Jacobson and Galat, 2006; Tracy-Smith et al., 2012).

Habitat by default is interdisciplinary and assumes a combination of physical and biological components (Odum, 1971). Important physical factors include planform and channel-bed macro- and micromorphology features, substratum, hydraulics (velocity, depth), and thermal gradients (Poff and Ward, 1990). Important biological factors include the species behavioral, physiological, and life history characteristics for survival and reproduction strategies and also specific responses or adaptations to physical disturbances or environmental gradients (Poff and Ward, 1990; Lytle and Poff, 2004). The interplay between how these factors influence riverine habitat structure and function for a given species, population, or community is highly complex and variable across space and

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Table 1
Summary of professional meetings on the integration of physical and biological elements of riverine ecosystems.

Year	Meeting	Description, goals, or objectives, of symposium	Journal, year	Organizers
1987	Invited Symposium on: "Community structure and function in temperate and tropical streams", Hosted by Flathead Lake Biological Station of the University of Montana Foundation	Meeting of forty-eight scientists from 13 countries sponsored by the Ecology Program of the U.S. National Science Foundation (NSF)	Journal of North American Benthological Society, 1988:7	Stanford J.A. and A.P. Covich
1993	Third International Geomorphology Conference, Master University, Hamilton, Ontario, Canada	Addressed research topics at the interface between fluvial geomorphology and vegetation	Geomorphology, 1995: 13 (4)	Osterkamp, W.R., and C.R. Hupp
1995	Binghamton Geomorphology Symposium: Biogeomorphology, Terrestrial and Freshwater Systems	Examine relationships between biota and geomorphic form and process	Geomorphology, 1995: 13 (1–4)	Hupp, C.R., W.R. Osterkamp and A.D. Howard
2001	First International Symposium on Riverine Landscapes, Switzerland	Synthesized the present understanding of riverine landscapes from the perspectives of different disciplines.	Freshwater Biology, 2002: 47	Tockner, K., J.V. Ward, P.J. Edwards, and J. Kollman
2002	Joint Meeting on Environmental Flows for River Systems and 4th International Ecohydraulics Symposium, Cape Town, South Africa	Demonstrated progress on advancing research on the assessment and implementation of environmental flows	River Research and Applications, 2003: 5–6	Petts, G.E.
2002	The Structure, Function, and Management Implications of Fluvial Sedimentary Systems, International Symposium, Alice Springs, Australia	Discuss management objectives for sustaining riverine ecosystems focus on spatial and temporal variability, ecogeomorphology, floodplain ecological processes, and techniques	IAHS Publication, 2002, No. 276. 484 pp.	Dyer, F.J., M.C. Thoms, J.M. Colley
2003	Ninth International Symposium on River Research and Applications:"The Nature Causes, Consequences, of Variability in Riverine Ecosystems", Albury, Australia	Addressed concepts of variability in the structure and function of riverine ecosystem and incorporating variability into the management and restoration of riverine ecosystems.	River Research and Applications, 2006: 22	Thorp, J.H., M.C. Thoms, M.D. Delong
2005	Binghamton Geomorphology Symposium: Geomorphology and Ecosystems	Examined current status of disciplines, difficulty in bridging the disciplines, and emerging research priorities	Geomorphology, 2007: 89 (1–2)	Renschler, C.S., M. W. Doyle, and M.C. Thoms
2008	American Geophysical Union Special Session: Multiscalar Feedbacks in Ecogeomorphology	Elucidated interdisciplinary research that shows clear physical-biological feedbacks	Geomorphology, 2010: 126	Wheaton, J.M., C. Gibbons, J. Wainwright, L. Larsen, B. Elroy
2008	Integrating Science into the Restoration and Management of Floodplain Ecosystems of the Southeast	Evaluate current management and restoration practices for supporting sustainability of southeastern floodplain ecosystems.	Wetlands, 2009: 29 (2)	King, S.L., R.R. Sharitz, J.W. Groniger, and L.L. Battaglia
2010	Meeting of Young Researchers in Earth Sciences (MYRES): Dynamic interactions of life and it's landscape	Examined research at the interface of biology and geomorphology: co-evolution of landforms and biological communities, and humans as modifiers of the landscape.	Earth Surface Processes and Landforms, 2010:35	Reinhardt, L., D. Jerolmack, B.J. Cardinale, V. Vanacker, and J. Wright
2007–2010	Special Issue in Freshwater Biology which includes resources from the Brisbane International Environmental Flows Conference (2007) and the Third International Symposium on Riverine Landscapes (2007)	Presented new analytical and modeling approaches to support hydroecological models and environmental flow standards at multiple scales and all rivers, to achieve water-related goals of the Millennium Ecosystem Assessment	Freshwater Biology, 2010: 55	Arthington, A.H., R.J. Naiman, M.E. McClain, and C. Nilsson

time (Poff and Ward, 1990; Poff et al., 1997; Newson and Newson, 2000; Fausch et al., 2002; Thorp et al., 2008).

The integration of bio-eco-geo-hydro focused research has emerged over the last few decades in response to growing popularity of interdisciplinary studies. Biogeomorphology (Viles, 1988; Hupp et al., 1995; Naylor et al., 2002; Stallins, 2006; Francis et al., 2009; Stine and Butler, 2012) and ecogeomorphology/ecomorphology (Frothingham et al., 2002; Thoms and Parsons, 2002; Parsons et al., 2003; Fisher et al., 2007; Murray et al., 2008) are the terms most widely used for describing the study of *bidirectional influences of geomorphic and biologic processes* on each other. Other common interdisciplinary riverine-related terms include ecohydrology, hydroecology (Baird and Wilby, 1999; Kundzewicz, 2002; Hannah et al., 2004) and hydrogeomorphology (Sidle and Onda, 2004; Wheaton et al., 2011); however, the former two lack a geomorphic element, whereas the latter lacks a distinct biological inference. Clarke et al. (2003) and Vaughan et al. (2009) suggested the development of an ecohydromorphology field of river sciences which is defined as 'the interactions of the biological entities and ecological processes of a river with the hydrological and geomorphological forms and dynamics'. Ecohydromorphology includes processes and causal mechanisms, spatial structure of the riverine landscape, and variability of spatial and temporal scales. Ecohydromorphology is the most inclusive of all the integrated terms and as such, we use it throughout this review when referring to interdisciplinary-based riverine ecosystem processes.

