

RIVER RESTORATION

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Abstract

River restoration is currently at the forefront of applied hydrologic science. However, many river restoration projects are conducted with minimal scientific context. We define river restoration as assisting the recovery of ecological integrity in a degraded watershed system by reestablishing hydrologic, geomorphic, and ecological processes, and replacing lost, damaged, or compromised biological elements. Major scientific advances are needed for applying existing knowledge of river ecosystem processes to restoration, and hydrologic scientists are central to the development of those advances. We propose two themes around which a research agenda to advance river restoration can be built. First, because natural biophysical 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 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 of degradation. Second, because physical and biological processes are interconnected in complex ways across entire watersheds and across time scales, we hypothesize that all restoration projects are far more likely to be more successful in achieving ecological goals if undertaken in the context of entire watersheds. Advancement of the science of river restoration must include: an explicit recognition of the known complexities and uncertainties; the application of increasingly advanced technologies for measuring relevant processes; continual development of a theoretical framework that enables us to draw generalities between river systems and to ask relevant questions, to consider the correct temporal and spatial scales of measurement, and to measure the most effective set of variables to achieve restoration objectives; enhancing the science and use of restoration monitoring; linking science and practitioners; and developing methods of restoration that are feasible within existing constraints. Current limitations to the science of river restoration include a lack of technical knowledge of watershed-scale dynamics of biophysical processes, institutional structures that are poorly suited to large-scale adaptive management, and a lack of political support to correct socioeconomic causes of river degradation.

Introduction: Problem statement

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, streams and rivers continue to deteriorate as a result of human influences (Karr and Chu, 1999). Further, 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, it is

imperative that we work vigorously to enhance the state and perception of restoration science. Many projects designed to restore rivers are currently being conducted throughout the U.S. with minimal scientific context. Specifically, many projects lack (i) the inclusion of a solid conceptual model of river ecosystems; (ii) a clearly articulated understanding of ecosystem processes; (iii) recognition of the multiple, interacting temporal and spatial scales of river response; and (iv) long-term monitoring of success or failure in meeting project objectives following completion (Pedroli et al., 2002).

Despite the absence of a rigorous scientific foundation and well-tested principles, river restoration is one of the most “high profile” aspects of the hydrologic sciences (Malakoff, 2004). 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 quite 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), non-governmental organizations (e.g. The Nature Conservancy, American Rivers, local watershed groups), and academia (e.g. the National River Restoration Science Synthesis www.nrrss.umd.edu).

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 stream and 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 recovery of ecological integrity in a degraded watershed system by reestablishing natural hydrologic, geomorphic, and ecological processes, and replacing lost, damaged, or compromised biological elements.* 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.

The need for scientific advances

The majority of restoration projects focus on a single, isolated reach of stream or river, yet the definition proposed above suggests that a watershed is the most appropriate spatial unit to use for river restoration. This reflects our view that successful restoration requires that key processes and linkages beyond the channel reach – upstream/downstream connections, hillslope, floodplain, and hyporheic/groundwater connections – also be considered (Sear, 1994; Angermeier, 1997; Frissell, 1997; Poff et al., 1997; Stanford and Ward, 1992; Graf, 2001; Palmer et al., 2004b). The importance of these linkages is biophysically without question; water, sediment, heat, 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 portions of 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 piece-meal basis, with little to no monitoring, 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.

We assert that major scientific advances are needed for applying existing knowledge of river ecosystem processes to restoration (Graf, 2001), and that hydrologic scientists are central to the development of 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 biophysical 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 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 of degradation. Second, because physical and biological processes are interconnected in complex ways across entire watersheds (laterally, vertically, and cross-channel) and across time scales from seconds to centuries, *we hypothesize that all restoration projects are far more likely to be ecologically successful if undertaken in the context of entire watersheds.* Using these two themes as a backbone, an intellectual context that can be used to guide the practice of river restoration must be built on research that addresses 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, biological integrity and the amenities valued by society?
3. What are the critical knowledge gaps in our understanding of these interrelationships?
4. What are the scales of the processes and the knowledge gaps?
5. What is the societal context that constrains and/or dictates approaches to advancing restoration at the appropriate scale(s)?
6. What are the "best" approaches and tools for resolving uncertainty in restoration outcomes?
7. How can scientists best serve societal needs in restoring rivers?

