## Hydroecology and river restoration: Ripe for research and synthesis

Margaret A. Palmer<sup>1</sup> and Emily S. Bernhardt<sup>2</sup>

Received 13 June 2005; revised 18 October 2005; accepted 21 October 2005; published 14 February 2006.

[1] Research at the intersection of hydrology and ecology is central to a future in which human and ecological needs for water are met. We briefly identify several compelling research questions at this intersection, then focus on a critical research area central to hydroecology: river and stream restoration. Challenges in this area include the development of science to evaluate the effectiveness of restoration, particularly the cumulative effects of many small projects; to restore ecosystem processes under highly constrained conditions such as below dams or in urban settings; to push some aquatic ecosystems beyond "restoration" to boost their ability to perform functions of value to society; and to identify feedbacks associated with critical thresholds beyond which restoration is not possible. Meeting these research challenges requires research at the interface of social science and the disciplines of hydrology, geomorphology, ecology, and engineering, but hydroecology will be the central science.

Citation: Palmer, M. A., and E. S. Bernhardt (2006), Hydroecology and river restoration: Ripe for research and synthesis, *Water Resour. Res.*, 42, W03S07, doi:10.1029/2005WR004354.

#### 1. Introduction

[2] Water is essential to life on earth. It is a determinant of biodiversity, ecological patterns and ecological processes. Meeting human water needs and sustaining the services that aquatic ecosystems provide remain one of the greatest challenges of the 21st century. The natural hydrologic variability that is pivotal to the ability of rivers and wetlands to absorb disturbances and be resilient has been greatly reduced through the construction of dams, the diversion of surface water, and the extraction of groundwater [Poff et al., 2003]. Urbanization has caused dramatic changes in hydrologic regimes that have led to lower water tables and lake levels, loss of wetlands, and more intense flooding in streams [Booth, 1990; Paul and Meyer, 2001; Gleick, 2003]. All of these impacts have had dramatic ecological consequences ranging from changes in the rate of biogeochemical processes to the extinction of species [Brunke and Gonser, 1997; Postel and Richter, 2003]. Indeed, freshwater species are 6 times more likely to be at risk than their terrestrial or avian cousins [Ricciardi and Rasmussen, 1999].

[3] The science of hydroecology is center stage in both understanding and solving these problems. The term hydroecology refers to the intricate link between ecological systems and water and is broadly applied to research integrating the physical processes of hydrology with the biological processes of ecology. As such, it encompasses critical research questions that cannot be addressed without integration of the disciplines. It includes diverse research

foci spanning multiple scales. At global and regional scales, hydrological processes interact with climate and terrestrial vegetation to determine water availability for humans and their ecosystems. At regional and local scales, flora and fauna have coevolved with hydrological regimes such that changes in the frequency or magnitude of floods may lead to extirpation of species or shifts in distribution. Flow regimes and their interaction with the soils and aquatic sediments influence nutrient cycling, reproductive success of plants and biota and food web dynamics. Just as flow influences ecological processes and patterns, the latter exert a strong influence on water availability and quality. The ecological effects of water extractions and transfers may result in ecological feedbacks that in turn lead to new patterns of flow and water mixing.

- [4] A great deal of new research and synthesis is needed in the emerging field of hydroecology to help provide answers to many critical questions: Will the intensity and spread of biotic outbreaks, disease, and invasive species increase as interbasin transfers of water and groundwater extractions increase? How will changes in the amount and flow paths of water affect vegetation and rates of nutrient transformation, and what level of feedback effects will there be on water availability and quality? How will urban and exurban expansion affect interception of rainfall, evapotranspiration, albedo, erosion, runoff and nutrient fluxes? Collectively, will these changes alter local humidity and temperature regimes, as well as fluxes of nutrients, within the system and into marine systems? The list of questions is endless because hydroecology is truly a frontier discipline.
- [5] We focus specifically on the science needed to advance river and stream restoration because of the central role hydroecological research must play in advancing this field and, because restoration is emerging as an essential component of effective surface water management. We argue that hydrologists and ecologists must not only forge new research partnerships but must bring

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<sup>&</sup>lt;sup>1</sup>Chesapeake Biological Laboratory, University of Maryland Center for Environmental Sciences, Solomons, Maryland, USA.

