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Stream Restoration in Dynamic Fluvial Systems

Scientific Approaches, Analyses, and Tools

Andrew Simon, Sean J. Bennett,
and Janine M. Castro
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Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools

Andrew Simon
Sean J. Bennett
Janine M. Castro
Editors

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PREFACE

Stream restoration is a catchall term for modifications to streams and adjacent riparian zones undertaken to improve geomorphic and/or ecologic function, structure, and integrity of river corridors, and it has become a multibillion dollar industry worldwide. A vigorous debate currently exists in research and professional communities regarding the approaches, applications, and tools most effective in designing, implementing, and assessing stream restoration strategies given a multitude of goals, objectives, stakeholders, and boundary conditions. More importantly, stream restoration as a research-oriented academic discipline is, at present, lagging stream restoration as a rapidly evolving, practitioner-centric endeavor.

Our initial discussions for an edited volume on stream restoration led to a preliminary list of potential contributors assembled by the editors and Colin Thorne. Our approach for soliciting contributions to the volume was simple: we extended invitations to as many leading stream restoration scholars and practitioners as possible (though initially limited to 25). In addition, we made a concerted effort to have a diversified group of contributors. On the basis of the comments from the proposal peer reviewers, the editors altered a few of the contributions in consultation with select authors and solicited a few additional papers to achieve parity in both scope and content as suggested.

The final product of these efforts is a volume that brings together leading experts in both the science and practice of stream restoration, providing a comprehensive, integrative, and interdisciplinary synthesis of process-based approaches, tools, and techniques currently in use, as well as their philosophical foundations. Here nearly 70 researchers from North America, Europe, and Australia contribute papers divided into six broad categories: (1) general approaches, (2) stream hydrology and hydraulics, (3) habitat essentials, (4) sediment transport issues, (5) structural approaches, and (6) model applications. The result is a concise, up-to-date treatise addressing key issues in stream restoration, stressing scientifically defensible approaches and applications from a wide range of perspectives and geographic regions. Most importantly, the volume furthers the ongoing dialogue among researchers and practitioners.

We should like to extend our appreciation to those who made this publication possible. We thank the authors who contributed to the volume, and those individuals who provided constructive and timely reviews of these papers (listed below). We thank Colin Thorne for offering many helpful suggestions in preparing the book proposal. Finally, we gratefully acknowledge the continued support of the University at Buffalo, the U.S. Fish and Wildlife Service, and the Agricultural Research Service of the U.S. Department of Agriculture.

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The Evolving Science of Stream Restoration

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Stream restoration is a general term used for the wide range of actions undertaken to improve the geomorphic and ecologic function, structure, and integrity of river corridors. While the practice of stream restoration is not new to geomorphic, ecologic, or engineering communities, the number of restoration activities and their associated costs has increased dramatically over the last few decades because of government policies intended to protect and restore water quality and aquatic species and their habitats. The goals and objectives, tools and technologies, approaches and applications, and assessment and monitoring standards promoted and employed in stream restoration are rapidly evolving in response to this increased focus and funding. Because technology transfer is an important activity in scientific discourse, this volume provides a comprehensive, integrative, and interdisciplinary synthesis of process-based approaches, tools, and techniques currently used in stream restoration, as well as their philosophical and conceptual foundations. This introductory paper provides a brief summary of the history and evolving science of stream restoration and emerging areas relevant to the stream restoration community.

1. INTRODUCTION

Stream restoration is a catchall term used to describe a wide range of management actions and as such is difficult to define. The definition of stream restoration can vary with the perspective or discipline of the practitioner or with the temporal and spatial scale under consideration. For example, to environmental engineers, stream restoration could mean the return of a degraded ecosystem to a close approximation of its remaining natural potential [*Shields et al.*, 2003], while geomorphologists and hydrologists might define restoration as improving hydrologic, geomorphic, and ecological processes in degraded watershed systems and replacing lost, damaged, or compromised elements of those natural systems [*Wohl et al.*, 2005]. Ecologists further note that restoration of rivers should result in a watershed's improved capacity to provide clean water, consumable fish, wildlife habitat, and healthier coastal waters [*Palmer and Bernhardt*, 2006]. Any of these definitions could include a spectrum of management activities, from replanting riparian trees to full-scale redesign of river channels [*Bernhardt et al.*, 2007]. The wide range of definitions used for stream restoration, and its variation in time, is summarized by *Dufour and Piégay* [2009].