Goal setting in river restoration

A key feature distinguishing ecosystem restoration from other management actions is the intent to reestablish “natural” (less impaired) rates of certain ecological and chemo-physical processes and/or to replace damaged or missing biotic elements. That is, restoration is fundamentally about enhancing ecological integrity (Angermeier, 1997; Baron et al., 2002). Goals of individual restoration projects typically reflect this general theme but details vary widely because the particular ecological processes and biotic elements of interest can differ greatly among projects and biophysical settings. In many urban channels, the potential for ecological improvement is limited, and the principal benefits from a restoration project are social, building a sense of community by involving residents of a neighborhood, increasing pride in place, etc. Even in rural areas, the

cooperation of landowners and support of other members of the community (and local agencies) are needed to implement and sustain restoration projects. It is important to remember that river restoration projects are as much, and perhaps more, 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 (or not) often involve debates about which ecosystem amenities should take precedence and how benefits should be distributed; for example, whether consumptive uses of rivers (e.g. commercial transport, hydropower, irrigation) take precedence over recreational uses or esthetic interests. Thus, restoration project success is often judged on social considerations (sometimes highly contentious) rather than ecological performance (e.g., Connin, 1991).

The type of ecosystem amenity motivating restoration dictates the types and complexity of scientific expertise germane to a given restoration project (Table 1). Restoring water quality, a common goal in river restoration, 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 ever initiated 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, 2000). The primary goal of this program is to restore self-sustaining populations to hundreds of at-risk species over the next twenty years.

Table 1. River restoration scenarios based on five ecosystem amenities that commonly motivate restoration projects. 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.

| Amenity of interest | Key conditions | Components to model | Potential restorative actions |
|----------------------------|--|---|--|
| Clean water | Water/sediment chemistry Pathogen density | Contaminant/pathogen loading Water/sediment transport Pathogen population dynamics | Clean up point-sources of pollution Alter land use in catchment |
| Uncontaminated food | Body-loads of contaminants | Contaminant loading Water/sediment transport Food-organism/contaminant contact Food-organism metabolism of contaminant | Clean up contaminant sources Constrain contaminant contact with food-organism |

| | | | |
|----------------------|---|--|--|
| Aesthetic appeal | Water clarity Bank stability Channel shape Riparian/aquatic vegetation | Nutrient loading Water/sediment transport Suspended solids dynamics Flow (disturbance) dynamics Flow/vegetation interactions Native/ exotic vegetation interactions | Alter land/water use in catchment Reinstate natural channel shape Reinstate natural flow regime Manipulate sediment composition Manipulate vegetation composition |
| Rare or valued biota | Water/sediment chemistry Habitat structure Flow regime Production dynamics Other nonhuman biota | Contaminant loading Water/sediment transport Organism/ contaminant contact Habitat requirements/limitations Organism/flow interactions Trophic requirements/limitations Interactions with competitors, predators, parasites | Clean up contaminant sources Alter land/water use in catchment Reinstate natural habitat structure Reinstate natural flow regime Reinstate natural productivity Stock target biota Reduce biota with adverse effects |
| Productive fishery | Water/sediment chemistry Habitat structure Flow regime Production dynamics Other nonhuman biota Harvest regime | Contaminant loading Water/sediment transport Organism/contaminant contact Habitat requirements/limitations Organism/flow interactions Trophic requirements/limitations Interactions with competitors, predators, parasites Impacts of harvest | Clean up contaminant sources Alter land/water use in catchment Manipulate habitat structure Manipulate flow regime Manipulate system productivity Stock target biota Reduce biota with adverse effects Reduce harvest |

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 non-food) biota, and esthetics. The capacities of rivers to provide these services depend on maintaining or 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 possible (sociopolitically acceptable) in restoration scenarios. Thus, notions about what counts as a restoration constraint versus a restoration opportunity are continually evolving. For example, should reduced flood flows downstream from a dam be a constraint to the kind of restoration we can achieve, or

should we allow greater flood-flow releases from the dam, thereby deliberately reinstating many of the hydrogeomorphic processes that sustain the biota? Many factors that would have been assumed to be constraints twenty years ago are being re-examined as opportunities to restore rivers today.