<sup>&</sup>lt;sup>2</sup>Department of Biology, Duke University, Durham, North Carolina, USA

engineers, geomorphologists, and social scientists firmly into the partnerships.

# 2. River Restoration as a Hydroecology Research Frontier

- [6] Ecological restoration of rivers should result in a watershed's improved capacity to provide clean water, consumable fish, wildlife habitat, and healthier coastal waters. Throughout the U.S., management agencies are already investing heavily in this approach. Our work with the National River Restoration Science Synthesis (NRRSS) project documented an exponential increase in the number and costs of river restoration projects in the U.S. over the last decade. However, we also found that little is known about the relative effectiveness of most restoration practices in meeting ecological goals [Palmer et al., 2003; Bernhardt et al., 2005; Hassett et al., 2005]. As ecological restoration of rivers becomes more prevalent, it is essential to examine the history of restoration and to suggest a future that moves the diverse disciplines involved in river restoration forward toward an integrated approach for improving the health and function of freshwater and coastal ecosystems.
- [7] Developing sound science to maximize the ecological and societal benefits of river restoration is now critical. Here we identify several research priorities that should be central to this process.
- [8] We begin with our perspective on the paths that the practice and science of river restoration have taken, why we believe those paths should converge, and what directions those paths must take in the future. We argue that a broad-scale increase in the number of projects that are ecologically effective [Palmer et al., 2005] will not happen unless several, currently divergent paths meet: engineering, hydroecology, geomorphology, ecology, landscape design, and cultural anthropology. Expertise from different disciplines toward a common goal is essential for hydrological synthesis and is also essential for dealing with complex problems such as declining biodiversity and altered ecosystem processes, both of which are related the flux of water and sediments.

### 3. Toward a Convergence of Restoration Paths

- [9] River and stream restoration has historically been the purview of hydrologists, particularly hydraulic engineers. A brief glance at many restoration manuals will reveal engineering-based instructions on "restoring meanders to straight channels," "revetting river banks," and "controlling river beds" [e.g., Tuttle and Wenberg, 1996; Richardson et al., 2001; River Restoration Centre, 2002]. The historical roots of this first restoration path, the engineering path, grew out of an emphasis on flood control. Engineering methods were developed to increase the flow capacity of channels by, for example, deepening and straightening channels. Thus the historical engineering focus was on designing river channels to efficiently route water away from infrastructure and/or toward agricultural fields or city water supplies often without much regard for these conduits as functioning ecosystems.
- [10] The second path of river restoration was one that focused on rivers as natural, living systems. This path developed in response to infrastructure failures in engineered rivers and a growing appreciation of the key role