The primary focus of stream restoration has, not surprisingly, been on corridors impaired or degraded by anthropogenic activities. These activities include channelization and

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hydromodification, alteration of land use and land cover, the discharge of pollutants and contaminants into surface and ground waters, and the introduction of new aquatic species [*Wohl et al.*, 2005; *Palmer and Bernhardt*, 2006]. On the basis of recent reports, leading causes of water quality impairment in U.S. rivers include water quality, habitat alterations, impaired biota, nutrients, and sediment [*U.S. Environmental Protection Agency (U.S. EPA)*, 2009]. The majority of low-order U.S. streams, which constitute 90% of all stream miles, have some level of biological impairment, and the most frequent stressors include nutrient loadings, riparian disturbance, and streambed sediment [*U.S. EPA*, 2006]. The most commonly stated goals for river restoration in the United States are to enhance water quality, to manage riparian zones, to improve in-stream habitat, to provide for fish passage, and for bank stabilization [*Bernhardt et al.*, 2005].

The objectives of this introductory paper are to provide a brief history of stream management, to summarize the evolving science of stream restoration, and to identify emerging areas relevant to the stream restoration community. While the emerging areas identified here are not intended to be all inclusive, they do represent the continually changing issues and challenges surrounding stream restoration research and practice and include the following: (1) conflicts within the stream restoration community, (2) the communication of "failure" or lack of success, (3) policy, uncertainty, and practice, (4) landscape trajectories and rise of the social dimension, (5) the future of flow redirection techniques, and (6) the role of models. Finally, the intended goals and thematic focus of this edited volume are presented and contextualized.

2. A BRIEF HISTORY

While "stream restoration" has been vigorously debated from theoretical and philosophical bases over the past few decades, the implementation of stream restoration projects has grown into a multibillion dollar industry. The term "stream restoration" is fairly recent in our river management lexicon, yet the practice of modifying channels for benefit is not.

Early stream management efforts were aimed at bringing water to settlements, reducing the ravages of floods, and irrigating croplands [*Hodge*, 2000, 2002]. The oldest known artificial watercourses were irrigation canals, built in Mesopotamia circa 4000 B.C., in the area of modern day Iraq and Syria. In what is now Jordan and Egypt, the earliest known dams were constructed between 3000 and 2600 B.C. The Indus Valley civilization in Pakistan and north India (circa 2600 B.C.) developed sophisticated irrigation and storage systems, including the reservoirs built at Girnar in 3000 B.C. [*Rodda and Ubertini*, 2004]. In Egypt, canals date back to 2300 B.C. when one was built to bypass the cataract on the Nile near Aswan [*Hadfield*, 1986], while construction of embankments and drainage ditches took place in Italy and Britain 2000 years ago during Roman rule [*Brookes*, 1988; *Billi et al.*, 1997]. Greek engineers were the first to use canal locks, which regulated water flow in the ancient Suez Canal as early as the third century B.C. [*Moore*, 1950; *Froriep*, 1986; *Schörner*, 2000].

By the nineteenth century, large-scale agricultural development associated with European settlement in North America, Australia, and India led to the clearing of large tracts of land and alteration of rainfall-runoff relations. Poor soil conservation practices led to massive erosion of fields and upland areas [*Ireland et al.*, 1939], causing infilling of channels and increasing the magnitude and extent of flooding [*Hidinger and Morgan*, 1912]. To alleviate this, programs were undertaken to dredge and straighten channels particularly in low-gradient valleys [*Moore*, 1917]. Such "channel improvements" were conducted during the first half of the twentieth century in the United States [*Simon*, 1994]; almost 98% of the Denmark's watercourses have been straightened [*Brookes*, 1988].