The process for determining environmental flows requires input from many specialists including hydrologists, geomorphologists, biologists, and ecologists; as well economists, social scientists, and lawyers. Geomorphologists' greatest strength within this collaboration is their ability to address the complex questions surrounding flow, sediment, and morpho-dynamics — a task which is fundamental to the field tradition in geomorphology. The classic studies by Wolman and Miller (1960) and Leopold and Wolman (1960) provide context for large-scale sediment dynamics and planform channel patterns, which more recent studies have detailed as drivers of morphological complexity capable of creating habitats for a variety of riverine biota (Rhoads et al., 2003; Jacobson and Galat, 2008; Pritchett and Pyron, 2011). Contributions such as these can only be realized by deliberate engagement in interdisciplinary applied riverine management situations. As Graf (1996) argued, geomorphologists have a responsibility to extend themselves beyond basic research and apply their knowledge to environmental resource management, public policy, and social issues. However, the involvement of geomorphologists in environmental flow management has (to date) been limited, with exceptions (Gippel and Stewardson, 1998; Schmidt et al., 2001; Graf et al., 2002; Thoms and Sheldon, 2002; Jacobson and Galat, 2006, 2008; Newson and Large, 2006; NRC, 2008). In support with Graf (1996), we encourage more field-oriented fluvial geomorphologists to become involved with environmental flow assessments to ensure that geomorphic considerations are adequately accounted for in policy and implementation.

In this review we illustrate how geomorphology influences the biota or riverine ecosystems at a range of scales; and show geomorphology to be as integral as hydrology for maintaining ecological function and

biodiversity. We cover a discussion of the natural flow regime concept and its significance from a geomorphic perspective, the importance of communicating ecohydromorphic interactions across disciplines and scales, and a summary of empirical examples where geomorphic field observations are pertinent to environmental flow assessments.

2. The "*natural flow regime*" in context

Hydrologic-based management objectives have dominated environmental flow assessments, and most can be classified into four positions: (i) managing flows relative to low or minimum flow standards (see review in Tharme, 2003); (ii) establishing presumptive standards for minimizing flow alterations (Richter, 2009; Richter et al., 2011); (iii) managing a range of flows defined relative to a historic, unaltered natural flow regime of a stream (Petts, 1996; Poff et al., 1997; Richter et al., 2006; Mathews and Richter, 2007); and (iv) managing a natural flow regime relative to basin wide variations defined by physiographic thresholds (Thoms and Sheldon, 2002; Parsons et al., 2003; Dephilip and Moberg, 2010). The third and fourth positions include elements of ecologically effective discharges, therefore, offering the greatest potential for managing relative to ecohydromorphic considerations (Doyle et al., 2005).

The natural flow regime concept advocates for managing for a natural dynamic character of a stream relative to a range of flow regime components, such as, magnitude, frequency, duration, timing, and rate of change (Poff et al., 1997). Various elements of the natural (pre-altered) flow regime, such as seasonal high and low flow pulses, support different ecological functions (longitudinal, vertical, and lateral connectivity and exchanges) and interannual flow variability and intraannual flow variability are necessary for maintaining the complex array of channel and floodplain processes that support physically and biologically diverse riverine ecosystems. Most biota adapt to patterns of natural flow variability such that the life-history, behavioral, or morphological forms derive from, and in some cases, depend on these conditions (Lytle and Poff, 2004). A natural flow regime ascribed to a river may only reflect flow patterns indicative of a snapshot in the systems complex geologic evolution, and as such, the significance of a given natural flow regime should be considered with special attention to biogeographic patterns and processes of species distributions in space and time. Natural flow regimes vary among river basins dependent on climatic and geomorphic/geologic constraints and different regional to global geographies will express different flow patterns (Poff et al., 2006).

Relatively unaltered flows (i.e., no major dam regulations) for the free-flowing Tar River, North Carolina, illustrate the inter- and intraannual flow variability characteristics of large rivers in the southeast U.S. (Fig. 1). In this region, seasonal flows are highest between the late fall and early spring and lowest through the summer months, except for occasional tropical storms and hurricanes. Periodic episodes of dry, normal, and wet years characterize the interannual variability. Bald cypress (*Taxodium distichum*) trees are an ideal example of the ecological adaptations of a species to this naturally variable flow regime. Bald cypress are bottomland hardwoods that depend on lateral migration and flood processes for the development of meander scroll and abandoned channels that serve as habitat (Shankman, 1993). The occurrence of winter flood pulses disperses the buoyant bald cypress seeds with an associated flux of sediment and nutrients to suitable swale and abandoned channel habitats (Schneider and Sharitz, 1988) and summer low flows enable germination and seedling survival (Schneider and Sharitz, 1986; Shankman, 1991). Regulated flows in this region typically reduce winter flood peaks and increase the magnitude of summer low flows (Pearsall et al., 2005; Richter et al., 2006; NPS, 2008; Conrads et al., 2009),which respectively limit fall–winter seed dispersal and flood late-summer seedlings. Sustainable management for this species requires consideration for the flow regime to which it has adapted for survival.

The natural flow regime concept introduced a new paradigm for river management globally, and was intended to move beyond managing water allocations for low or minimum flow standards. It proved challenging to implement, however, because ecosystem benefits are difficult to assess and quantify (Pearsall et al., 2005; Arthington et al., 2006; Jacobson and Galat, 2008; NPS, 2008; Ward and Meadows, 2009; Konrad et al., 2012). In the United States, adaptive natural flow management of the Savannah River has received substantial support and resources from stakeholders in academia, nonprofit, and government agencies. Yet after eight years of implementing prescribed natural flow releases, measurable ecosystem benefits are minimal (or have been difficult to detect) (Ward and Meadows, 2009; Konrad et al., 2012). Managed flows for the Savannah include experimental releases in the timing and magnitude of pulses to improve; (i) Shoals' Spider Lily (*Hymenocallis coronaria*) reproduction; (ii) fish, macroinvertebrate, seed, and carbon dispersal and exchanges between the river and floodplain; and (iii) diadromous fish passage through dam gates. To date, the most substantial measureable benefit is the positive link between spring pulse releases and macroinvertebrate community responses (Ward and Meadows, 2009); a relatively minor gain given the level of investment. As is the case with many environmental flow strategies, geomorphic adjustments and monitoring are absent from the list of management goals.

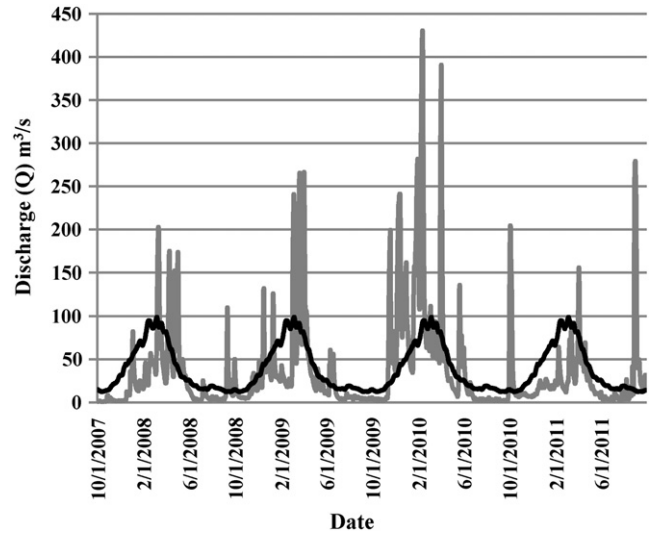

Fig. 1. Tar River, North Carolina, hydrograph from water years 1 October 2007–30 September 2011. The gray line shows daily mean flow data for the 4 year period. The black line represents the daily mean calculated from a 30 year record 1976–2011. The combination of the records illustrates the intraannual seasonal variability between the wet season (winter-spring) and dry season (summer-fall) and interannual variability between wet and dry years that is typical of the southeast U.S.