- that intact river ecosystems play in providing vital ecosystem services [Gilvear, 1999; Wohl et al., 2005]. Recognizing that purely technological approaches to managing rivers were insufficient led to the hydrogeomorphic engineering path which modified the historical, strict engineering approach to a merger of design and geomorphological principles. The aim was now to imitate natural alluvial systems using softer engineering approaches that focus on the dynamics of sediment and water movement [Soar and Thorne, 2001]. Hydrogeomorphic restoration attempts to restore natural channel forms and hydrographs to degraded rivers [Shields et al., 2003].
- [11] The third path was opened when ecologists began to get involved in restoration. While this path is not really even cleared yet, it is one that focuses on supporting biodiversity and ecosystem services by restoration of natural processes [Clarke et al., 2003; Palmer et al., 2005; Wohl et al., 2005]. Ecological endpoints such as biodiversity, or more often restoration of a single species, have also been identified as desired endpoints for some engineering or hydrogeomorphic engineering restoration projects but these projects do not typically focus on restoration of the underlying ecological processes that support these endpoints. The historic assumption behind hydrogeomorphic restoration is that "if we build it, they will come," "they" being loosely defined as the suite of species and the ecosystem functions found in reference streams. Determining under what conditions this assumption is true by explicitly linking hydrogeomorphic and ecological research in river ecosystems should be the driving force behind ecological river restoration research. For example, channels can be regraded to reduce erosion but physical stability often requires vegetation. If the ecological process of seed dispersal is not restored (e.g., by ensuring floodplain inundation or removing dams that isolate river reaches), native vegetation is unlikely to recruit and even if planted may not survive. Often what happens is that invasive species take hold and may cause unanticipated problems.
- [12] Where are we now with respect to these paths? The scientific and engineering community is struggling to be at the point of intersection of these paths. Each discipline (hydrology, geomorphology, ecology, and engineering) has something to offer yet this is an awkward intersection, each discipline is characterized by different knowledge structures, different cultures, and very different approaches to problem solving [Benda et al., 2002]. Our observation has been that each group is a little suspicious of the others and while there is discussion of bridging these disciplines to develop restoration principles for rivers, this is certainly not a path well worn. However, biological diversity and ecological processes are inextricably linked to the flux of water and sediments. If we hope to return running water ecosystems to "healthier" states, we must evaluate the interplay between restoration of ecological processes (e.g., productivity, biogeochemical transformations, habitat suitability, etc.) and the hydrologic and geomorphic context in which these processes are grounded. We next explore research frontiers at these disciplinary intersections.

### 4. Research at the Convergence Point

[13] The successful intersection of the engineering, hydrogeomorphic and ecological sciences to inform river

restoration not only requires a cultural shift among the scientific community but also requires new research. Right now some of the research needs could be easily met if more data on the outcome of restoration projects were available. The fraction of written project records that indicate monitoring was planned or implemented is shockingly low (<4000 of  $\sim$ 37,000 projects [Bernhardt et al., 2005]). While conversations with project managers suggest that much more information on outcomes is known, this information is extremely difficult to obtain (Bernhardt, unpublished data). It has certainly not been synthesized. A synthesis of this would allow us to identify what types of restoration approaches and in what contexts (watershed position, land use, climatic and flow regime, etc.), are most successful in meeting the desired goals. If we can identify common elements of success or failure, this would allow us to adapt our restoration methods and/or adaptively manage projects post implementation. Thus a top research priority should be data synthesis efforts to evaluate the ecological effectiveness of past restoration projects, particularly those types of projects that are extremely expensive (e.g., floodplain reconnection) or are highly interventionist (e.g., channel reconfiguration).

[14] To complete such a synthesis requires new research on how best to measure ecological effectiveness and more broadly how to quantify multiple ecosystem services in meaningful ways [Meyerson et al., 2005]. Most river restoration projects are intended to achieve multiple goals with the most common being riparian and water quality management [Bernhardt et al., 2005]. Yet even for those projects that are monitored, only one or two parameters are typically tracked; most often these are physical parameters such as cross-sectional area. When multimetric "indices of biological integrity" [e.g., Karr and Chu, 1999] are used, they assess ecological structure such as biodiversity and habitat but do not evaluate the processes that underlie this structure (e.g., primary production). Quantifying less tangible ecosystem services such as water purification or climate control that are provided by riparian restoration are even more of a research challenge. Can we design restoration projects to not only meet immediate societal needs (e.g., stabilize eroding banks) but to enhance ecosystem services (e.g., removal of excess nutrients or moderate temperature extremes), and, can we measure these less tangible benefits then include them in models to quantitatively explore benefits and trade-offs?

[15] A second research frontier that would help merge ecological and hydrogeomorphic approaches to restoration includes the development and testing of theory on how "much" restoration of a natural flow regime is "enough." Considerable research has documented the extensive link between natural flow variability (particularly the timing of floods) and life history events such as fish spawning and aquatic insect emergence [Poff et al., 1997]. This has led to efforts to restore flow regimes, particularly on impounded rivers [Postel and Richter, 2003]. Yet often it is not possible to return a system to its historic flow regime. The question then becomes how best to manage flows for particular ecological benefits, are there threshold levels of variability that should be restored, and how do these levels differ across species and ecological processes?

