# River restoration

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[1] River restoration is at the forefront of applied hydrologic science. However, many river restoration projects are conducted with minimal scientific context. We propose two themes around which a research agenda to advance the scientific basis for river restoration can be built. First, because natural variability is an inherent feature of all river systems, we hypothesize that restoration of process is more likely to succeed than restoration aimed at a fixed end point. Second, because physical, chemical, and biological processes are interconnected in complex ways across watersheds and across timescales, we hypothesize that restoration projects are more likely to be successful in achieving goals if undertaken in the context of entire watersheds. To achieve restoration objectives, the science of river restoration must include (1) an explicit recognition of the known complexities and uncertainties, (2) continued development of a theoretical framework that enables us to identify generalities among river systems and to ask relevant questions, (3) enhancing the science and use of restoration monitoring by measuring the most effective set of variables at the correct scales of measurement, (4) linking science and implementation, and (5) developing methods of restoration that are effective within existing constraints. Key limitations to river restoration include a lack of scientific knowledge of watershed-scale process dynamics, institutional structures that are poorly suited to large-scale adaptive management, and a lack of political support to reestablish delivery of the ecosystem amenities lost through river degradation. This paper outlines an approach for addressing these shortcomings.

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## 1. Introduction: Problem Statement

[2] Continuing degradation of river ecosystems and loss of aquatic biodiversity are widespread. River restoration is now accepted by government agencies and various stakeholders as an essential complement to conservation and natural resource management. However, despite legal mandates, massive expenditures, and the burgeoning industry of aquatic and riparian restoration, river ecosystems continue to deteriorate as a result of human influences [*Karr and Chu*, 1999]. Furthermore, many restoration activities have failed [*Williams et al.*, 1997]. Given that river restoration is increasingly viewed as a litmus test for the hydrologic and ecological sciences, we believe that scientists must work vigorously to enhance the state and perception of restoration science. Many projects designed to restore rivers are currently being conducted throughout the United States with minimal scientific context. Specifically, many projects lack (1) the inclusion of a solid conceptual model of river ecosystems, (2) a clearly articulated understanding of ecosystem processes, (3) recognition of the multiple, interacting temporal and spatial scales of river response, and (4) long-term monitoring of success or failure in meeting project objectives following completion [*Pedroli et al.*, 2002; *Bernhardt et al.*, 2005]. These problems suggest that the scientific practice of river restoration requires an understanding of natural systems at or beyond our current knowledge, and presents a significant challenge to river scientists.

[3] Despite the absence of a rigorous scientific foundation and well-tested principles, river restoration is one of the most visible aspects of the hydrologic sciences [*Malakoff*, 2004]. The number of river restoration projects in the United States has increased exponentially in the last decade, and expenditures on small and midsize projects alone (e.g., excluding projects like the Kissimmee or the Colorado)

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average > $1 billion a year [*Bernhardt et al.*, 2005]. Rivers are highly valued by the public; everyone interacts with and pays attention to rivers [*Tunstall et al.*, 2000]. As the practice of river restoration continues to grow, the need to develop a sound scientific basis is obvious, as evidenced by the number of working groups and policy initiatives devoted to this topic within the federal government (e.g., USGS interagency River Science Network), nongovernmental organizations (e.g., The Nature Conservancy, American Rivers, local watershed groups), and academia (e.g., the National River Restoration Science Synthesis project [*Palmer et al.*, 2003] and the National Center for Earth-Surface Dynamics).

[4] Various perceptions of what is meant by 'restoration' reflect the wide disparities in stakeholder interests, scientific knowledge, scales of interest, and system constraints encountered in practice. In the parlance of river management, 'restoration' describes activities ranging from "quick fixes" involving bank stabilization, fencing, or engineering fish habitat at the reach scale, to river-basin-scale manipulations of ecosystem processes and biota over decades. We define river restoration as assisting the establishment of improved hydrologic, geomorphic, and ecological processes in a degraded watershed system and replacing lost, damaged, or compromised elements of the natural system. This definition is broad in that there is room for subjectivity and societal values in the definition of what constitutes "improved." Improved may include protection of property, enhanced aesthetic values, facilitating recreation and so on. The restoration of ecological functions and services of river systems is particularly important [*Covich et al.*, 2004]. We define ecological river restoration as assisting the recovery of ecological integrity in a degraded watershed system by reestablishing the processes necessary to support the natural ecosystem within a watershed. Because both technical and social constraints often preclude 'full' restoration of ecosystem structure and function, rehabilitation is sometimes distinguished from restoration. Our definition encompasses rehabilitation to the extent that it focuses on causes of system degradation through attainable reestablishment of processes and replacement of elements, rather than treating symptoms to achieve a particular condition or static endpoint.

[5] In this paper, we review the current status of river restoration and suggest strategies for improving its science and implementation. After outlining the need for scientific advances, we discuss how goals are set for restoration projects. We then review the science available to reach these goals, crucial gaps in scientific understanding, and major social challenges. Finally, we develop a research vision of how to advance the science of river restoration.

## 2. Need for Scientific Advances

[6] Most restoration projects focus on a single, isolated reach of river, yet the definition proposed above suggests that a watershed is the most appropriate spatial unit to use for most river restoration [*National Research Council*, 1999]. This reflects our view that successful restoration requires that key processes and linkages beyond the channel reach (upstream/downstream connectivity, hillslope, floodplain, and hyporheic/groundwater connectivity) also be considered [*Sear*, 1994; *Angermeier*, 1997; *Frissell*, 1997; *Poff et al.*, 1997; *Stanford and Ward*, 1992; *Graf*, 2001; *Palmer et al.*, 2005]. The importance of these linkages is without question; water, sediment, organic matter, nutrients and chemicals move from uplands, through tributaries, and across floodplains at varying rates and concentrations. Migratory fish move upstream and downstream during different stages in their lifecycles. These obvious examples of the inextricable linkages within watersheds are too often ignored in river restoration. To date, restoration has largely been done on a piecemeal basis, with little to no monitoring to assess performance, and little integration with other projects. This reflects the lack of process-based approaches in current practice as well as the fact that comprehensive restoration strategies that reestablish watershed-scale connections and processes are more difficult to implement because of sociopolitical and financial constraints.