Another major challenge associated with the natural flow regime is the presumed potential for a contemporary process–response relationship between river flows, geomorphic processes, and ecologic dynamics indicative of pre-altered conditions (Newson and Large, 2006). The relationship between discharge, sediment supply, and the gradient of a river explains process–response relationships, such as channel planform, e.g., whether a channel is straight, meandering, braided, or anastomosing (Schumm, 1981, 1985). Within a given channel type, the relationship between stream power and the composition of the suspended load and bedload controls the morphology and pattern, with different types of channels having an array of habitat assemblages. A threshold change of any of the driving variables will result in geomorphic adjustment, eventually leading to a new type of channel and new habitats. Changes of this caliber will alter fundamental flow–habitat–biota relationships, and disrupt the link between effective discharges and specific geomorphic (Wolman and Miller, 1960) and/or ecological processes (Doyle et al., 2005). Other factors, such as riparian vegetation, in-stream wood, and local geologic constraints, may influence the process–response expectations and should also be considered as sources of additional variability and complexity (Schumm, 2005).

In many river systems, the previously extant flow, sediment, and form coupling that set the stage for biota survival, growth, and reproduction have been disconnected by dams, channel modifications, land use conversions, and other human impacts (Wilcock et al., 1996a,b; Graf, 2006; Jacobson and Galat, 2006, 2008; Tracy-Smith et al., 2012). These persistent and severe human-induced changes can decouple an array of process–response relationships; and in some river systems it is insufficient to propose management strategies designed solely to mimic a historically referenced, naturally variable flow regime — particularly in working rivers that no longer reflect characteristics indicative of the pre-altered historic range of variability. Such managed flows will likely be ecologically irrelevant when implemented within a fundamentally altered and subsequently different channel morphology (Jacobson and Galat, 2006; Tracy-Smith et al., 2012).

Long-term sustainability of environmental flow approaches requires strategies designed to prevent further process–form decoupling and promote rehabilitation of ecohydromorphic integrity within the boundaries of the current conditions (Richter et al., 2006; Ward and Meadows, 2009). This may involve working with the current flow, sediment, and form conditions to evaluate new options that may not necessarily reflect the historic natural flow regime (Tracy-Smith et al., 2012). Regardless, environmental flow scenarios should address scale-specific (spatial and temporal) strategies regarding sediment regimes, channel and floodplain forms and processes, ecological conditions, biotic targets, and system adjustments to historic and current human impacts.

3. Communicating river sciences across disciplines and scales

The goals for determining environmental flows are often biased by the discipline leading the assessment. Biologists are often concerned with maintaining species, populations, community dynamics, and ecosystem processes; whereas geomorphologists focus on flows that maintain structure and function of morphological features and processes. The collective agenda of complementary perspectives, however, provides the most valuable approach (Dollar et al., 2007; Vaughan et al., 2009; Arthington et al., 2010). A major challenge for assessing environmental flows involves prioritizing the objectives driving the policy decision. Agreement among disciplines requires identifying the common process-based links that influence abiotic and biotic riverine structures, functions, and ecological health. In many cases, these links will include process–response interactions where various ecohydromorphologic elements are operating at different spatial and temporal scales, and it is important for all disciplines to share a framework for communicating the appropriate links and scale considerations between causal factors.

Hierarchical frameworks link the disciplines across multiple temporal and spatial scales, levels of organization, and complexity to help identify the relevant flow components that drive physical processes, which in turn sustain biological life-history, behavior, and morphological strategies. A hierarchical organization of a riverine ecosystem — such as that first developed by Schumm (1968); later refined by Frissel et al. (1986), Poff and Ward (1990), Petts and Amoros (1996), Thoms and Parsons (2002), Fausch et al. (2002) and Dollar et al. (2007) to a current form described by Thorp et al. (2008) and conceptually similar to Brierly and Fryirs (2005) river styles framework — provides a useful framework for matching appropriate scales between disciplines. The river ecosystem synthesis from Thorp et al. (2008) arranges a river landscape as a series of nested elements that represent progressively finer resolution units, i.e., drainage basin (largest)–functional process zone–river reach–functional wet–functional unit–mesohabitat (smallest) (Thorp et al., 2008) (Fig. 2). Although the structure and characterization of the framework are predominantly physically based on geomorphology and hydrology, elements within the organization can be linked to ecologically relevant terms (Table 2). At the drainage basin or functional process zone scale, ecologists may be most interested in gamma diversity (total number of species in a given area); whereas at the scale of the functional set or functional unit, a measure of alpha diversity (number of species in a given set of habitats) or beta diversity (amount of species change between habitats) might be most appropriate (Table 2). As a management or conservation planning tool, this framework helps identify which hydrologic, geomorphic, and ecological variables are important at different spatial and temporal scales.

This framework has been applied to the Condamine–Balonne River system, Australia (Thoms and Parsons, 2002; Thoms and Sheldon, 2002; Dollar et al., 2007) and to the Murray–Darling River system, Australia (Thoms et al., 2004) for the purpose of examining whole-system variability and spatial and temporal ecohydromorphic interactions in the context of environmental flows. In the Condamine–Balonne River system, recommendations varied according to elements of the natural flow regime as they related to the physiographic basin-scale structure; the shorter term pulse flow variables were most important in the headwater reaches, the annual flow history variables were most important to the mid-zone reaches, and the longer term flow regime scale variables were most important in the lower zones (Thoms and Sheldon, 2002). An important contribution of this study showed the correlation between increasing spatial scale of riverscape units and increasing temporal scale of flow regimes—a relationship which theoretically applies to a diversity of river basins.

4. Geomorphology and environmental flows

Geomorphologists can offer their expertise to environmental flow assessments in numerous ways. Here we provide empirical examples

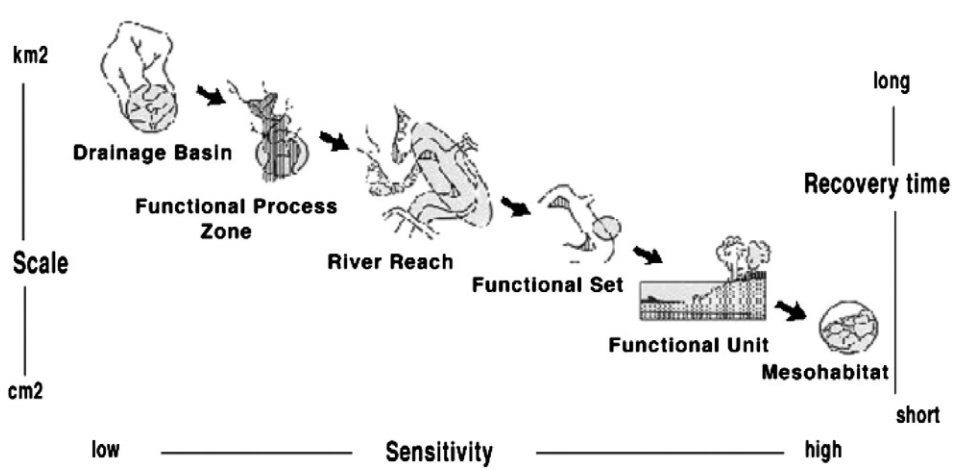

Fig. 2. Hierarchical physical-based organization of a river system. This figure corresponds to Table 3. Modified from Petts and Amoros (1996), Thoms and Sheldon (2002), and Thorp et al. (2008).