Given the cycles of intense, deliberative stream management through history, it is not surprising that a new cycle has emerged: "stream restoration." The expansion and popularity of stream restoration today is a societal response to protect water and aquatic habitat. Legislative measures in the mid to late twentieth century, such as the Clean Water Act in the United States and the Water Framework Directive in Europe, continue to be major drivers for the rapid development of stream restoration practice. The concept that streams are the "information superhighway of watersheds," transporting energy and mass from the system as a whole, has taken root in academic institutions and in the psyche of the general public.

3. CONFLICTS WITHIN THE STREAM RESTORATION COMMUNITY

Within the stream restoration community, including practitioners and researchers, there continues to be a wide divergence of what is considered an acceptable stream restoration approach. These differences often are expressed in terms of form-based versus process-based approaches to design and analyses [e.g., *Rosgen*, 2008; *Simon et al.*, 2007, 2008]. Although these differences may be due to the divergent perspectives of the stream restoration practitioner and scholar [*Gillian et al.*, 2005; *Lave*, 2009], this simplistic view is not advocated here. The stream restoration practitioner, no doubt, learns primarily through direct experience and networking with other practitioners, but virtually no written record of these activities exists [*Bernhardt et al.*, 2007]. Moreover, while stream restoration practitioners may produce design reports and engineering drawings, few practitioners provide adequate technology transfer of their methods and procedures. This lack of technology transfer is partially due to the competitive nature of the private sector and a reluctance to share such details, and there is often a lack of critical peer review of these practices. While stream restoration scholars recognize the need to include well-vetted scientific principles into the design and implementation of such activities [*Wohl et al.*, 2005], no such mechanism for the practitioner (scientific, policy, regulatory, etc.) currently exists, and there actually may be a disincentive to do so. Professional journals and panel discussions at technical meetings have, on occasion, aired this tension [e.g., *Rosgen*, 2008; *Simon et al.*, 2007, 2008] but without any significant resolution [*Lave*, 2009].

Recognizing the diversity of stream restoration theory and practice, numerous agencies and scholars have proposed guidance for successful stream restoration in the form of design manuals [*Doll et al.*, 2003; *Natural Resources Conservation Service (NRCS)*, 2007], professional short courses [*Marr*, 2009], journal articles advocating standards and protocols [*Palmer et al.*, 2005; *Woolsey et al.*, 2007], and authored and edited textbooks attempting to compile relevant literature and case studies [*Brookes and Shields*, 1996; *Watson et al.*, 2005; *Brierley and Fryirs*, 2008; *Darby and Sear*, 2008; *Thorp et al.*, 2008]. Most efforts recognize that diverse perspectives shape stream restoration projects, but the emphases for goal setting and evaluation typically reflect the dominant technical disciplines and perspectives within their institution, vocation, or agency. In some cases, government agencies have mandated a specific stream restoration approach, which has intensified conflicts across professional disciplines [*Lave*, 2009; *Lave et al.*, 2010].

Conflicts also can occur across scientific disciplinary boundaries. Hydraulic engineers and geomorphologists often view stream restoration as primarily concerned with producing dynamically stable (not static) channels that do not markedly change their dimensions over periods of years. Ecologists often argue that such practices should focus more explicitly on improving habitat [*Palmer et al.*, 2005] and dispute the use of physical indicators to assess ecological integrity [*Palmer et al.*, 2010]. Differences such as these are shaped by group membership, conflicting values (economic versus ecologic), and different underlying philosophies of science [*Reiners and Lockwood*, 2010]. While many of these conflicts will remain unresolved in the near future, the evolving practice of stream restoration is placing greater emphasis on interdisciplinary, scientifically based approaches well vetted by critical peer review [*Simon et al.*, 2007].