[7] We assert that major advances in knowledge of river ecosystem processes are needed for application to river restoration [*Graf*, 2001], and that hydrologic scientists are central to those advances. We stress two themes around which a research agenda to advance river restoration must be built; these can be treated as hypotheses that require testing. First, because natural variability is an inherent feature of all river systems, we hypothesize that restoration of an acceptable range of variability of process is more likely to succeed than restoration aimed at a fixed endpoint that precludes variability. Restoration of process is also more likely to address the causes of river ecosystem degradation, whereas restoration toward a fixed endpoint addresses only symptoms. Second, because physical, chemical, and biological processes interconnect in complex ways across watersheds and across timescales from seconds to centuries, we hypothesize that all restoration projects are far more likely to be successful if undertaken in the context of entire watersheds. Using these two themes as a backbone, we suggest that the efficacy of river restoration can be enhanced by addressing seven critical questions: (1) What are the critical ecosystem processes that apply to all rivers and thus are fundamental to all restoration efforts? (2) What are the functional relationships between these ecosystem processes, hydrologic processes, ecological integrity and the amenities valued by society? (3) What are the critical knowledge gaps in our understanding of these interrelationships? (4) What are the spatiotemporal scales of the processes and the knowledge gaps? (5) What social factors constrain and/or dictate approaches to implementing restoration at the appropriate scale(s)? (6) What are the most efficient and cost effective approaches and tools for resolving uncertainty in restoration outcomes? (7) How can scientists best serve societal needs in restoring rivers?

## 3. Goal Setting in River Restoration

[8] A key distinction between river restoration and other management actions is the intent to reestablish "natural" rates of certain ecological and chemophysical processes and/or to replace damaged or missing biotic elements. That is, restoration is often fundamentally about enhancing ecological integrity [*Angermeier*, 1997; *Baron et al.*, 2002]. We define ecological integrity as the ability to self-sustain ecological entities (population, community, ecosystem) and processes (e.g., nutrient dynamics, sediment transport). Goals of individual restoration projects typically

**Table 1.** River Restoration Scenarios Based on Five Ecosystem Amenities That Commonly Motivate Restoration Projects[a]

| Amenity of Interest | Key Conditions | Components to Model | Potential Restorative Actions |
|---|---|---|---|
| Clean water | Water/sediment chemistry<br>Pathogen density | Contaminant/pathogen loading<br>Water/sediment transport<br>Pathogen population dynamics | Clean up point-sources of pollution<br>Alter land use in catchment |
| Uncontaminated food | Body-loads of contaminants | Contaminant loading<br>Water/sediment transport<br>Food organism/contaminant contact<br>Food organism metabolism of contaminant | Clean up contaminant sources<br>Constrain contaminant contact with food organism |
| Aesthetic appeal | Water clarity<br>Bank stability<br>Channel shape<br>Riparian/aquatic vegetation | Nutrient loading<br>Water/sediment transport<br>Suspended solids dynamics<br>Flow (disturbance) dynamics<br>Flow/vegetation interactions<br>Native/exotic vegetation interactions | Alter land/water use in catchment<br>Reinstate natural channel shape<br>Reinstate natural flow regime<br>Manipulate sediment composition<br>Manipulate vegetation composition |
| Rare or valued biota | Water/sediment chemistry<br>Habitat structure<br>Flow regime<br>Production dynamics<br>Other nonhuman biota | Contaminant loading<br>Water/sediment transport<br>Organism/contaminant contact<br>Habitat requirements/limitations<br>Organism/flow interactions<br>Trophic requirements/limitations<br>Interactions with competitors, predators, parasites | Clean up contaminant sources<br>Alter land/water use in catchment<br>Reinstate natural habitat structure<br>Reinstate natural flow regime<br>Reinstate natural productivity<br>Stock target biota<br>Reduce biota with adverse effects |
| Productive fishery | Water/sediment chemistry<br>Habitat structure<br>Flow regime<br>Production dynamics<br>Other nonhuman biota<br>Harvest regime | Contaminant loading<br>Water/sediment transport<br>Organism/contaminant contact<br>Habitat requirements/limitations<br>Organism/flow interactions<br>Trophic requirements/limitations<br>Interactions with competitors, predators, parasites<br>Impacts of harvest | Clean up contaminant sources<br>Alter land/water use in catchment<br>Manipulate habitat structure<br>Manipulate flow regime<br>Manipulate system productivity<br>Stock target biota<br>Reduce biota with adverse effects<br>Reduce harvest |

[a]Each amenity is typically limited by a few key conditions. Science-based restoration requires development of various conceptual models that explicate current knowledge of the determinants of key conditions and inform decisions about how to invest restoration resources. Herein the amenities are ordered by the approximate scientific complexity of their restoration. More complex restoration problems require more types of models and a broader array of scientific expertise. Scientific complexity is probably unrelated to socio-political feasibility. Examples of management actions that might facilitate restoration of the respective amenities are also listed.

reflect this general theme but details vary widely because the particular ecological entities and processes of interest differ greatly among projects and environmental settings. In many urban rivers, for example, the potential for ecological improvement is limited, and the principal benefits from a restoration project are social, such as building a sense of community by involving residents of a neighborhood or increasing pride in place.