Table 2
Examples for translating conceptual scale-dependant framework to ecohydromorphic interactions: the conceptual hierarchical framework is from Thoms and Parsons (2002), and the addition of the examples of ecohydromorphic interactions is from the authors.

Conceptual hierarchical Framework					Examples of ecohydromorphic interactions		
Spatial and temporal scales		Hydrology	Geomorphology	Ecology	Channel processes	Floodplain processes	Biological diversity
Large	Long-term: Holocene -Millennia	Flow regime	Drainage basin	River ecosystem	Sediment regime	Meander belt formation and floodplain width	γ Gamma: total number of species in the region
	Intermediate: Millennia to Decadal	Flow history	Functional process zone	Aquatic communities	Planform channel pattern	Depositional floodplain forms and terrain complexity	α Alpha: species number in a set of habitats
	Intermediate: Decadal–Annual	Flood pulse	River reach	Species populations	Meander bend development, growth, and geometry	Structural and functional connectivity among deposition features	α Alpha, and β Beta: amount of species changes between habitats
Small	Short: seasonal, daily, instantaneous	Flow hydraulics	Functional set > functional unit > mesohabitat	Individuals	Depositional pointbar bed form features and substrate characteristics	Morphology and sedimentology of specific feature, e.g., abandoned channel	α Alpha and β Beta: biotic abundance, age-classes, number of habitats in set and unit

in three broad areas of geomorphic research that are central to the discipline: (i) instream sediment transport, deposition, and storage processes and dynamics; (ii) river channel forms and processes; and (iii) floodplain forms and processes. These categories influence ecohydromorphologic interactions across a range of spatial and temporal scales and inherently involve consideration for other fundamental geomorphic topics, such as basin-scale physiographic variability and human impacts to rivers and subsequent system responses. The empirical examples span different tiers of the river ecosystem hierarchy (Fig. 2, Table 2), and in a few cases we link the examples to the position in the framework.

4.1. Instream sediment erosion, transport, deposition, and storage processes

The erosion, transport, deposition, and storage of sediments by flowing waters directly influence the substratum character of the river bed and consequently influence habitat conditions for aquatic biota (Chapman, 1988; ASCE, 1992; Milhous, 1998). Sediment dynamics are spatially and temporally complex and, thus, notoriously difficult to quantify and predict outside of controlled experiments (Reid et al., 1997) which makes incorporating sediment dynamics into environmental flows a major challenge (Andrews and Nankervis, 1995; Kondolf and Wilcock, 1996; Wilcock et al., 1996a,b; Milhous, 1998; Schmidt et al., 2001). One way to accomplish this is by calculating the rates of sediment transport relative to channel morphologies and discharges that can be incorporated into environmental flows (Andrews and Nankervis, 1995; Wilcock et al., 1996a,b; Milhous, 1998). This application falls completely in the realm and responsibility of geomorphologists (Gilvear, 1999; Church, 2002), and the inherent complex nature of sediment dynamics and geomorphic thresholds for entrainment, transportation, and deposition require field work to answer such questions.

Dams alter flow and sediment regimes. They reduce flow magnitudes and sediment loads, limiting the capacity and competence of sediment transport. This impact creates an abrupt change in sediment texture, composition, and volume which is often further altered by the effects of local bed and bank erosion, and tributary inputs below the dam (Wilcock et al., 1996a,b). These changes can facilitate the accumulation of finer grained deposits that negatively affect habitat quality for biota adapted to coarser grained substrates (Chapman, 1988). Milhous (1998) outlined a three-part technique, that includes a biological component, a hydraulic component, and a selection component, for linking aquatic habitat needs, sediment dynamics, and discharges to specific environmental flow recommendations (Milhous, 1998). The biological component involves the relationship between the sediment and the organism — during given life stages, certain species require specific substrate conditions. For example, fish eggs deposited on gravel will not incubate if they are covered by sand and finer material (Chapman, 1988). The hydraulic component involves the conditions required to transport various sized sediments and is best estimated by using field measurements of the wash load, suspended load, and bedload. Additional variables, including the channel slope and hydraulic radius, enable calculations of substrate movement parameters and sediment transport capacity indices for moving various particle sizes (Milhous and Bradley, 1986). The final selection component identifies the given flow needed to support the hydraulics to transport a given sediment size determined from the biological–sediment relationship.

This module was used for the Gunnison River, Colorado, to evaluate sediment flushing for three different habitats (riffles, pools, and side channels) critical to the Colorado squawfish (*Ptychocheilus lucius*) reproduction and survival (Milhous, 1998). In this example, the sediment transport processes occur across multiple scales from the functional process zone scale down to the mesohabitat scale where sediment removal is necessary for species-level reproduction and survival. Flow regime and flow history influence the continual source of sediments, but it is the individual pulse events that influence the temporary transport and depositional fluctuations at the mesohabitat scale. This technique transfers to other rivers where instream sediment issues are a concern for fish and benthic macroinvertebrate habitats.

In addition to dam releases for periodically flushing sediments from aquatic habitats, controlled floods are another substantial opportunity to facilitate natural geomorphic work downstream from dams (Patten et al., 2001; Schmidt et al., 2001). Three controlled floods on the Colorado River downstream of Glen Canyon dam have proven to be a valuable management strategy for increasing the accumulation of sediment deposits on channel bars for the colonization of riparian vegetation and scouring side- and backwater channels for aquatic nursery habitat and refuge during low-water conditions (Schmidt et al., 2001; Topping et al., 2010). Post dam-release field-monitoring results indicate that managing floods relative to ecologically effective discharges (i.e., magnitude and frequency of specific flood recurrence intervals) and available sediment supply is necessary for maintaining persistence and habitable conditions in dam regulated rivers (Topping et al., 2010). The complexity associated with the sediment supply sources, transport, and deposition dynamics represents the greatest challenge for this management objective (Topping et al., 2010).