Scientists have several important roles to play that ensure that the knowledge citizens need to make informed decisions about river management is readily available. First, educating the public about the relations between the operation of a river and its delivery of valued amenities is critical (Norton, 1998). Second, scientists can 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 (Healey et al., in review). Third, field experience and implicit knowledge of scientists can help refine prescriptions for implementing the restorative actions selected by stakeholders. Fourth, scientists can develop tools and techniques to monitor and assess river responses to restorative actions. Knowledge of such responses empowers stakeholders to evaluate restoration success and cost-effectiveness. Finally, restoration seldom, if ever, returns a river ecosystem to the historical range of variability existing before numerous human activities within the basin altered the ecosystem. Our inability to truly “restore” rivers highlights the fact that, because preservation is easier than restoration, scientific expertise may be most effective in assisting river conservation when applied to prioritizing development.

Achieving restoration goals may be limited by a variety of scientific and non-scientific factors (Angermeier, 1997; Hennessy, 1998). Scientific limitations include unavailable information on critical ecosystem conditions or processes, inadequate synthesis of available information during model development, and infeasibility of certain desired restorative actions (e.g., eradication of exotic species, reintroduction of extinct native species). Non-scientific limitations include philosophical differences among stakeholders and disagreements over who bears the social and economic costs of restoration. Resolving resource-management issues across entire river basins and resolving competing 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.

Science available to reach goals: central concepts

Spatio-temporal concepts: As stated at the outset of this paper, 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 linkage between large and small scale spatial and temporal processes in watersheds. 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 suite of 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 channels and floodplains (Junk et al., 1989; Bayley, 1991); 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).

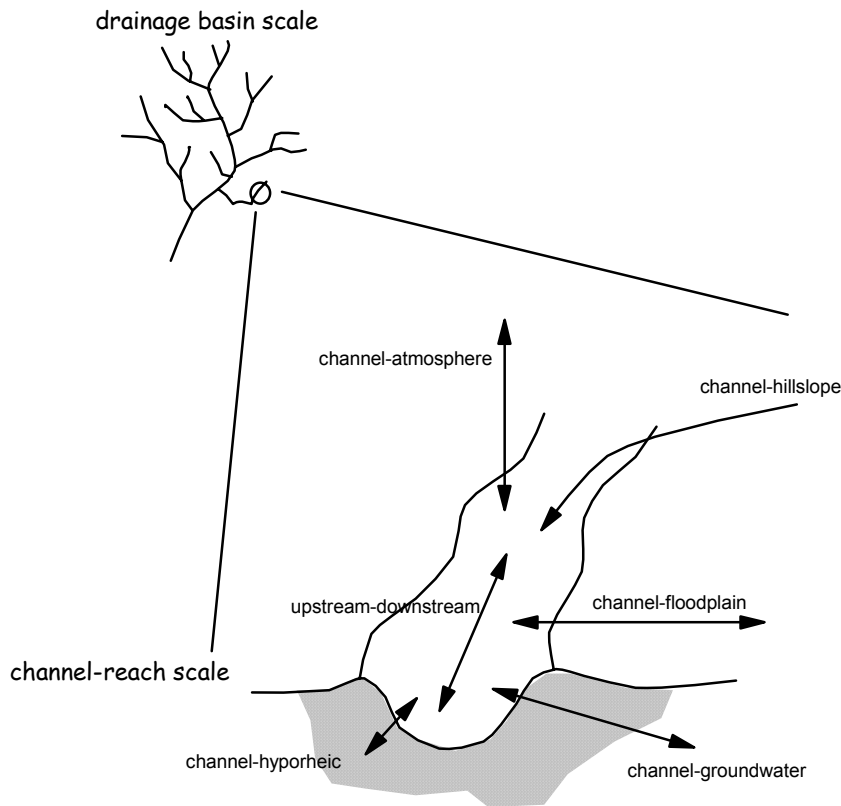


Figure 1. Schematic diagram of the connections between a river segment and the surrounding landscape, including the atmosphere and the subsurface. The shaded zone beneath the channel indicates the hyporheic zone. Examples of interactions: mercury deposition into stream from coal-burning emissions (channel-atmosphere); 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).

In the same way that spatial considerations are fundamental to river science, temporal considerations are critical. The timing, frequency, duration, 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 or unique occurrences 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 or has not changed and what the options are for restoration (Jaquette et al., in review).

Rivers as dynamic systems: River ecosystems are constantly subject to changing conditions resulting from environmental flux and human activities. To persist, river ecosystems must be able to adjust to and absorb change on the time scales over which change occurs (e.g., months, years, centuries). An 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., 2004b). Natural river ecosystems are self-sustaining, even though they are dynamic and have high variability that is often generated by natural disturbances rather than anthropogenic ones. Distinctly different states (e.g., channel position, levels of productivity) are the norm, not the exception (Palmer et al., 1997). However, this natural variability does have boundaries and for some rivers the variability is predictable in probabilistic terms.