[9] Despite the importance of an ecosystem context, river restoration projects are as much a social undertaking as an ecological one [*Kates et al.*, 2001; *Anderson et al.*, 2003]. Societal perceptions and expectations of ecosystem performance ultimately determine whether restoration is a viable management option. The involvement of stakeholders in restoration decisions is growing and they have diverse preferences, institutional mandates, and expertise. Decisions to restore rivers often involve debates about which ecosystem amenities should take precedence and how benefits should be distributed; for example, whether commercial uses of rivers (e.g., transportation, hydropower, irrigation) take precedence over recreational uses or esthetic interests. Restoration success is often judged on social considerations, which can be highly contentious, rather than ecological performance [e.g., *Connin*, 1991].

[10] The type of ecosystem amenity motivating restoration dictates the types and complexity of scientific expertise germane to a given restoration project (Table 1). From a study of >38,000 restoration projects, *Bernhardt et al.* [2005] found that the most commonly stated goals for river restoration in the United States are to (1) enhance water quality, (2) manage riparian zones, (3) improve in-stream habitat, (4) fish passage, and (5) bank stabilization. Enhancing water quality where a point source introduces contaminants requires relatively little scientific expertise to prescribe effective restorative actions. By contrast, the most complex, risky, and expensive projects are motivated largely by biological goals. For example, one of the largest, most ambitious restoration programs focuses on the San Francisco Bay ecosystem, which encompasses the San Joaquin and Sacramento river basins, as well as the delta, bay, and coastal ocean [*CALFED Bay-Delta Program*, 2000]. The primary goal of this program is to restore self-sustaining populations to hundreds of at-risk species over the next 20 years.

[11] When ecological considerations do motivate restoration, it is typically because the provision of ecosystem goods or services has been compromised. The primary amenities are typically clean water, productive fisheries, and edible (nontoxic) biota. Less commonly, restoration is also driven by desires for reliable water supply, persistence of valued (but nonfood) biota, and esthetics. The capacities of rivers to provide these services depend on maintaining or

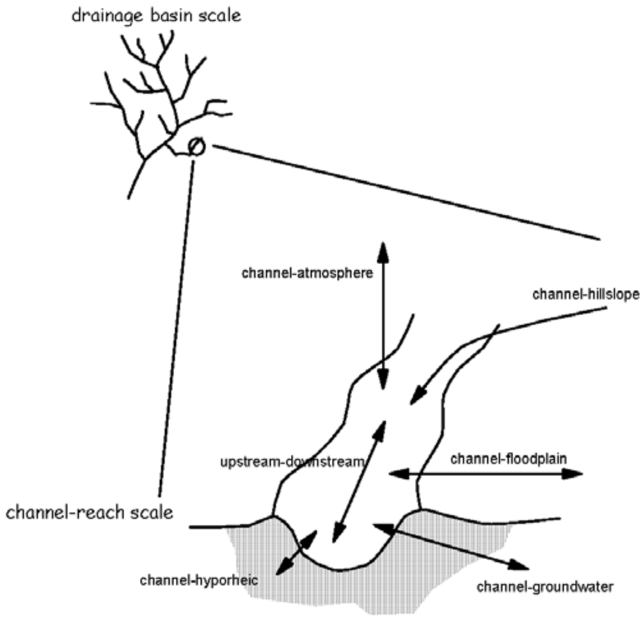


**Figure 1.** Schematic diagram of the connections between a river segment and the surrounding landscape, including the atmosphere and the subsurface. The shaded zone beneath the channel indicates the hyporheic zone. Examples of interactions include mercury deposition into stream from coal-burning emissions (channel-atmosphere); introduction of water, sediment, and wood from adjacent hillslopes (channel-hillslope); use of seasonally flooded valley bottom for fish nursery habitat and introduction of plant litter to channel during waning stages of flood (channel-floodplain); migration of fish and stream insects (upstream-downstream); migration of stream insects between surface and subsurface habitats (channel-hyporheic); and upwelling of inorganic nutrients into stream (channel-groundwater).

restoring high levels of ecological integrity [*Baron et al.*, 2002; *Richter and Postel*, 2003]. As the public increasingly recognizes the link between ecological integrity and these services, shifts in values may induce people to rethink assumptions about what is sociopolitically acceptable in restoration scenarios. For example, should reduced flood flows downstream from a dam constrain restoration efforts, or should restoration include greater flood-flow releases from the dam? Many factors assumed to be constraints twenty years ago are being reexamined as opportunities to restore rivers today.

[12] Scientists have several important roles to play that ensure that the knowledge citizens need to make informed decisions about river management is readily available. Educating the public about the relations between the operation of a river and its delivery of valued amenities is critical [*Norton*, 1998]. Scientists can also define the scope of ecological problems and help refine restoration strategies. In particular, conceptual models are very helpful in conveying the key relations, causal links, and uncertainties, which help stakeholders identify strategies with the greatest likelihood of success. Field experience and implicit knowledge of scientists can help refine prescriptions for implementing the restorative actions selected by stakeholders. Scientists can develop tools and techniques to monitor and assess river responses to restorative actions and convey recovery trends to the public in a meaningful way. Knowledge of such responses empowers stakeholders to evaluate restoration success and cost-effectiveness. Giving stakeholders a realistic timeframe within which various restoration interim goals may be achieved can allay false expectations of quick fix restoration approaches. Finally, because restoration seldom returns a river to the range of variability existing before humans substantially altered the ecosystem, scientists can influence restoration by assisting stakeholders in the difficult process of prioritizing development.