4. THE COMMUNICATION OF “FAILURE” OR LACK OF SUCCESS

Practitioners often refer to “success” or “failure” of individual projects in terms that contradict formally established goals and objectives. Unfortunately, “failure” is often equated with the displacement or loss of a structure, thus promulgating the perception that stream restoration is synonymous with “stability” and is essentially an engineering practice. Anecdotal accounts of “failure” are common components of “in-stream” discussions held during professional development workshops, but very few publications define failure or offer diagnoses or lessons learned from such projects [*Smith and Prestegaard*, 2005; *Shields et al.*, 2007]. Furthermore, the multidisciplinary compositions of project teams, whose members may have very different perceptions of the value of stream restoration, challenge the development of a consistent evaluation protocol. That is, stream restoration evaluations can be highly dependent on the individual reviewer and chosen methodology [*Whitacre et al.*, 2007]. Thus, it is common for stream restoration projects to demonstrate “success” for an incomplete subset of the project objectives [*Palmer et al.*, 2005].

Results from stream restoration projects often are not well communicated, even when project objectives and evaluation criteria have been formalized [*Palmer and Bernhardt*, 2006]. Improved communication between stream restoration practitioners and scholars must occur if advancements in the field are to be made and current design methods more fully understood [*Nagle*, 2007]. In particular, outcomes of both successful and failed stream restoration projects, and the criteria used in these determinations, should be shared more widely in a language understood by all interested parties.

5. POLICY, UNCERTAINTY, AND PRACTICE

Policy clearly has affected the practice of stream restoration. From the U.S. Clean Water Act of 1972 and Endangered Species Act of 1973 [*U.S. EPA*, 2006] to the recent European Union Water Framework Directive and the ongoing debate over stream mitigation credits, legislation provides both the motivation and funding for stream restoration. The Clean Water Act required the U.S. Environmental Protection Agency to regulate water quality and to report on the success or failure of efforts to protect and restore U.S. waterways [*U.S. EPA*, 2006], while the European Union Water Framework Directive requires that streams be restored to “good surface water status.”

Current discussion of mitigation credits [*Lave et al.*, 2010] reveals the policy implications of not evaluating projects and their risks clearly. This includes quantifying and accepting, where necessary, the uncertainties within each phase of the stream restoration process [*Wheaton et al.*, 2008; see *Darby and Sear*, 2008]. Moreover, the discussion with policy makers of uncertainty in stream restoration design and practice is not trivial [*Stewardson and Rutherford*, 2008]. The reduction of uncertainty through advancing the science and application of process-based tools and technology will help address many of the issues raised by policy makers.

The social and political dimensions of stream restoration also can be affected by uncertainty. Sites selected for restoration may not be prioritized by their likelihood of success but rather by socioeconomic constraints, perceived ecological condition, geographic location, land ownership, or the community's perspective on project benefits [*Miller and Kochel*, 2010]. Moreover, the social and economic aspects of restoration projects often are not mentioned in the literature or considered in evaluation protocols, even though these aspects may be the impetus behind a stream restoration project [*Eden and Tunstall*, 2006]. At present, there are few established methods for assessing social values in stream restoration, as many rely on questionnaires [*Bernhardt et al.*, 2005] and interviews [*Bernhardt et al.*, 2007; *Lave*, 2009].

6. LANDSCAPE TRAJECTORIES AND RISE OF THE SOCIAL DIMENSION

Because it is an evolving science, the conceptual framework of stream restoration projects, as well as the goals and expectations of such activities, also are changing with time. Stream restoration's formative years as a developing science were focused on water quality issues [*Dufour and Piégay*, 2009]. Over the last few decades, this emphasis shifted to riverine ecosystems adversely affected by anthropogenic activities and the use of reference conditions and then to ecosystem goods and services. As the definition of stream restoration has evolved, so too have the expectations of such projects.

Two important shifts in this evolving science have occurred recently, which will continue to shape future restorations activities. The first is the recognition that fluvial landscapes follow a complex trajectory with time and that naturalness of river corridors has significant value for ecosystems and society [*Dufour and Piégay*, 2009]. This concept, while not new to geomorphologists, does challenge the practitioner to consider stream restoration activities more holistically. That is, localized fixes of rivers at the stream bank or reach scale generally are just symptomatic palliatives, not genuine restoration actions [*Booth*, 2007], and the reliance on concepts such as "reference conditions" should be reduced significantly. Moreover, large financial investments for localized fixes should not be made when stream restoration and ecological targets may be unattainable or unrealized [*Booth*, 2005].