Physical and ecological conceptual models of rivers acknowledge that rivers are inherently dynamic. Channel form may constantly shift to maintain a balance with changing water and sediment input and bank stability. Geomorphologists describe these changes partly as a function of time (Figure 2). One of the implications of this understanding of stream processes and form is that monitoring and evaluation of stream condition both before and after restoration must recognize the variability inherent even in “stable” streams.

Restoration projects that attempt to create a static or fixed form, such as meanders with riprapped banks, have very high failure rates (Kondolf et al., 2003). Restoration that focuses on process rather than form can also be more flexible in addressing varied goals, from improving water quality in urban streams by changing infiltration-runoff paths, to stabilizing banks, adjusting channel planform and increasing pool volume in streams draining agricultural lands by allowing riparian vegetation to remain along stream banks. Rivers possess physical integrity when their processes and forms maintain active connections with each other in the present hydrologic regime (Graf, 2001), and physical integrity in turn is necessary for creating and maintaining biological integrity.

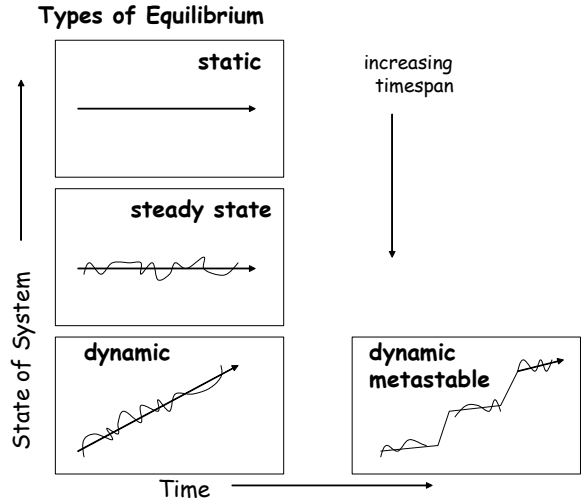


Figure 2. Schematic representation of changes in a river system through time. The variable on the y-axis could be river cross-sectional dimension, channel planform, etc. This variable is likely to be unchanging over very short timespans (static equilibrium). As the timespan increases, the variable is likely to fluctuate about a consistent mean (steady state), whereas over longer timespans the variable will exhibit progressive changes (dynamic or dynamic metastable equilibrium). (After Schumm, 1977, Figure 1-2).

Dynamic systems in complex space-time contexts – implications for research: The interconnectedness of a river with its landscape, and the inherent instability of rivers over varying time and space scales, as well as the consequent unpredictability of river ecosystem behavior, mean that river restoration is far too complex for any single discipline to undertake successfully (Benda et al., 2002; Palmer et al., 2003). Hydrologists and geomorphologists may be best qualified to understand the processes that create the habitat that biota need, but biologists must determine the type and amount of habitat needed by biota, and stream ecologists must explain the biotic interactions that govern which populations can survive in the restored stream (Nilsson et al., 2003).

Gaps in scientific understanding

Scientific conceptual understanding of how stream and 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, water managers and other stakeholders also typically ask scientists to predict how specific management actions will translate into geomorphic or ecological responses. Unfortunately, restoration science is beset by fundamental problems of uncertainties in our knowledge and limited predictive capability. The gaps in scientific understanding of how to restore rivers pose several challenges for effective restoration, and identification of these gaps points to critical research needs.

We suggest that scientific understanding of river function is limited by three factors. First, because detailed knowledge arises from studies conducted at a particular place and at particular space-time scales, transferring knowledge from one specific place to another involves untested assumptions of transferability and in scaling (Walters and Korman, 1999). On the one hand, all rivers or river components (e.g., reaches) are

unique due to specific combinations of climate, watershed condition, geologic setting, the composition of biota, and historical legacy. On the other hand, this variation among rivers or river segments can be minimized by grouping them into classes of similar behavior and potential. All riverine scientists practice classification to some degree, and several classifications have arisen for hydrologic, geomorphic, and biological components (see Naiman et al., 1992). However, *riverine scientists have not yet reached a consensus on what are the limits to transferability of knowledge gained from one system or situation. River scientists need to define the context of understanding to better predict the outcomes of restoration activities. Achieving and clearly articulating this consensus would be a major advance in riverine science.*