[13] Achieving restoration goals will be limited by a variety of scientific and nonscientific factors [*Angermeier*, 1997; *Hennessy*, 1998]. Scientific limitations include unavailable information on critical ecosystem conditions or processes, and inadequate synthesis of available information during model development. Nonscientific limitations include infeasibility of certain desired restorative actions (e.g., eradication of exotic species, reintroduction of extinct native species), and philosophical differences among stakeholders and disagreements over who should bear the social and economic costs of restoration. Resolving resource management issues across entire river basins and resolving conflicting interests among stakeholders requires degrees of coordination and cooperation rarely achieved in human society [*Naiman*, 1992]. For example, PACFISH, an interim strategy to restore watersheds supporting anadromous salmonids in federally owned portions of the U.S. Pacific Northwest, encompassed activities in 15 national forests, 7 districts of the U.S. Bureau of Land Management, 4 regions of the U.S. Forest Service, and 4 states [*Williams and Williams*, 1997]. In highly human-altered ecosystems, severe socioeconomic constraints and existing infrastructure can preclude significant improvement in ecosystem performance.

## 4. Science Available to Reach Goals: Central Concepts

### 4.1. Spatiotemporal Concepts

[14] We hypothesize that self-sustaining, ecologically successful restoration efforts are designed in relation to broad spatial (watershed) and temporal contexts (Figure 1). We already know a great deal about the linkages between large- and small-scale spatial and temporal processes in watersheds. Regional patterns of climate, geology, and topography impose important constraints on the physical and biological processes that regulate river structure and function [*Edmonds et al.*, 2003; *Montgomery and Bolton*, 2003]. Physical scientists recognize downstream zonation within river basins, from the headwater zone where most sediment is produced on adjacent hillslopes and introduced to stream channels, through the midsection of the basin that is dominated by transport, and into the lower river basin where sediment is deposited in floodplains and deltas [*Schumm*, 1977]. Any particular segment of a river has continual erosion and deposition through time. The energy of the river segment, as determined by hillslope and channel gradients, stream discharge, and sediment supply, will create a distinct geomorphic process and disturbance regime that in turn influences the aquatic and riparian communities [*Montgomery*, 1999]. Biological scientists have emphasized the importance of lateral connections between stream chan-

**Figure 2.** Photographs looking downstream along the channel of Uvas Creek in coastal California. (a) In January 1996, approximately 2 months after construction of a channel reconstruction project that emplaced a meandering channel form, and (b) in June 1997, after the project was destroyed during storm flows with a return period of 5–6 years. Historical geomorphological analysis indicated that the channel reach had been braided historically, typical of streams draining the Franciscan Formation in the California Coast Ranges, with episodic flows and high sand and gravel transport. (After *Kondolf et al.* [2001, Figure 5] with kind permission of Springer Science and Business Media.)

nels and floodplains [*Junk et al.*, 1989; *Bayley*, 1991; *Molles et al.*, 1998]; patterns of downstream continuity or discontinuity in physical and biological parameters [*Vannote et al.*, 1980; *Fischer et al.*, 1998; *Poole*, 2002; *Benda et al.*, 2004]; and vertical connections between the channel and underlying hyporheic zone [*Ward*, 1989; *Stanford and Ward*, 1993].

[15] Temporal as well as spatial considerations are fundamental to river science. The natural timing, frequency, duration, magnitude, and rate of change in flows (the "natural flow regime" [*Poff et al.*, 1997]) are each vital in governing ecological processes along a stream. Rare events can have an important and continuing effect on river morphology and biological communities [*Poff*, 1997]. In other words, a river has a history that continues to influence its present and future. These "legacy effects" can be studied by examining historical records such as photographs and discharge data, which may help in establishing prior conditions [*Petts*, 1989; *Koebel*, 1995; *Toth et al.*, 1995; *Kondolf and Larson*, 1995]. This historical information can provide valuable insights into how the channel has (not) changed and the options for restoration [*Kondolf et al.*, 2001; *Jaquette et al.*, 2005] (Figure 2).

### 4.2. Rivers as Dynamic Systems

[16] River ecosystems are constantly responding to environmental flux and human activities. Distinctly different states (e.g., channel position, levels of productivity) are the

norm, not the exception [*Palmer et al.*, 1997]. However, natural variability in ecological systems does have boundaries and for some rivers the variability is predictable in probabilistic terms [*Suding et al.*, 2004]. To persist as healthy ecosystems, rivers must be able to adjust to and absorb change at the timescales over which change occurs. An ideal ecologically successful restoration creates hydrological, geomorphological, and ecological conditions that allow the targeted river to be self-sustainable in its new context [*Palmer et al.*, 2005]. One of the implications of this understanding of river dynamics is that monitoring and evaluation of conditions before and after restoration must recognize the variability inherent even in "stable" rivers. Restoration that focuses on process rather than form will more effectively address most restoration goals. Process is more crucial than form in goals such as (1) improving water quality by changing infiltration-runoff paths and (2) stabilizing banks and increasing pool volume by allowing riparian vegetation to remain along river banks. Restoration projects that attempt to create a static or fixed form, such as meanders with riprapped banks (Figure 2), commonly fail [*Kondolf et al.*, 2003]. Rivers possess physical integrity, an aspect of ecological integrity, when their processes and forms maintain active connections with each other in the present hydrologic regime [*Graf*, 2001].

## 5. Challenges Arising From Gaps in Scientific Understanding

[17] Scientific understanding of how river ecosystems function provides a strong foundation for general restoration strategies [*Naiman et al.*, 1995; *Poff et al.*, 1997; *Trush et al.*, 2000; *Graf*, 2001]. However, for any particular restoration project, watershed managers and other stakeholders also typically ask scientists to predict how specific management actions will translate into geomorphic or ecological responses. Restoration science is beset by fundamental uncertainties in knowledge and by limited predictive capability. A number of tools, including watershed assessment, historical reconstruction, and decision support models, have been developed to help scientists inform restoration decisions [*Pess et al.*, 2003]. Nevertheless, gaps in scientific understanding pose several challenges for effective river restoration, and identification of these gaps points to critical research needs.