The second important shift in this evolving science is the recognition and promotion of human, societal, or cultural requirements for stream restoration [*Wohl et al.*, 2005; *Kondolf and Yang*, 2008]. While stakeholder participation is recognized universally as an integral component of stream restoration practices, especially in the design, funding, and authorization of such projects, the weight now placed on human requirements offers new complexity to this evolving science and prompts new questions. One may wonder if human or societal valuation of river corridors is wholly concordant with ecosystem services and river function and form. Moreover, such emphasis on human requirements may place even greater emphasis on urban stream projects, presumably at the expense of river corridors in less populated regions.

7. THE FUTURE OF FLOW REDIRECTION TECHNIQUES

The dominant paradigm in stream restoration today is one of creating stability and increasing habitat heterogeneity [*Hey*, 1996; *Palmer et al.*, 2010], and the installation of structures to redirect flow, to protect vulnerable stream banks, and to create such habitat is a popular approach amongst practitioners [*NRCS*, 2007]. While these in-stream structures can produce aquatic habitat such as scour pools [*Kuhnle et al.*, 2002; *Shields et al.*, 2005], the linkages between channel changes induced by these in-stream structures and ecological function are now under new scrutiny. There is growing empirical evidence to suggest that hydraulic structures for flow redirection may not provide sustained or long-lived positive benefits to biota such as macroinvertebrates and fish, in part because habitat heterogeneity alone does not solve the issues of ecologic impairment occurring at larger spatial scales [*Shields et al.*, 2007; *Baldigo et al.*, 2010; *Palmer et al.*, 2010].

While flow redirection techniques clearly provide hydraulic benefits to river corridors, the positive effects on stream ecology and biota must be examined further. The simple creation of habitat heterogeneity by hydraulic structures should no longer be used as conclusive evidence for or demonstration of ecologic restoration.

8. ROLE OF MODELS

Both physical and numerical models have emerged as important tools for transformative research in stream restoration. Physical models include a wide range of experimental apparatuses used to explore various aspects of open-channel flow. Numerical models can span from simple analytic formulations to multidimensional algorithms predicting turbulent flow, mass flux, and biological agents and indices in rivers.

Physical models provide unrivalled opportunities to examine key attributes of river restoration design and their relation to ecologic indices. Such models have examined, for example, the effects of large wood or riparian vegetation on river form and process [*Wallerstein et al.*, 2001; *Bennett et al.*, 2008], the habitat potential of hydraulic structures [*Kuhnle et al.*, 2002], alluvial response to dam removal [*Cantelli et al.*, 2004], and hyporheic flow exchange in heterogeneous sediments [*Salehin et al.*, 2004]. Experimental facilities also can be used to examine biological responses to hydrologic events and channel complexity [*Kemp and Williams*, 2008; *Rice et al.*, 2008; *Merten et al.*, 2010]. Experimental programs such as these ensure that data quality is high and parameters critical for stream restoration designs are included explicitly.

Numerical models, once validated and verified, provide the opportunity to examine the efficacy of stream restoration projects, assessing those already in existence and facilitating the design of planned installations. Such models have examined, for example, stream bank stability [*Simon et al.*, 2000], the effects of stream restoration installations [*Wu et al.*, 2005; *Langendoen*, this volume], turbulent flow around spur dikes [*Kuhnle et al.*, 2008], and fish movement through riverine bypass structures [*Goodwin et al.*, 2006].

The future practice of river restoration will further embrace the use of models for project design and assessment. Moreover, numerical models will become more commonplace in designing stream restoration projects. By default, stakeholders also will expect that models be used to demonstrate that proposed stream restoration projects will be resilient and sustainable and that water quality and ecologic goals will be met. As such, there will be a growing demand for user-friendly, scientifically robust tools and technology to meet these challenges.