A second scientific challenge arises from the need to consider restoration projects as ecosystem experiments. To date most restoration projects have been implemented without the study design, baseline data, and post-project appraisal needed to learn from the 'experiments' (Downs and Kondolf 2002). 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 projects. 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). 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 has been argued as the best approach to learning in the long run (Walters, 1997). *A learning-by-doing approach may be a prerequisite for effective management of complex river ecosystems (Rogers, 2003). 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.***

A third scientific challenge facing river restoration is the difficulty of integrating disciplinary knowledge into interdisciplinary understanding. This is a familiar but enduring problem that 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). Although interdisciplinary challenges are widely recognized, there is ample evidence that riverine scientists are attempting to integrate principles of hydrology, geomorphology, and ecology into synthetic frameworks to better understand and predict how river systems function. Given the obvious multi-disciplinary dimensions of riverine structure and function, *effective restoration science must continue to be explicitly grounded in interdisciplinary research and understanding. We must acquire better models for rapidly developing effective collaborations as new problems arise and the need for rapid responses by interdisciplinary groups of scientists increases (Palmer et al., 2004a).*

Finally, we 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 simply unrealistic to expect that restoration science will be rapidly transformed 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); Fuzzy Cognitive Mapping (Hobbs et al., 2002), which can be used to distill expert scientific judgments about ecosystem components and interactions to identify effective management strategies that account for stakeholder concerns; 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).

Challenges that arise from social limitations to scientifically based river restoration

Environmental management, including river restoration, is fundamentally a social process that typically invokes science to varying degrees. Effective environmental management recognizes and seeks to improve the economic, political, and social contexts from which problems arise (Bryant and Wilson, 1998). River restoration becomes a viable management option when current ecological conditions 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. The prevailing economic view, which espouses an ever-expanding conversion of natural capital to human money, typically discounts the amenities that accrue to society from ecological restoration. *Substantive cultural change, with greater value placed on environmental justice, ecological stewardship, and citizen participation, must occur before scientifically sound restoration of ecosystem processes can become an important, common theme in managing rivers* (Preister and Kent, 1997).

Long-term strategies for managing flow regimes, land use change, riparian areas, and native species are often critical for restoring ecological integrity to rivers, but inevitably provoke controversy and require a much greater investment in the political process. The sociopolitical 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. This presents a substantial challenge for river

scientists because *conducting (and improving) river restoration science requires opportunities for scientists to become involved in real-world projects*; unlike many sciences, restoration cannot advance through small-scale, laboratory or mesocosm experiments alone.

Another component of the social context of restoration is the interface between stakeholders (non-scientists) and scientists. 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 by scientists in these debates are value-laden, although underlying values are often not explicated (Barry and Oelschlaeger, 1996; Allen et al., 2001). These socially constructed communication tools strongly influence stakeholder perceptions of environmental quality and the appropriateness of management actions. Scientists have privileged access to environmental knowledge and to influence on environmental issues. *A restoration science in which scientists make the values underlying their conceptualizations more accessible to non-scientists might alter the demand for river restoration.* Such science is consistent with the new "post-normal science", which is emerging to complement conventional science when environmental risks are complex and potentially severe (Funtowicz and Ravetz, 1993).

Research vision: How do we advance the science of river restoration?

Advances in our understanding of the intrinsic complexities of riverine ecosystems have resulted in large part from recognition of the inherent dynamism and multidimensional nature of rivers. Advancement of the science of river restoration must include (i) an explicit recognition of the known complexities and uncertainties, (ii) the application of increasingly advanced technologies for measuring relevant processes (hydraulics, sediment movement, plant physiological attributes, and the movement of organisms (sonar and telemetry)), and (iii) continual development of a theoretical framework that enables us to draw generalities between river systems and to ask relevant questions, to consider the correct temporal and spatial scales of measurement, and to measure the most effective set of variables to achieve restoration objectives. 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. We have a great deal of data and are rapidly designing various tools to gather more. *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 pattern in riverine 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 non-academic practitioners who are conducting most of the applied river science taking place today.