[18] We suggest that scientific understanding of river function is limited by three factors. First, because detailed knowledge arises from studies conducted at particular space-time scales, transferring knowledge from one study to another involves untested assumptions of transferability and scaling [*Walters and Korman*, 1999]. Despite individual uniqueness that reflects specific combinations of factors such as climate, biota and human alteration, rivers or river segments can be grouped into classes of similar behavior and potential. Several useful classifications have arisen based on hydrologic, geomorphic, and biological criteria [see *Naiman et al.*, 1992]. However, river scientists have not yet reached a consensus on the limits to transferability of knowledge gained from one system or situation. River scientists need to develop a framework for ecological understanding of restoration outcomes. Achieving and clearly articulating this consensus would be a major advance in river science.

[19] A second scientific challenge arises from the need to consider restoration projects as experiments that can teach us about ecosystem operation. Most restoration projects have been implemented without the study design, baseline data, and postproject appraisal needed to learn from them [*Downs and Kondolf*, 2002; *Bernhardt et al.*, 2005]. Much of the published literature, which forms the basis of our ecological understanding, describes research conducted at space-time scales much smaller than those appropriate for restoration. Furthermore, many restorative actions are applied at scales too small to produce the intended effects on biotic populations and assemblages [*Pretty et al.*, 2003]. A major limitation in advancing scientific knowledge to guide predictive restoration is the lack of opportunities to conduct large-scale experiments, where whole system responses can be evaluated at scales that match management actions. For example, restoration of flow regimes below existing water control structures presents tremendous opportunities to learn about system-specific responses that can guide future restoration actions [*Poff et al.*, 2003]. Experimental flood releases such as those on the Colorado River in Grand Canyon [*Collier et al.*, 1997] or the Murray River in Australia [*Arthington and Pusey*, 2003] provide opportunities to pose and test hypotheses regarding the ecosystem effects of these floods. Despite the lack of standard experimental features such as randomization of controls and treatments, or replication, the flood releases create quasi-experiments that provide important knowledge about river response to restoration efforts [*Block et al.*, 2001].

[20] Viewing restoration projects as experiments affords a framework for engaging scientific involvement early in the process and strengthens the rationale for monitoring the results of the restoration action. The adaptive management paradigm coupled with effective monitoring facilitates learning from experience [*Walters*, 1997; *Rogers*, 2003], and has been repeatedly identified as a critical and missing component of existing river management programs such as that on the Platte River [*National Research Council*, 2005]. We currently have far too few experiments at appropriate scales that are conducted adaptively and thus we have not yet developed scientific guidelines for how best to restore adaptively or over what timescale adaptive management should be applied.

[21] A third scientific challenge facing river restoration is the difficulty of integrating disciplinary knowledge into interdisciplinary understanding. This familiar but enduring problem arises from mismatches in language, conceptual frameworks, scales of operation, research methods, and historical underpinnings of the disciplines involved in river science, management and restoration [see *Benda et al.*, 2002]. There is ample evidence that river scientists [*Nilsson et al.*, 2003] are attempting to integrate principles of hydrology, geomorphology, and ecology into synthetic frameworks to better understand and predict how river systems function and respond to manipulation. Given the obvious multidisciplinary dimensions of river structure and function, effective restoration science must continue to be explicitly grounded in interdisciplinary research and understanding. We believe that scientists must acquire better models for rapidly developing effective collaborations as

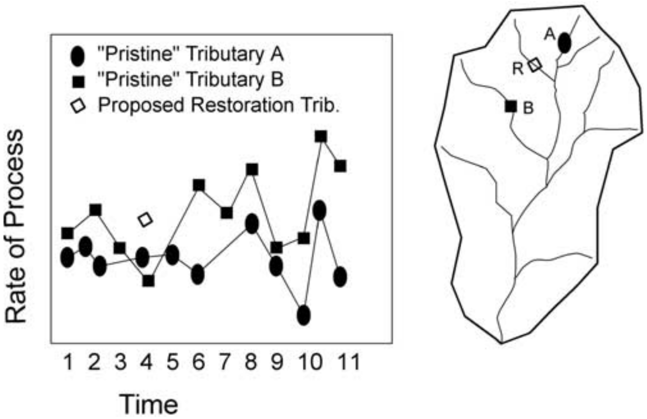


**Figure 3.** Schematic to illustrate that the ecological and geomorphic processes in a stream vary naturally over time and space. Determining when a site is degraded sufficiently to warrant restoration requires an understanding of the range of natural variability. For simplicity, we assume that the process of interest has only been measured once in the proposed restoration tributary but the pristine or "reference" tributaries are routinely monitored. The graph suggests that if only pristine tributary A had been sampled during times 1–6, one might conclude that tributary R was in need of restoration because the rates of some key process such as sediment flux or organic matter decomposition appear too high. However, with the addition of a second reference site (pristine trib B) it appears that processes in the trib R are within the natural range of variability. Similarly, if sampling of reference sites continues over longer time periods (through time 11), this indicates that trib R is well within the range of natural variability in the process being measured and restoration is not warranted.

new problems arise and the need for rapid responses by interdisciplinary groups of scientists increases [*Palmer et al.*, 2004].