Many organisms show preference for specific substratum and bar morphologies, yet these conditions can be highly dynamic in space and time. Sediment transport and depositional dynamics can drive spatial shifts in substratum materials, hydraulic conditions, habitat heterogeneity, and biological communities (Pritchett and Pyron, 2011). Over a four-year period (2005–2008) on the Wabash River, Indiana, Pritchett and Pyron (2011) found a correlation among year-to-year changes in bedload grain sizes, water depth, water velocity, and fish in reaches that

were characterized by the greatest interannual variability of flows as measured by ecologically relevant flow statistics. Biological communities demonstrated fidelity to preferential substrate materials and migrated with the spatial shifts in substrate materials and hydraulic habitat conditions. Static, local cross-section surveys such as those used in a majority of instream flow study physical habitat models, such as PHABSIM (Maddock et al., 2004), would be insufficient for quantifying the ecohydromorphology connection between river flows, reach-scale bedload morphological adjustments, and community responses that occur along spatially-shifting gradients, such as that identified by Pritchett and Pyron (2011). Repeated measurements of reach-scale morphological surveys and bathymetric mapping would be useful for mapping and monitoring these types of sediment driven habitat shifts controlled by interannual flow variability. A combination of field and remotely sensed bathymetry surveying techniques — such as those proposed by the three-dimensional riverscape model (Carbonneau et al., 2012) and the satellite–based mapping of river depth (Legleiter and Overstreet, 2012) — offers great potential for applications where the segment or reach geomorphology is highly dynamic over space and time. Such observations are critical for identifying the flow-form link that sustains these dynamic ecological processes.

Sediment volume and longitudinal variability in alluvium storage control patterns of river channel morphology. In the Kingdom of Lesotho, Africa, six main valley floor physiographic segments occur along the Senqu, Senquyane, Malibamatso, and Matsuko River systems. Each is characterized by distinctly different sets of river channel morphologies where a difference among in-channel alluvium storage is reflected in the presence, structure, and diversity of sediment bars. Sediment bars are a dominant morphological feature of these gravel bed rivers, often occupying up to 75% of the active channel. Five main bar forms were characterized: longitudinal, transverse, point, diagonal, and tributary mouth bars. The hydraulic habitat is significantly different between bar forms, and subsequently each supports different macroinvertebrate and fish assemblages (Thorp et al., 2008). Whereas the inclusion of geomorphology aided in the environmental flow assessments of these rivers, this knowledge was limited to basic descriptions and reach characterizations and no process data were included in the recommendations.

The examples provided here illustrate the significance of sediment dynamics as they influence morphology and riverine habitat. Field data on sediment entrainment, transport, and depositional processes and patterns are necessary for managing sediment flushing flows (Kondolf and Wilcock, 1996; Wilcock et al., 1996a,b; Milhous, 1998), quantifying spatial shifts in available habitat (Pritchett and Pyron, 2011) and identifying target reaches with preferential mesohabitats characterized by specific substrates, bar morphologies, and hydraulic conditions for prioritizing flow recommendations (Thorp et al., 2008).

4.2. Stream and river channel processes and forms

Forms of river channels, in a natural context, are controlled primarily by a physical relationship between discharge, sediment, and gradient, operating within the limits of basin physiography, climate, and vegetation (Knighton, 1998). Extensive human impacts and modifications to river channels through dams, channelization, and other engineering actions have interrupted natural channel forms and processes and consequently the habitat they provide (Graf, 2006; Jacobson and Galat, 2006; Tracy-Smith et al., 2012). In situations where extensive geomorphic modifications have occurred, the altered morphology can act as a limiting factor to the effectiveness of a prescribed environmental flow regime. Thus, managing for flows purely relative to a historic natural flow regime may be insufficient without the appropriate considerations for the resulting hydraulic and morphological habitat conditions.

Engineering and channelization of the lower Missouri River over the last century have stabilized the channel and resulted in the conversion of a shifting, braided channel to a single, deep, narrow, and nearly straight form (Jacobson and Galat, 2006). These large-scale channel form changes have led to a loss of important aquatic habitats, including the low velocity, shallow water habitats that are important to fish, turtles, wading birds, and other riverine organisms (Jacobson and Galat, 2006; Tracy-Smith et al., 2012). A modeling analysis of historic and modern channel forms and flow regimes provided evidence that channel form and morphologic complexity are more important for providing shallow water habitat than just flow alone (Jacobson and Galat, 2006). The depositional complexity of bar forms in the historic channel produced 3 to 7 times more available shallow water habitat than the modern, modified channel form under the same historic and modern flow regimes and in the modern geomorphic setting the historic natural flow regime provided minimal ecological benefits (Jacobson and Galat, 2006). Their study illustrated how the same flow regime in different morphologies can produce significantly different ecological conditions; and understanding the reach-scale geomorphology, and how it has changed over time, are just as important of a consideration for environmental flow assessments as the flow regime.

Tracy-Smith et al. (2012) examined the effect of four different flow regimes (natural pre-managed flow, current managed flow and two environmental flow scenarios) on six different types of habitats (linked to flow levels) for wing-dike and pointbar sandbar deposits at the aquatic–terrestrial transition zone of select locations along the Lower Missouri River. The sandbar morphologies were field mapped under varying flows, and these repeat measures were used to develop discharge–area relationships for modeling varying gradients of sandbar inundation and exposure with the four different flow scenarios. The areas of exposure and inundation under flow scenarios were linked back to the six habitat conditions and life-history cues defined for soft-shell turtles, shore and wading birds, and riverine fish to measure the ecological benefits of each flow scenario. The flow scenarios produced different ecological benefits for the selected biota, but overall indicated minimal increases in suitable habitat when switching to a natural flow regime. This field-intensive approach combined with sophisticated modeling exemplified the value of examining the effects of contemporary morphology on habitat, instead of assuming that a historically defined flow would meet the ecological requirements. This type of approach can be focused on identifying relevant river reaches (series of meander bends), functional sets (sand bar deposits), functional units (complexity of habitat variations with flow), and mesohabitats (site of preferential submergence or exposure for given species); biologically important measurements would include alpha, beta, and gamma species diversity.

While not explicitly an environmental flow application, Rhoads et al. (2003) reached the conclusion that, among modified agricultural streams, channels with greater planform curvature supported healthier biotic integrity than straighter channels and that the presence of wood debris was important for creating local morphologic complexity. Their study examined planform curvature, three-dimensional velocity profiles, channel-bed elevation complexity, and fish communities in four streams, which varied from highly sinuous (last modified in the 1930s) to straight/smoothly curving (channelized in 1996). The results showed a positive multi-responsive feedback effect whereby greater complexity of channel planform produced greater variability of cross-sectional channel forms, which increased variation of vertical flow velocities, which increased spatial variation in scour and deposition, which enhanced structural complexity of the bedforms, and consequently supported greater species richness, biodiversity, and total biomass. This ecologically beneficial, geomorphically driven sequence was only made apparent by direct field investigations of the morphological differences between historic and recently modified channels (Rhoads et al., 2003) yet has significant implications for environmental flow management and the rehabilitation of modified streams.

Channel forms and processes vary in space and time relative to a variety of natural and anthropogenic controls. In relatively undisturbed river systems, a dynamic process–response relationship exists that is geomorphically and ecologically linked to effective

discharge characteristics of the historic, naturally variable flow regime in the river (with the exception of major geologic or climatic disturbances). Anthropogenic disturbances to the channel pattern, flow, or sediment regime will trigger morphological adjustments that influence the habitat suitability in space and time. In such cases, the contemporary geomorphology limits the effectiveness of environmental flows designed from the historic, natural flow regime. Solutions should include strategies for improving the morphology and habitat, and the proposed flow regimes need to be evaluated relative to the ecosystem benefits within the boundary of the contemporary morphology, particularly in intensively modified rivers.