Because riparian and aquatic vegetation and aquatic biota are so closely associated with channel morphology and the effects of channel morphology on water availability, predictions of changes in riparian vegetation in response to changes in flow regimes are, in many fluvial systems, dependent on the determinism of geomorphic process. Graf (2001) suggested the concept of the probabilistic river in which, rather than trying to predict the specific locations of features and the spatially explicit changes of a channel in response to flooding, a reach of river should be modeled probabilistically so

that a grid of probable responses of the channel is created. In this way the absolute prediction of spatially explicit change is avoided and a grid of probabilities reveals the most likely outcome of a perturbation as well as the uncertainty in geomorphic change (Figure 3). *The development and refinement of probabilistic models are essential, as they will be very effective in project planning, project funding, project implementation, and education.*

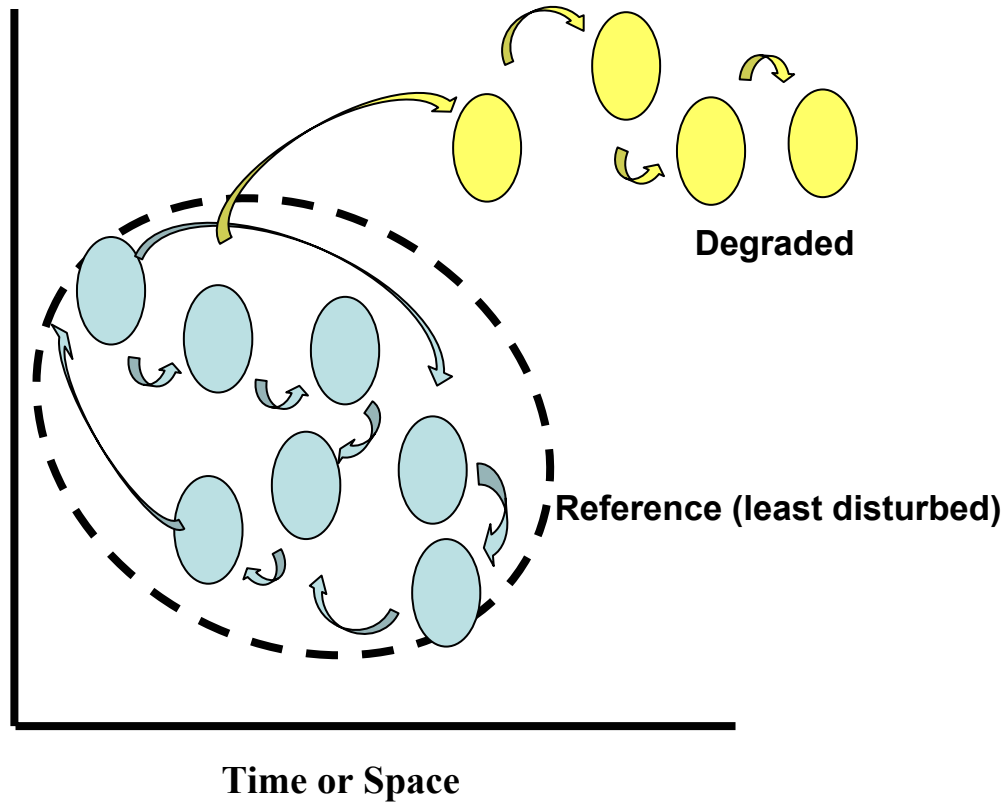


Figure 3. Schematic representation of variability in ecosystem “state” (e.g., channel planform, biotic community composition, etc), which is portrayed along the y-axis, as a function of time and space for relatively undisturbed and degraded river ecosystems. Both undisturbed and degraded rivers exhibit a range of ecosystem states, but these ranges do not necessarily overlap. Adapted from Palmer et al., 1997.

Defining restoration success in aquatic and riparian ecosystems is an issue clouded by the common failure of project designers to clearly define goals 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., 2004b). The objectives of the restoration dictate what physical and biological variables should be measured. Successful restoration in an urban setting may be largely based on the enhancement of esthetic values, whereas success on a wildland river may be gaged by elevated fishery productivity, improved water quality, riparian forest restoration, or enhancement of a variety of other functions. In the case of the former, 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 options of parameters to measure can be staggering. Although lack of sufficient data for a particular river is often implicated as a hurdle to restoration, theoretical constraints far outweigh information constraints. Given excessive information on fisheries, vegetation, three-dimensional hydraulic models, particle size distributions, and extensive topographic and bathymetric survey information for a particular river reach, we still do not have the theoretical capacity to forecast with much certainty, explicitly where and to what degree the morphology of the river channel will be modified (Graf, 2001) or precisely how the organisms will respond (Nilsson et al., 2003). Developing a probabilistic basis for mapping change in channel morphology would greatly facilitate the ability to better predict biotic change. In general, *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.*