[22] Finally, we assert that scientists and society must acknowledge that restoration decisions will continue to be made in the face of substantial scientific uncertainty, and thus there will continue to be a role for "qualitative" scientific judgments in informing restoration actions. It is unrealistic to expect restoration science to rapidly transform into a predictive, quantitative discipline in the near term, particularly in light of the fact that we do not yet have the ability to make specific predictions about natural and completely functioning systems, much less those that are highly modified. Being able to confidently specify the direction of ecosystem response to a restoration action, if not the exact magnitude, is often adequate to inform a management decision. Some examples of appropriate tools include Bayesian belief networks, which express complex system behavior probabilistically, and thus facilitate predictive modeling based on knowledge and judgment [e.g., *Reckhow*, 1999; *Graf*, 2001] (Figure 3); Fuzzy Cognitive Mapping, which can be used to distill expert scientific judgments about ecosystem components and interactions to identify effective management strategies that account for stakeholder concerns [*Hobbs et al.*, 2002]; and the weight-of-evidence approach applicable where there are confounding factors, unreplicated experiments, and/or long response times (i.e., many restoration projects), which impair our ability to interpret outcomes with conventional straightforward statistical analyses [*Lowell et al.*, 2000]. Given this outlook, there is a pressing need to employ analytical tools that allow sound scientific advice to be offered in spite of residual uncertainty. These tools should be decision-oriented and should accessibly link modeled components with the amenities (decision endpoints) valued by stakeholders (Table 1).

## 6. Challenges Arising From Social Limitations to Science-Based River Restoration

[23] River restoration, like other environmental management, is fundamentally a social process that invokes science to varying degrees. Effective environmental management seeks to improve the economic, political, and social contexts from which perceived problems arise [*Bryant and Wilson*, 1998]. River restoration becomes a viable management option when ecological conditions currently perceived by stakeholders no longer meet their expectations. Human expectations of ecosystems reflect the prevailing culture and views of how ecosystem operation is related to quality of life. If no such relation is thought to exist, any ecosystem state may be acceptable and restoration would be viewed as frivolous. Functional rivers contribute to human quality of life [*Costanza et al.*, 2002] along several dimensions, including emotional, esthetic, intellectual, physical, social, and spiritual. However, the prevailing economic view, which espouses an ever-expanding conversion of natural capital to human money, discounts the amenities that accrue to society from ecological restoration. The foremost social challenge for river scientists is to assume more responsibility as public educators, both in the capacity of providing scientific information and as catalysts for changing societal values.

[24] Advancing the science of river restoration and advancing the implementation of restoration are separate but related problems. The science advances by improving our understanding of ecosystem operation, whereas implementation advances by energizing stakeholder demand for restoration (and so, for the science informing that restoration). Failure to cultivate societal demand for restoration not only limits opportunities for scientific advancement, but also jeopardizes the science's long-term relevance and vitality. Because large-scale restoration is infeasible without broad stakeholder support, future opportunities to advance restoration science depend on future demand for the ecosystem amenities that restoration can potentially provide. Therefore a crucial educational role for river scientists is to communicate the many ways in which functional ecosystems enhance stakeholders' quality of life, as well as how delivery of those benefits is impaired when rivers are degraded.

[25] Environmental management debates are ultimately about what form of nature we want and why [*Clark*, 1989; *Hull and Robertson*, 2000]. The language and concepts used in these debates are value laden, although underlying values are often not elaborated [*Barry and Oelschlaeger*, 1996; *Allen et al.*, 2001]. For example, a basic value judgment underpinning the notions of ecological integrity and resto-

ration is that naturally evolved genomes, communities, and landscapes are more valuable than artificial ones [*Angermeier*, 2000]. Scientific terms used in environmental debate strongly influence stakeholder perceptions of environmental quality and the appropriateness of available management actions. As river scientists collaborate with stakeholders on restoration projects, they create opportunities to articulate the values underlying applicable scientific concepts [*Funtowicz and Ravetz*, 1993]. Relating these values to real-world situations can go a long way toward catalyzing the cultural changes needed to enhance public demand for science-based restoration of rivers [*Preister and Kent*, 1997].

[26] Conducting (and improving) restoration science requires scientists to participate in real-world, politically complex projects. Long-term strategies for managing flow regimes, land use, and native biota are critical for restoring ecological integrity to rivers, but inevitably provoke controversy and require great investment in political processes. The challenges associated with forging such long-term strategies are further complicated by financial constraints, fragmentation among agency mandates, and a lack of decision-oriented scientific tools designed to help stakeholders envision future scenarios and prioritize actions. Another important social challenge for river scientists is to become adept at working with a broad range of nonscientists, including economists, landowners, lawyers, and resource managers, in pursuit of common restoration goals. This may require river scientists to develop new skill sets that enable them to communicate and negotiate in common, less technical terms and in unconventional venues.

[27] The social context of restoration can also limit or preclude independent scientific review of restoration projects. Although scientists necessarily hold values, the system of scientific peer review ensures that individual values are scrutinized and challenged. Large, federally sponsored restoration projects such as those in the Grand Canyon or the Kissimmee River of Florida undergo rigorous review scientific peer review. Extending the process of peer review to the majority of river restoration projects would strengthen the science behind individual project decisions and likely improve public confidence in the ability of scientists to restore rivers.

## 7. Research Vision: How Do We Advance the Science of River Restoration?

[28] 1. Advances in our understanding of the intrinsic complexities of river ecosystems have resulted in large part from recognition of the inherent dynamism and multidimensional nature of rivers. Although there are needs for additional research into basic issues pertaining to restoration science, the bottleneck to progress in river restoration is not necessarily lack of data or information. An urgent need is to couple data collection with a distillation and refinement of what is known about the physical and biological drivers that govern process in river landscapes. Such models and tools could be used to inform and guide those involved in restoration activities, to inform the general public, to influence policy makers, and to educate and empower the nonacademic practitioners who are conducting most of the applied river science taking place. The River Styles Framework developed by *Brierley and Fryirs* [2005] provides an excellent example of a tool for communicating existing understanding of rivers to those undertaking river restoration.