9. FOCUS OF THIS EDITED VOLUME

Technology transfer is an important activity in scientific discourse. Because it is a rapidly evolving science, few treatises today concisely summarize scientifically defensible approaches and applications in stream restoration from a wide range of perspectives and geographic regions. The goal of this edited volume is to bring together leading experts in both the science and practice of stream restoration and to provide a comprehensive, integrative, and interdisciplinary synthesis of process-based approaches, tools, and techniques currently in use, as well as their philosophical and conceptual foundations. Here nearly 70 researchers from North America, Europe, and Australia have contributed papers presenting, discussing, and reviewing current and emerging trends critical to the evolving science of stream restoration. These contributions can be divided into six broad categories.

9.1. General Approaches

In this section, conceptual frameworks and systematic strategies for stream restoration are presented and discussed. The strength of this collection of papers is its richness of diversity, as it offers differing perspectives on stream restoration from both practitioners and scholars from a range of geographic regions.

9.2. Stream Hydrology and Hydraulics

Success in stream restoration design depends heavily on a fundamental understanding of hydrology and channel hydraulics. Here critical aspects of these topics, including the geomorphic significance of design discharge and fluid and mass exchange with the hyporheic zone, are presented.

9.3. Habitat Essentials

As many restoration projects address biological indices, this section focuses on critical aspects of stream channel and floodplain habitat, and it reviews approaches to improve these important ecologic attributes.

9.4. Sediment Transport Issues

This section highlights the important relationship between sediment transport and stream restoration, including the role sediment plays in conditioning channel stability, water quality and ecologic indices, and project design.

9.5. Structural Approaches

The use of structures is nearly ubiquitous in stream restoration. This section reviews the efficacy of some commonly used structures in rivers as well as the design criteria for hydraulically stable pool-riffle sequences.

9.6. Model Applications

As noted above, there is growing demand for stream restoration assessment tools, and this section presents a wide range of technology currently available to design river channels, to assess channel stability, and to determine the impacts of restoration projects on channel hydraulics and sediment transport.

10. CONCLUSIONS

Stream restoration is a rapidly evolving science for the wide range of activities enacted to improve the function, form, and water quality and ecologic indices of river corridors. The focus of these activities has been those streams impaired or degraded as a result of anthropogenic activities. Several emerging areas relevant to the stream restoration community include the following.

10.1. Conflicts Within the Stream Restoration Community

There continues to be a wide divergence of what is considered an acceptable design and analysis approach within the stream restoration community. While diverse perspectives shape stream restoration projects, the goals and evaluation of projects typically reflect dominant technical disciplines.

10.2. The Communication of "Failure" or Lack of Success

There is little formal presentation of restoration projects that fail to meet their project's goals, and the valuation of such projects can be highly variable. Both successful and failed stream restoration projects, and the criteria used in these determinations, should be more widely shared in a language understood by all interested parties.

10.3. Policy, Uncertainty, and Practice

Government policy clearly has affected the practice of stream restoration, yet there is much uncertainty in the formulation and implementation of this policy, as well as in the social and political dimensions of these activities.

10.4. Landscape Trajectories and Rise of the Social Dimension

Because fluvial landscapes follow a complex trajectory with time, stream restoration practitioners are challenged to consider the design, implementation, and evaluation of these activities in more holistic rather than local terms. Moreover, the recognition and promotion of human, societal, and cultural requirements further complicates the practice of stream restoration.

10.5. The Future of Flow Redirection Techniques

In-stream hydraulic structures can produce potential aquatic habitat such as scour pools, but empirical evidence now suggests that these structures may not provide sustained positive benefits to biota. The use of flow redirection techniques in ecologic stream restoration deserves further attention.

10.6. Role of Models

The future practice of river restoration will further embrace the use of physical and numerical models for project design and assessment. As such, there will be a growing demand for user-friendly, scientifically robust tools and technology to meet these challenges.