4.3. Floodplain processes and forms

Floodplains are a significant component of riverine landscapes. They provide an additional diversity of landforms not commonly found within the in-channel environment — landforms that are periodically wetted and dried at a range of frequencies — adding to the complexity of process form relationships in these environments. Floodplains can represent the dominant landform of river basins: in the Murray Darling basin, Australia, they account for over 60% of the basin area (Thoms and Sheldon, 2006); and in the southeast U.S. they commonly span 4–8 km wide and >100 km downvalley through the Coastal Plain (Sharitz and Mitsch, 1993). Despite widespread knowledge of the importance of floodplains to the health of riverine landscapes and the long research history of floodplains in the field of fluvial geomorphology (Hudson, 2003), the specific inclusion of these habitats in environmental flow management is often cursory, with the majority of implementation strategies placed on instream flows.

Lateral channel movements and flood processes control significant characteristics of the floodplain geomorphology, hydrology, and ecology through the longitudinal and lateral exchange of energy, materials, and organisms between the river and floodplain at scales extending from days to millennia (Ward et al., 1999; Richards et al., 2002; Hupp and Bornette, 2003; Thoms, 2003; Meitzen, 2009). Approaches for managing floodplains often focus on matching natural temporal patterns of inundation and quantifying the spatial inundating processes (Richter et al., 2006; Thoms and Sheldon, 2006; NPS, 2008; Opperman et al., 2010; Wilder et al., 2012). Common models of floodplain inundation support a simple process of water expansion and contraction, such as that provided by the flood pulse concept (Junk et al., 1989), however, this focus disregards the inherent spatial and temporal complexity associated with the inundation and recession of flood waters and the influence this has on floodplain productivity and biodiversity.

Flood pulses hydrologically connect different areas of the floodplain, and the relationship between the characteristics of the discharge event and the floodplain topography control wetting and drying processes including the spatial extent, frequency, connectivity, duration, and depth of flooded areas (Middleton, 2002a,b; Murray et al., 2006; Powell et al., 2008; Meitzen, 2011; Parsons and Thoms, 2012). In the Narran Lakes ecosystem, Australia, Murray et al. (2006) examined complex flood processes by quantifying relationships between inundated surface area and the number of inundated patches, richness of patch area, and shape and the proximity of inundated patches to each other. In an extension of this work, Shilpakar (2012) showed the complexity of inundation mosaic to be directly related to flood magnitude.

Flood pulses for environmental flow assessments should be examined relative to the influence on process–form relationships and the habitat they provide to a diversity of riverine species. On the Guadalupe River floodplain in Texas, Hudson et al. (2012) measured the hydrologic connectivity of two oxbows over a 3.4-year period using pressure transducers and found that differences in the connectivity to the main stem and duration of inundation were more a function of the geomorphology (age and stage of infilling) than the flow regime. In this setting, different species of shad (*Dorosoma*) and sucker (*Catastomidae*) use oxbows as their primary habitat; and as part of a trophic link, the Alligator gar (*Atractosteus spatula*) depends on hydrologic connectivity of oxbow lakes to feed on these prey (Robertson et al., 2008). Sustainable management of these ecohydromorphic interactions requires more than just flow management, but instead an integrated floodplain management that would also incorporate the effect of geomorphology into environmental flow recommendations (Hudson et al., 2012).

Establishing links between floodplain geomorphology and vegetation community dynamics has long been a focus of field geomorphologists (Hupp and Osterkamp, 1985; Marston et al., 1995; Hupp and Osterkamp, 1996; Hupp and Bornette, 2003; Marston et al., 2005; Meitzen, 2009; Osterkamp and Hupp, 2010) and a key area where they can bring floodplains into environmental flow assessments (Thoms and Parsons, 2011; Graf and Meitzen, 2006; Jacobson and Faust, 2013). Seed reserves in floodplain soils are the foundations for the germination of each species, and a diversity of seeds must be present and viable for different plant communities to develop (van der Valk and Davis, 1978). The inundation regime and wetting patterns are often the mechanism that selects which species develop and where (Moore and Keddy, 1988; Thoms and Parsons, 2011; Murray et al., 2006; Webb et al., 2006; Kupfer et al., 2010).

Research by Murray et al. (2006) and Thoms and Parsons (2011) has shown the expansion and contraction of flood waters to produce a dynamic mosaic of inundated patches where varied hydraulics control the emergence of vegetation from seed banks contained with floodplain soils and the spatial distribution of vegetation communities across floodplain surfaces (Parsons and Thoms, 2012). Similarly in the Narran Lakes Floodplain, Australia, the flooding and drying pattern of the floodplain soils controlled the species composition, whereas the seed bank load influenced the population abundance (Webb et al., 2006). In clear-cut bottomland forests of the Congaree River in South Carolina, USA, forest recovery resulted from the germination and resprouting responses of specific species to hydrogeomorphic soil conditions controlled by flood regime (Kupfer et al., 2010). Establishing these complex biogeomorphic linkages from field observations is a natural progression for geomorphologists collaborating with forest ecologists and has direct implications for floodplain management. Recommendations for wetting and drying regimes (including the flow magnitude, frequency, timing, and duration) are necessary for maintaining or enhancing current levels of biodiversity and abundance in floodplain vegetation communities.

Models of floodplain inundation are common decision support tools used for environmental flow assessments; however, the resolution (spatial and temporal) and type (one- or two-dimensional) of model can have a substantial effect on the representation of the floodplain geomorphology and flood pulse processes. Consequently, this discrepancy can affect the interpretation of ecologically relevant flows (Graf and Meitzen, 2006; NPS, 2008; Powell et al., 2008; Wilder et al., 2012). Because we know that variations in flood magnitude influence flood depths, spatial flood extents, hydrologic connectivity patterns, and consequently an array of ecological processes, it is imperative to use high resolution elevation data (e.g., <0.2-m vertical and 5-m horizontal) on the channel and floodplain topography and high resolution discharge or stage data (e.g., <15 min to hourly increment), both of which involve field validation, to accurately quantify the ecological effects of various high flows (Graf and Meitzen, 2006; Meitzen, 2011; Hudson et al., 2012). Lower resolution data constrains our ability to make well-informed decisions for making recommendations for environmental flows.