[29] 2. Defining restoration success in aquatic and riparian ecosystems is an issue clouded by the common failure of project designers to define goals clearly at the onset of restoration. Without clear goals or objectives it is impossible to develop criteria from which the degree of success or failure of a project may be quantitatively assessed [*Kondolf*, 1995; *Palmer et al.*, 2005]. The objectives of the restoration dictate what variables should be measured. Successful restoration in an urban setting may be largely based on the enhancement of esthetic values or minimization of flood risk, whereas success on a wildland river may be gauged by elevated fishery productivity, improved water quality, riparian forest restoration, or enhancement of a variety of other functions. In the case of esthetics, quantitative measures of recovery may be unnecessary and a public opinion survey might be the most appropriate way to gage a project's success. In the latter cases, the range of parameters to measure can be staggering. *Palmer et al.* [2005] recently proposed standards for ecologically successful river restoration projects. Although these standards were endorsed by an international group of river scientists [*Jansson et al.*, 2005] and practitioners [*Gillilan et al.*, 2005], guidelines for evaluating projects with respect to these criteria remain an important and active area of research. It is critical that guidelines for defining realistic and measurable river restoration goals be developed with broad input from both the scientific and practitioner communities and that these guidelines be endorsed by agencies at local and national levels.

[30] 3. We do not wish to imply a need for universal success criteria (however, see *Palmer et al.* [2005]). Developing criteria for measuring the baseline condition of a system and for monitoring responses of biota to changes in physical processes are complex tasks that vary greatly by stream and according to project goals. It may be easier to gage the condition of physical properties, such as stream channel "integrity," for which the options for measurement are fairly well defined [*Graf*, 2001], than to assess the recovery of biota. Organismal response is complicated because organisms have complex physiologies, variable life histories, and mobile populations. It remains unclear whether biotic metrics can simultaneously provide sensitivity to changes in driving variables over short time scales; a good short-term measure of response of individuals to restoration; a robust view of the recovery or state of the system; and compelling factors with which restoration success can be demonstrated to the general public. However, factors such as population structure (age-class distribution), incremental or annual growth of organisms, and mortality can be both sensitive and robust. Other synthetic metrics to gage ecosystem integrity or health have also been developed (i.e., index of biotic integrity [*Karr et al.*, 1986]) and may prove fruitful in some circumstances. We believe that scientists need to dramatically increase the number of assessment tools, especially those that are synthetic in nature and capture status of processes, not just channel form or ecosystem structure.

[31] Alberta Environment developed an ecosystem approach for determining in-stream flow needs of rivers in Canada for restoration of river processes downstream from dams [*Clipperton et al.*, 2003]. The approach constructs flow duration curves for high, medium, and low-flow years and links specific attributes of water chemistry, channel maintenance, fish life history, and cottonwood (*Populus* spp.) life history to flows. Such approaches are very compelling because they link life history attributes and abiotic processes to a variable that may be manipulated. The resulting flows that are built based upon the needs of each of the ecosystem components reflect the minimum flows necessary to maintain the desirable attributes of the system. Such simple approaches to complex problems are useful because the concept is transferable to any system, and the components may be customized to societal values or recreational demands.

## 8. Strategy for Achieving Vision

[32] Returning to the seven critical research questions outlined in the introduction, we propose a five-point research strategy for advancing the science of river restoration.

[33] 1. Continually develop a theoretical framework that enables us to ask relevant questions, quantify river and ecosystem response to change, and measure the most effective set of variables to achieve restoration objectives (questions 1–3, 6, and 7): Given the inherent dynamism of rivers, and the resulting uncertainty in restoration projects, one of the most important contributions that scientists can make to restoration is to develop means of quantifying predictions relevant to restoration. These include quantification of (1) channel response to physical changes using concepts such as the probability of various river configurations, (2) ecologically relevant aspects of flow regime at ungauged sites, or aspects of flow relevant to restoration, (3) diagnostic biological indicators of hydrologic and/or geomorphic restoration, and (4) methods for regionalizing hydrologic response in terms that are biologically relevant. Regionalized models of hydrologic response can provide a context for restoration in the many ungauged river basins within which restoration is undertaken. Hydrologic observatories could provide a basis for such regionalization by serving as field laboratories in which to document regional patterns of hydrologic and biological response to variability associated with climate and land use.

[34] 2. Explicitly recognize known complexities and uncertainties of river systems by addressing the effects of differing time and space scales as these affect river restoration (question 4): We believe that scientists need to develop studies examining the relative contributions of processes operating at different time and space scales for particular restoration goals. Well-designed studies can determine the minimal set of processes that need to be incorporated in a particular restoration project to achieve success, as well as the time and space scales at which these processes occur. Better understanding of time and space scales relevant to restoration will facilitate design of the most effective configuration of multiple restoration projects within a basin, and identification of the appropriate scale for restoration (for example, is it necessary to reforest a whole watershed or is it sufficient to facilitate the establishment of riparian revegetation?). Such understanding can also be used to define the meaning of a "watershed context" for restoration.