[16] A third research frontier is in the area of urban stream restoration. What approaches can be used to maximize environmental benefits when restoring in a built environment? Restoration of urban streams requires a focus on multiple assaults: thermal stress, high peak flows and low base flows, chemical pollution, and eroding banks. Further, urban streams are routinely subjected to "accidents" such as failed storm water infrastructure and pulses of sediments following new construction projects. This leads directly to a fourth research frontier that extends even beyond the urban setting: Are there thresholds past which riverine systems cannot recover or are there threshold events in which a small assault to the system can result in a large change in ecosystem state? Restoration research may need to identify internal feedbacks in rivers that contribute to the resilience of the system.

[17] Increasingly, the scientific community is being asked to think beyond ecosystem resilience and develop restoration methods that will actually boost ecological performance. Thus a fifth research frontier includes restoration approaches to design ecosystems that provide maximum rates of ecosystem services such as denitrification and sediment removal. Here "restoration" projects might involve creating novel ecosystems (e.g., treatment wetlands or floodplains akin to water treatment facilities) that have little historic precedent, but allow downstream surface waters to recover from upstream insults. Thus this frontier requires that we conceive of restoration success more broadly than within individual projects, toward protecting/restoring conditions for the greatest extent of river.

[18] In a similar vein, the sixth frontier is finding new and creative ways to measure the cumulative contribution of individual projects to overall watershed improvement. Empirical data and landscape models are needed to prioritize the selection of future restoration sites and to develop basin-scale monitoring approaches that look not at on-site improvements, but catchment-scale changes in species diversity and abundances and water quality. Robust, coupled hydrogeomorphic-ecologic models have the potential to revolutionize all of these frontier areas of research and to link them together. Models also allow us to identify areas where we need more information and even experimentation.

# 5. End of the Path: The Most Challenging Research Frontier

[19] Is the convergence of engineering and hydroecogeomorphic principles sufficient to move restoration science into the 21st century? We believe not. The final research frontier is restoration science that is informed by social science scholarship. Rarely are restoration decisions based entirely on environmental issues and even if they are, city planners, managers, and citizens influence project designs and prioritization. Views on restoration goals and approaches differ among all these groups and, of course, from those of the scientists and engineers. Even if we had the scientific knowledge to guide stream restoration for multiple benefits, the likelihood of that knowledge playing a key role in the design of restoration projects is slim unless we develop mechanisms for ensuring that knowledge is used and viewed as valuable. This requires input from

cultural anthropology, environmental education, landscape architecture and city planners.

- [20] Restoration will be most effective when watershed inhabitants, scientists, planners and designers understand the views, values and cognitive models each has toward rivers and the place of rivers in the lives of people [Gross, 2003]. As citizens are educated about river degradation, when they support intervention to improve their rivers, and when they feel ownership of and pride in the resulting restoration project, the projects are far more likely to be successfully implemented. Similarly, when scientists and planners better understand stakeholder needs and values, they may be able to develop scientifically informed designs that balance environmental needs and human needs. However, scientists need the tools to accomplish this and developing those requires research at the interface of social science and the restoration disciplines of hydrology, geomorphology, ecology and engineering.
- [21] Hydroecology will be the central science linking the traditional restoration disciplines. Thus hydrologists and ecologists must play leadership roles in initiating these linkages and extending linkages to the social sciences. Effective restoration project designs and site selection both depend on a thorough understanding of hydrologic connectivity, the interplay between land use change and water export, and the interaction between ecology and the flux of water.
- [22] **Acknowledgment.** This is contribution 3900 of the University of Maryland Center for Environmental Science, Chesapeake Biological Laboratory.

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E. S. Bernhardt, Department of Biology, Duke University, Durham, NC 27708, USA.

M. A. Palmer, Chesapeake Biological Laboratory, University of Maryland Center for Environmental Sciences, P.O. Box 38, Solomons, MD 20688, USA. (mpalmer@umd.edu)