On the lower Congaree River floodplain in South Carolina, a one-dimensional (ID) hydraulic model proved valuable for analyzing large magnitude floods that inundate the entire floodplain, i.e. >5-year recurrence floods (Graf and Meitzen, 2006; NPS, 2008; Kupfer et al., 2010). The 1D scheme, however, lacked the sophistication to accurately model the lower volume, more frequently recurring flood pulses (<1-year recurrence interval) that through field observation were shown to laterally connect the river and floodplain below bankfull stage and are important to numerous ecological functions. Field observations provided evidence

that crevasse channels, abandoned meanders, tributaries, and other flow pathways function as distributaries during these high pulse events and are important for inundating and hydrologically connecting an abundance of riverine floodplain habitats, well below overbank flood stage. After determining the limitations of the 1D model, a two dimensional (2D) hydrodynamic model was developed for this river-floodplain environment and validated in the field with real-time flood inundation depth data to provide a spatially explicit tool for quantifying the ecologically relevant flows required for connecting and inundating seasonally flooded habitats (Meitzen, 2011) (Fig. 3). Accurately simulating the hydrodynamic effects of these frequently recurring pulse events is important in quantifying the habitat needs of species that require access to floodplain lakes for spawning — such as the American shad (*Alosa sapidissima*), blueback herring (*Alosa aestivalis*), and Redfin pickerel (*Esox americanus*) (Marcy, 2005; Walsh, 2005) — as well as species that depend on seasonally inundated forests for depredation protection such as the Prothonotary warbler (*Protonotaria citrea*) (Wakely and Roberts, 1996; Hoover, 2006).

On the Roanoke River, North Carolina, a 1D hydraulic model is currently being used to inform environmental flow assessments on the flood processes that are necessary for supporting the community dynamics of the cypress-tupelo and bottomland hardwood forests (Wilder et al., 2012). The conservation stakeholders contend, however, that the 1D model is insufficient for representing the level of resolution and complexity of hydrologic and geomorphic processes that should be considered in the environmental flow assessment. The lower Roanoke River contains nearly 40,500 ha of protected floodplain forest, and the health of these ecosystems is a primary conservation concern. Dam operations have drastically reduced the peak flow magnitude of the lower river and have increased the frequency of moderate flows. These changes affect fish spawning (Carmichael et al., 1998), alter the hydroperiod of the bottomland and swamp-tupelo forests growing season (Pearsall et al., 2005), and may be increasing bank erosion (Hupp et al., 2009).

Instrumentation of 48 in situ gages on the lower Roanoke River floodplain better captured the longitudinal, downvalley, and cross-sectional gradients in a flow relationship between the river and floodplain relative to releases from the dam than produced by the 1D hydraulic model (Chuck Peoples, The Nature Conservancy, Northeast NC Program Director, personal communication, 2012). Of particular interest to this study is the effect of regulated flows on different geomorphic settings (near channel levees, backswamps, abandoned meander depressions) and how these effects translate to changes in hydroperiod, forest communities, and aquatic habitats. Preliminary results show patterns of soil saturation and/or floodplain inundation related to flood control operations and hydrologic peaking during the growing season and these patterns are most apparent in the normal-wet and wet years. Further evaluation of these data will be undertaken in the next year, and the results will be incorporated into recommendations for environmental flows.

Floodplain inundation processes have been a research domain of field geomorphologists (Hudson, 2003; Thoms, 2003; Meitzen, 2011, Jacobson and Faust, 2013). Flood pulses (wetting and drying) are a primary driver of ecosystem structure and function; and an accurate depiction and quantification of the flood pulse processes are necessary components for environmental flow assessments. Where feasible, in situ gaging provides higher resolution methods for mapping and measuring inundation and soil saturation patterns associated with different morphologic floodplain surfaces. For modeling applications, a 2D model provides greater capability for quantifying flood pulses that are not well represented by a 1D model. High resolution geomorphic and hydrologic data are a necessary element for accurately quantifying the ecohydromorphology relationships, whereas the use of lower resolution data can result in less-informed and less-effective decisions when quantifying environmental flows for floodplain management.

4.4. A few questions to drive geomorphic inferences

Motives for environmental flows are often driven by the need to establish flow-ecology relationships for guiding water allocations (Poff et al., 1997; 2010). This agenda has led to the wide-scale acceptance of flow as the master variable guiding ecological health and integrity, with

Fig. 3. Two-dimensional hydrodynamic flood inundation model illustrating the complexity of floodplain flow pathways that are active below overbank flood stage on the Congaree River floodplain, South Carolina. This example shows a frequently occurring (<1-year recurrence interval) flow pulse that is ecologically important for longitudinal and lateral exchanges of energy and materials. The photo shows field validation of the flooded channel widths and depths.

Table 3
Example design for a question-based framework that will facilitate holistic interdisciplinary environmental flow assessments.

Questions	Purpose	Methods, tools, or data sources
(1) What biotic and abiotic elements of a river system are we concerned about preserving, protecting, restoring, or sustaining?	Justify the management objectives and goals, and apply to all disciplines. Identify physical and biological targets.	Interdisciplinary workshop, science advisory boards, or planning meetings with stakeholders from state and federal government agencies, academics, private interests, non-profit, etc.
(2) What are the historic and current conditions for elements identified in Question 1? If relevant, how have they changed?	Evaluate (biotic and abiotic) resources status and identify threats, impacts, and sources of change.	Expert knowledge; literature review; historical databases; field reconnaissance surveys; remote sensing, GIS modeling analysis.
(3) What information currently exists for quantifying riverine biota flow-ecology relationships and what is lacking?	Designed for biologists and ecologists to synthesize the existing knowledge on riverine-species requirements.	Expert knowledge; literature reviews.
(4) Where are the historic and current documented biotic occurrence and habitat locations?	Spatially locate within the river basin where biological and or habitat data exists.	Expert knowledge; database analysis and GIS occurrence mapping.
(5) What are the morphological and hydrologic parameters of different riverine habitats?	Identify and classify fluvial forms and substrate composition, texture, sorting, and depositional and scour forms. Assess structure and function of the different forms and substrates relative to various flow levels.	Expert observation and field surveys: total station surveying, suspended and bedload sediment characterization, wetted channel perimeter, landform mapping, gradient/slope measurements, and remote sensing of channel bathymetry and floodplain terrain.
(6) What geomorphic and hydrologic processes influence the formation, maintenance, or availability of theses habitats?	Explain process–form relationships and controlling factors from multiple spatial and temporal scales, e.g., gradient, basin-scale controls on substrate sedimentation patterns (source, transport, storage, deposition, downstream fining, etc.).	Specify processes-form relationships that occur at different temporal (instantaneous, short, intermediate, long-term) and spatial (macro- to mesoscales) scales of analysis; quantify stage-discharge rating curves and habitat area, hydrologic and hydraulic modeling and spatial analysis of habitat availability.
(7) What are the contemporary links between flow, form, and biota?	Identify ecologically effective flows for sustaining physical and biological processes.	Develop flow-ecology relationships for various biota, habitats, and flow.
(8) What are the environmental flow strategies that can be proposed to meet the objectives of the first question relative to what has been learned through this process?	Develop multiple flow-based guidelines that provide a set of amenable management options.	Adaptive water allocation planning tools; ecological and socioeconomic trade-off comparisons between alternative flow scenarios.

geomorphology considered only minimally (Walker et al., 1995). We have shown that geomorphology provides the physical template that acts as a mediator of flow on ecological processes; and because of its dynamic nature, we suggest that geomorphic considerations should be included earlier rather than later. The following list (modified from Richter et al., 2006) provides examples of how geomorphologists can contribute to environmental flows:

(1) Have historic or recent topographic and bathymetric surveys been conducted for the river channel or floodplain?
(2) Is the channel and floodplain system in dynamic equilibrium or disequilibrium? (2a) Is the sediment input to each segment in equilibrium with the capacity of the channel to transport it through the segment? (2b) Are detectable trends present in the elevation of the river bed indicating degradation or aggradation? (2c) Has the longitudinal profile of the river changed over time?
(3) Has the channel or floodplain width changed over time?
(4) Has the planform pattern of the channel changed over time, such as between meandering and braided forms?
(5) Has the size distribution, composition, or volume of stream bed sediments changed over time?
(6) Has the availability of in-stream and floodplain physical habitats changed over time (e.g. changes in availability of pools or riffles, access to floodplain lakes)?
(7) Is lateral channel migration or bar formation important ecologically (e.g. to support riparian plant communities or reptile nesting sites)?
(8) Have human activity and land use significantly altered the stream channel and floodplain morphology and processes; and if so what are the ecohydrogeomorphic consequences of such changes?

Answering these questions and identifying causality of physical changes provide a context for geomorphologists to show managers, ecologists, engineers, etc., that rivers are historically dynamic and changeable by nature and that they rarely exist within a steady-state (Brierly and Fryirs, 2005; Newson and Large, 2006; Woelfle-Erskine et al., 2012;). No single good or natural state exists for a river to be in, and it is important to have an understanding of its contemporary condition relative to its historic range of variability. If the system is changing, managers need to identify the source and causal mechanisms and whether the change is 'natural' morphologic evolution indicative of the systems history or if it is evolving towards a new state induced by human impacts. In either case, with the proper geomorphic knowledge, environmental flows can be used as a soft-engineering tool to sustainably manage or restore river conditions to benefit the in-stream and floodplain ecology.

5. Discussion and conclusions

A global review of environmental flow assessments identified four method-based categories that included hydrological, hydraulic rating, habitat simulations, and holistic methodologies (Tharme, 2003). Whereas each of these methods incorporates some attributes of geomorphology, they are noteworthy for the limited acknowledgement of its central role in environmental flows. It is only a holistic approach that considers the dynamic ecohydrogeomorphology interactions across multiple spatial and temporal dimensions throughout a river basin. Holistic methodologies are typically more time and resource intensive and only possible with considerable interdisciplinary expertise; two examples include the downstream response to imposed flow transformation (DRIFT) philosophy (King et al., 2003) and the ecological limits of hydrologic alteration (ELOHA) method (Poff et al., 2010).

First developed in South Africa, the Downstream Response to Imposed Flow Transformation (DRIFT) philosophy states that all major physical and biological components of aquatic ecosystems must be managed; and specifically the flow regime must be managed at a range of temporal and spatial scales (King et al., 2003). DRIFT draws strongly on fluvial geomorphology in combination with hydrology, hydraulics, and the biology of the riverine biota to produce flow scenarios for water managers. DRIFT contains four modules, one which is focused on the biophysical elements and specifically depends upon fluvial geomorphological data. This module describes the morphology of selected representative river reaches nested within different functional process zones of the river network. Superimposed upon these functional process zones and reaches are various biotic targets in terms of the presence/absence and abundance,

and the links to morphological structures and associated flow influences. Of the remaining three modules, two are socioeconomic; whereas the final one compares scenarios of future flows and associated impacts on the river and local society.

Recent initiatives in the USA are providing better strategies for incorporating geomorphology into environmental flow assessments. The Ecological Limits of Hydrologic Alteration (ELOHA) method is a flexible five-step process for determining flow allocations (Poff et al., 2010; Kendy et al., 2012). The five steps involve: 1.) establishing a hydrologic foundation, 2.) classifying streams, 3.) measuring flow alteration, 4.) developing flow-ecology relationships, and 5.) determining criteria for environmental flows that are implemented through a social process into adaptive management. Stratification within step two includes a geomorphic sub-classification for incorporating important physical characteristics, such as gradient, substrate, planform channel patterns, zones of shifting sediment dynamics, or known locations/reaches that facilitate lateral floodplain connectivity. To date, however, few studies have employed the geomorphic sub-classification and have instead placed emphasis predominantly on hydrologic metrics and flow-biology indices (Kendy et al., 2012). We recognize this limitation as a research frontier for applied geomorphology.

Different morphological and process-based elements of geomorphology are important to studies of environmental flows and most require field-based information to understand the influence on ecological processes. Very different structural and functional linkages exist among the trilogy (geomorphic, biological, and ecological) of processes throughout the network of a river from the headwaters to base level. River systems are dynamic process-driven features; and as a result, the type of habitat, quality, availability they provide will change over space and time. This trilogy of interactions varies longitudinally, laterally, vertically, and temporally, and across macro- to mesoscale morphologies. This complexity of interactions makes it possible for the same flow to have widely different ecological outcomes depending on the underlying morphology, and also for the same morphology to have widely different ecological consequences dependent on varying flows. These complex and variable conditions create a heterogeneous abundance of spatially and temporally distinct habitats capable of supporting biologically diverse and resilient riverine ecosystems.

Management to sustain habitat heterogeneity requires a range of flow conditions. Assessments for determining environmental flows often result in an array of potential scenarios for maintaining the ecological integrity of a riverine system and include multiple objectives. It is nearly impossible to address all ecological concerns for a river, and thus, management priority may be given to a particular species (e.g., endangered or threatened), guild, niche, or key indicator flow for some aspect of functional ecological integrity (e.g., flood pulses). Identifying priority elements that stakeholders agree need to be maintained or restored is often the first most challenging step involved in any assessment for environmental flows. Once the physical and biological priority elements are selected, inquiry and field-based approaches can be used to deduce the process-based links between geomorphology, hydrology, and biology (Table 3).

A series of three questions, adapted from Kondolf et al. (2003), can be used to guide geomorphologists' involvement in sustainable river management situations: (1) How does the river work?; involves examining ongoing processes and forms; (2) Where has the river been and where is the river going?; requires surveying, monitoring, and predicting river responses to human impacts and future climate change impacts at various spatial and temporal scales; and finally (3) How can we improve the state of the river?; relates directly to an evaluation of sustainable management and/or restoration actions. This final question represents a fundamental goal of environmental flow management, and to successfully reach this goal we need to collaborate with other scientists to communicate clear answers in ecologically relevant contexts. Interdisciplinary riverine studies on the functional linkages between hydrology, geomorphology, biology, and ecosystem health can fill the information gaps that exist in the body of scientific evidence currently used to support flow recommendations. Environmental flow applications offer geomorphologists a high profile opportunity to collaborate and share their research expertise and to illustrate the significance of geomorphology as a master variable influencing riverine ecology and biota. This type of policy-driven management application presents a frontier for expanding the field tradition in geomorphology into the interdisciplinary field of ecohydromorphology and for bringing geomorphology into the spotlight of river system management.

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