[35] Quantifiable predictions most relevant to river restoration are inherently multidisciplinary [*Palmer et al.*, 2003]. Several national research initiatives are currently underway that are relevant to restoration, yet there is little or no coordination among these initiatives with respect to selection of measurement sites or research questions. Relevant proposed and existing initiatives include the NSF programs National Ecological Observatory Network (NEON), Long-Term Ecological Research Sites (LTER), Collaborative Large-Scale Engineering Assessment Network for Environmental Research (CLEANER), and Ocean Observatory Program, as well as the U.S. Geological Survey's National Water Quality Assessment program (NAWQA), and the proposed hydrologic observatories and hydrologic synthesis centers currently under discussion at NSF (both Earth Sciences and Bioengineering and Environmental Systems). Cross-directorate funding initiatives that link these programs could substantially enhance river restoration by supporting adaptive management that involves ecosystem-scale experiments with sufficient duration of research and monitoring to synthesize the outcomes of experiments and/or restoration efforts. Hydrologic observatories should incorporate chemophysical-ecological linkages relevant to river restoration (e.g., biological response to temporal and spatial variability in flow regime and sediment supply).

[36] 3. Enhance the science and use of restoration monitoring: We know little about the success of different restoration approaches because so little monitoring is done either before or after project implementation [*Bernhardt et al.*, 2005]. There are many reasons for the lack of monitoring and evaluation, but one is that funding sources often have narrow requirements. Another is that we need to develop easily useable and robust methods for prerestoration and postrestoration monitoring [*Dahm et al.*, 1995; *Palmer et al.*, 1997; *Holl et al.*, 2003]. For example, traditional scientific grants rarely include components for consulting with local groups, and such contacts carried out as part of research projects must usually be "bootlegged." Many restoration grant programs are explicitly for implementation only, not for "studies" or "monitoring" of built projects. In effect, the projects are implicitly assumed to be effective. Although more restoration funding programs now require good postproject appraisal than in the past, the best estimates to date suggest that only 10% of river restoration projects in the United States have any postproject evaluation conducted (www.nrrss.umd.edu) [*Bernhardt et al.*, 2005].

[37] 4. Link science, practitioners, and stakeholders (question 7): For river restoration projects to succeed, both good science and public support are needed. Restoration actions mandated by centralized agencies but not supported by local residents are less likely to succeed in the long run because residents are less likely to maintain the project, report problems, etc. On the other hand, although local support is valuable, it is not sufficient for a successful project. Restoration project goals ultimately reflect societal preferences, but if project objec-

tives are not shaped by scientific understanding, restoration projects may become little more than attempts to impose culturally preferred landscape ideals where they will not be sustained by channel processes [*Kondolf et al.*, 2001].

[38] Decision makers are charged with allocating (always) limited resources for river restoration. This is an exercise in triage, because the funds available are typically only a fraction of what would be needed to accomplish comprehensive restoration. Thus cost effectiveness is a key criterion in restoration decisions. Scientists can help by providing input such as the restoration potential of a given reach and the relative importance of the reach in the larger system. This will require the development of well-designed prioritization schemes based on sound scientific models and principles. For example, why invest heavily in salmonid spawning and rearing habitat enhancement in a coastal catchment if the main source of mortality is in the coastal lagoon downstream? Science clearly has an important role to play in helping decision makers and stakeholders formulate realistic goals and select restoration strategies, but for this interaction to be fruitful, the scientific input must be accepted early in the process, and the scientists must communicate their findings clearly to a lay audience [*Poff et al.*, 2003].

[39] Interactions between scientists and stakeholders interested in a project are typically limited. One of the reasons is that scientists approach information and use language differently from nonscientists, often leading to poor communication between scientists, stakeholders, and decision makers. Even when scientists work hard to communicate with stakeholders, the latter may lose confidence in a scientific perspective if they perceive it as too abstract or uncertain. In contrast, if someone with less technical training makes definitive predictions about river behavior, and is willing to design channels that better align with the desired landscapes of the public, then the public may embrace these designs. The trap is that the public may become disillusioned with restoration altogether if specifically predicted outcomes fail. Better public education and communication of science is thus essential, and the science should be presented as a basis for informing rather than making decisions [*Palmer et al.*, 2004]. Suggested improvements include developing curricula to teach students how to work successfully as scientists in complex social and multidisciplinary contexts.

[40] Synthesis centers may provide an opportunity to encourage interactions between scientists and practitioners of river restoration by developing workshops that bring together participants from both sides of river restoration. These types of workshops could also promote the involvement of science in restoration design early in the process, rather than after the restoration is begun or implemented.

[41] 5. Develop methods of river restoration that are effective within existing constraints (question 5): We believe that scientists need to identify the greatest limitations to restoration in general and within a particular project. Such limitations can be imposed by hydrology, geomorphology, ecology, or stakeholder attitudes. For example, restoration of self-sustaining channel morphology, habitat, and associated insect and fish populations in a particular segment of river might not be feasible because of upstream flow regulation, or it might be undesirable (even if feasible) because of other social costs. Identifying such limitations will help focus restoration research and policy. There is a particular need to develop methods to restore urbanized and/or highly constrained rivers. Scientists frequently lack adequate design criteria for accelerating the recovery of bank and floodplain vegetation given the hydrologic and hydraulic constraints encountered in these systems. This requires identification of what functions can be most efficiently restored that maximize river ecosystem sustainability (or some level of functionality) for some unit economic cost. Scientists also need to identify less disruptive modes of urban development before development occurs. For example, use of infiltration zones instead of storm sewers in urban areas reduces subsequent water quality impacts and associated need for restoration.

## 9. Summary

[42] Implementing the research vision and strategy outlined here has the potential to produce significant impacts on the practice of river restoration. We expect these to include coordinated communication within the scientific community with respect to river restoration, and thus more effective and applicable conceptual and predictive models of river ecosystem behavior. We also expect continual opportunity for improved restoration strategies and for successful restoration implementation as we learn from past projects through monitoring. Finally, improved communication and trust between scientists, restoration practitioners, and river stakeholders can only help both rivers and the people who live among them.

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