We do not wish to imply that the development of universal success criteria should be attempted. 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 is probably easier to gage the condition of physical properties, such as stream channel “integrity” (the options for measurement are fairly well-defined; Graf, 2001) than to determine the recovery of biota. If a desired morphologic state is chosen either through predetermined knowledge of what the channel should look like due to the physiographic setting and climate or through the use of a reference stream channel from which to compare, the measurement options for evaluating channel recovery are fairly constrained. At the cross sectional scale, channel geometry (width to depth ratio, hydraulic radius, symmetry, etc.) may be measured. At the reach scale, channel planform (sinuosity, width, bedform and landform configuration), substrate, and longitudinal profile are robust measures that are also sensitive to external factors (hydrology, sediment supply, and vegetation). This sensitivity varies depending upon several factors such as the severity of the change in flow or mechanical restructuring imposed and by the characteristics of the material comprising the bed and banks. In contrast, organismal response is very complicated because organisms can have complex physiologies, developmental histories that differ, and (at some timescale) populations of organisms (including plant populations, mussels, etc.) are mobile in the riverine landscape. Biotic measures may encompass ecosystem level properties such as species diversity, productivity, storage of carbon, or fluxes of nutrients.

Despite the fact that these processes provide an indication of the condition of the ecosystem, metrics at the ecosystem scale are not typically sensitive to changes in driving variables over short time-scales. Metrics that are extremely sensitive to changes in hydrologic regime and provide a good short-term measure of response of individuals to restoration include variables such as plant gas exchange, photosynthetic rate, and plant xylem water potential. Although these measures are sensitive, they do not provide a very robust view of the recovery or state of the system nor are they 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. In general, *we need to*

dramatically increase the number of assessment tools that we have at our disposal, especially those that are synthetic in nature and capture status of processes, not just channel form or ecosystem structure.

Alberta Environment developed an ecosystem approach for determining instream 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 ecosystems 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 even the components may be customized to societal values or recreational demands.

Strategy for achieving vision

Explicitly recognize known complexities and uncertainties of river systems by addressing the effects of differing time and space scales as these affect river restoration: This portion of the strategy applies to question 4 posed in the introduction; what are the scales of critical ecosystem processes and our knowledge gaps with respect to these processes?

We need to develop scientific 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 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 simply reconfigure the channel?). Such understanding can also be used to define the meaning of a “watershed context” for restoration.

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: This portion of the research strategy applies to questions 1-3, 6 and 7 posed in the introduction; what are the critical ecosystem processes that apply to all rivers and thus are fundamental to all restoration efforts? what are the functional relationships between critical ecosystem processes, hydrologic processes, biological integrity and amenities valued by society?, what are the critical knowledge gaps in our understanding of these relationships?, what are the “best” approaches and tools for resolving uncertainty in restoration outcomes?, and how can scientists best serve societal needs *vis a vis* river restoration?, respectively.

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 (i) channel response to physical changes using concepts such as the

probabilistic river, (ii) ecologically relevant aspects of flow regime at ungaged sites, or aspects of flow relevant to restoration (this can be addressed by identifying key linkages between the hydrograph and biotic response, considering more than one species, so that we can address how natural the flow regime must be to achieve desired restoration goals), (iii) diagnostic biological indicators of hydrologic and/or geomorphic restoration, and (iv) 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 ungaged river basins within which restoration is undertaken. CUAHSI 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.

Quantifiable predictions most relevant to river restoration are inherently multidisciplinary. 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 NEON (National Ecological Observatory Network), LTER (Long-Term Ecological Research Sites), CLEANER (Collaborative Large-Scale Engineering Assessment Network for Environmental Research), and Ocean Observatory Program, as well as the U.S. Geological Survey's NAWQA (National Water Quality Assessment program), and the proposed CUAHSI hydrologic observatories and hydrologic synthesis centers. 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. CUAHSI hydrologic observatories should incorporate physical-ecological linkages relevant to river restoration (e.g. biological response to temporal and spatial variability in flow regime and sediment supply).

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. 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 pre- and post-restoration 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 post-project appraisal than in the past, the vast majority of restoration projects constructed still do not undergo any objective post-project appraisal (the best estimates to date suggest that only 15-30% of river restoration projects in the U.S. have any post-project evaluation conducted (www.nrrss.umd.edu; Bernhardt et al., in review).