Edited volumes often capture the essence and immediacy of a scientific topic, and the collection of papers assembled here have achieved this goal. More importantly, it was the intent of the editors to participate positively in the discourse of stream restoration using scientifically defensible approaches and to provide important foundations for the continued success and evolution of the practice of restoration.

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Conceptualizing and Communicating Ecological River Restoration

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We present a general conceptual model for communicating aspects of river restoration and management. The model is generic and adaptable to most riverine settings, independent of size. The model has separate categories of natural and social-economic drivers, and management actions are envisioned as modifiers of naturally dynamic systems. The model includes a decision-making structure in which managers, stakeholders, and scientists interact to define management objectives and performance evaluation. The model depicts a stress to the riverine ecosystem as either (1) deviation in the regimes (flow, sediment, temperature, light, biogeochemical, and genetic) by altering the frequency, magnitude, duration, timing, or rate of change of the fluxes or (2) imposition of a hard structural constraint on channel form. Restoration is depicted as naturalization of those regimes or removal of the constraint. The model recognizes the importance of river history in conditioning future responses. Three hierarchical tiers of essential ecosystem characteristics (EECs) illustrate how management actions typically propagate through physical/chemical processes to habitat to biotic responses. Uncertainty and expense in modeling or measuring responses increase in moving from tiers 1 to 3. Social-economic characteristics are shown in a parallel structure that emphasizes the need to quantify trade-offs between ecological and social-economic systems. Performance measures for EECs are also hierarchical, showing that selection of measures depend on participants' willingness to accept uncertainty. The general form is of an adaptive management loop in which the performance measures are compared to reference conditions or success criteria and the information is fed back into the decision-making process.

1. INTRODUCTION

As rivers integrate water, energy, and material fluxes in watersheds, they also integrate human values and interests related to the goods and services they provide. As a result, river restoration can involve many people, institutions, diverse backgrounds, and interests. Interested groups of people (stakeholders) include political entities (countries, tribal groups, states, and municipalities), agencies that regulate commerce or environmental quality, commercial entities with interests in water quantity and quality, nongovernmental

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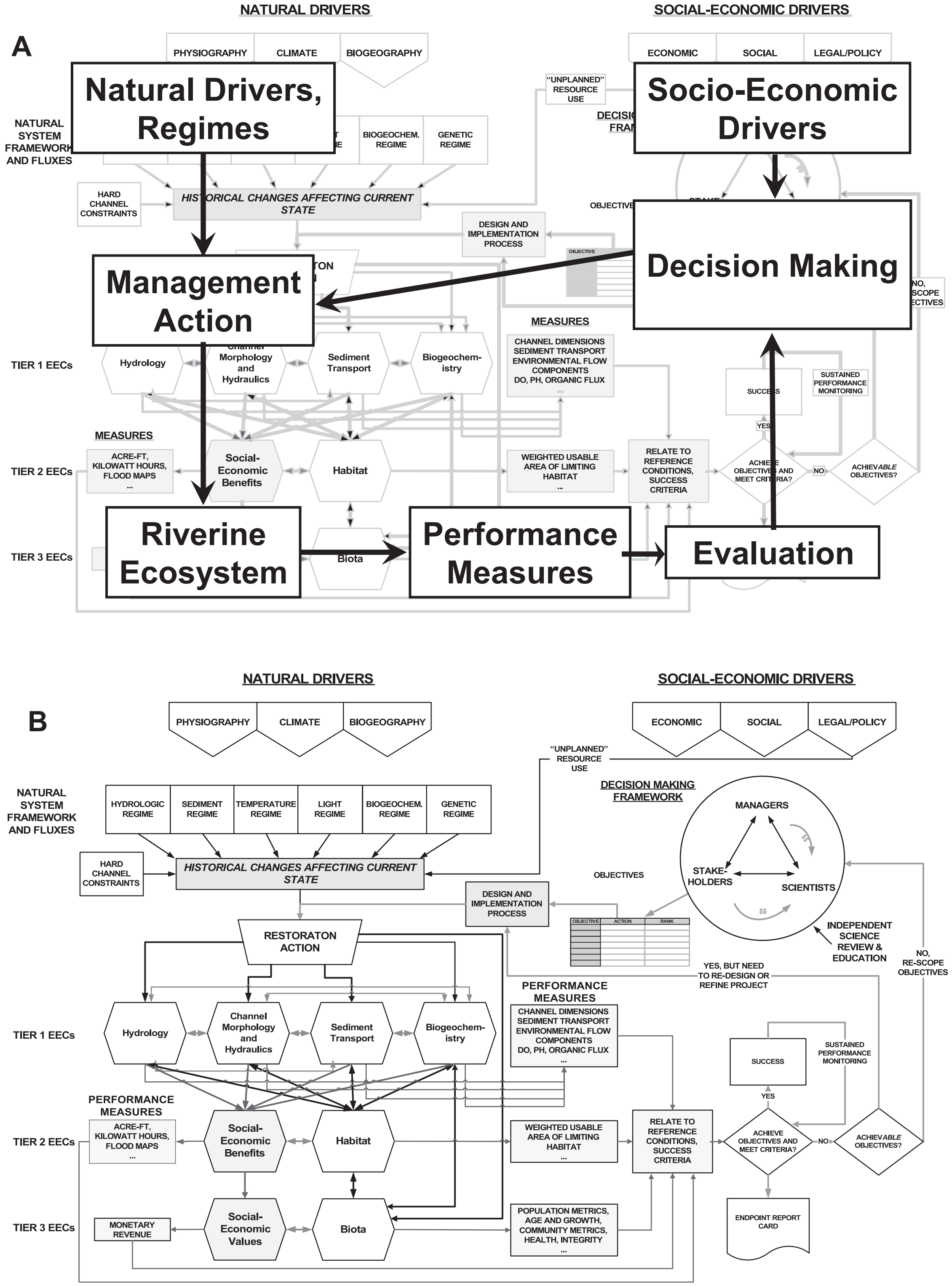