The need to develop methods of reporting and monitoring restoration projects, as well as protocols for future restoration projects, will be partly addressed by the National River Restoration Science Synthesis (NRRSS) currently being developed by Margaret

Palmer, Emily Bernhardt, and a team of 25 other scientists from seven major geographic regions across the United States. The NRRSS effort will undoubtedly identify further needs for reporting and monitoring (Bernhardt et al., in review); some of these needs may be effectively addressed within the framework of CUAHSI hydrologic information systems that will be developed within the next few years.

Decision makers are charged with allocating (always) limited resources for river restoration. This is implicitly or explicitly an exercise in triage, because the funds available are typically only a fraction of what would be needed to accomplish comprehensive restoration. Thus the question, "How to target restoration funds for the greatest benefit for the investment?" 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 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?

Unfortunately, managers and stakeholders don't always value scientific input, and scientists may be brought into the process too late, after project goals and even general approach have been decided. 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).

Link science and practitioners: 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, at least if performance is judged in terms of ecological benefits. Restoration projects not based on sound science are unlikely to be successful in the long term because the projects are unlikely to be sustainable or may not actually achieve intended ecological goals. Furthermore, in the absence of scientifically designed monitoring and evaluation criteria, it may be impossible to objectively gauge project success or failure.

Interactions between scientists and the public 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 and local groups, stakeholders, decision makers, and members of the public. 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 full of uncertainty. For example, many nonscientists are uncomfortable with concepts of risk and uncertainty. By employing careful language that does not go beyond what can be known with confidence, scientists can give the impression of lacking understanding or not being willing to predict outcomes. 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 is likely to embrace these designs. This may lead to the adoption of non-scientific recommendations and

project designs in lieu of more nuanced, complex interpretations of river behavior, in which uncertainty in outcome is explicitly acknowledged. Lacking the concept of uncertainty, the trap is that the public may become disillusioned with restoration altogether if specifically predicted outcomes fail.

Thus, better public education and communication of science is essential and the science should be presented in the context of informing decisions, not making decisions (Palmer et al., 2004a). Restoration project goals ultimately reflect societal preferences. However, if project objectives are not constrained by real scientific understanding, restoration projects may be little more than attempts to impose culturally-preferred landscape ideals where they will not be sustained by channel processes (e.g., Kondolf et al., 2001). Science alone can never set restoration goals, because the activity of restoration is essentially an activity carried out by society for goals valued by the society (Poff et al., 2003). Nonetheless, science can inform restoration goal-setting by constraining the universe of possible restoration actions to be considered, based on analyses of channel processes, the history of channel change and its underlying causes, and irrevocable changes in channel and catchment controls.

CUAHSI synthesis centers 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. It is particularly important that scientists be involved early enough in a particular project to influence the restoration goals and design of that project.

Develop methods of river restoration that are feasible within existing constraints: This portion of the research strategy addresses question 5 posed in the introduction: What is the societal context that constrains and/or dictates approaches to advancing scientifically sound restoration at the appropriate scale(s)? We need to identify the greatest limitations to restoration in general and within a particular project. Such limitations can occur in terms of hydrology, geomorphology, and ecology. 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. Identifying such limitations will facilitate the focus of research and policy initiatives within a restoration context. There is a particular need to develop methods to restore urbanized and/or highly constrained rivers. We 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 that we identify what functions can be most efficiently restored that maximize river ecosystem sustainability (or some level of functionality) for some unit economic cost. We also need to identify less disruptive modes of urban development initially. For example, use of infiltration zones instead of storm sewers in urban areas reduces subsequent water-quality impacts and associated need for restoration.

Expected impact

Implementing the research vision and strategy outlined here has the potential to produce the following significant impacts on the practice of river restoration:

- 1) 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.
- 2) Continual opportunity for improved restoration strategies and for successful restoration implementation as we learn from past projects through monitoring.
- 3) Improved communication and trust between scientists and practitioners of river restoration.

Presentations at an international workshop on river restoration held in Sweden during August 2004 strongly suggest that current river restoration efforts commonly focus on limited, site-specific goals implemented in ignorance of river ecosystem processes that are likely to prevent the restoration efforts from being self-sustaining. Restoration projects are unlikely to move forward until scientific understanding of river processes is more effectively integrated into restoration efforts. This requires multidisciplinary, quantitative predictions of river behavior; monitoring of existing efforts to continually improve restoration strategies; and full cooperation between scientists and practitioners of restoration. In other words, progress in river restoration requires implementation of the research strategy outlined in this paper. Strategies will of course continue to change and be refined as we learn from our mistakes and our successes.

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