Figure 1. (a) Simplified view of the conceptual model, illustrating the adaptive management loop structure. (b) Detailed view of the conceptual model.

organizations that may represent coalitions of commercial, environmental, or civic interests, and individual members of the public including owners of riparian lands and those who live far from the river but enjoy the river's cultural, recreational, or aesthetic values [*Klubnikin et al.*, 2000].

Interest in river restoration is growing rapidly, and large quantities of money are being committed annually to the practice [*Palmer et al.*, 2007]. Three trends are increasingly apparent. The first and most fundamental trend is the emphasis on restoration and management for ecological objectives. These objectives are institutionalized in the United States by the Endangered Species Act and the Clean Water Act [*Adler*, 2003; *Karr*, 1990] and in the European Union by the Water Framework Directive [*European Parliament, Council*, 2000]. These types of legislation reflect the shared social values of restoring ecological functioning to river systems. Such restoration is challenging, however, because of substantial uncertainties in understanding complex riverine ecosystems [*Christensen et al.*, 1996; *Frissel and Bayles*, 1996; *Palmer et al.*, 2007].

The second trend is increased use of adaptive management: a strategy that specifically addresses uncertainties in management actions [*Lee*, 1993; *Walters*, 1986]. Adaptive management embraces uncertainties in how restoration actions propagate through a river ecosystem by formulating actions as experiments and explicitly including learning in the management process. Adaptive management has become a key strategy for natural resource management in the United States [*Williams et al.*, 2007].

The third trend, increased participation of stakeholders in the river restoration and management process, is linked to the first two trends. Stakeholder involvement is considered a prerequisite to successful implementation of adaptive management because the political realities of many natural resource management decisions require the intentional buy in of stakeholders [*Williams et al.*, 2007]. Social learning that occurs within adaptive management is thought to provide a robust basis for implementing resource-management decisions [*Buijse et al.*, 2002; *Lee*, 1993; *Pahl-Wostl*, 2006; *Pahl-Wostl et al.*, 2007; *Rogers*, 2006]. Stakeholders may also bring specific and important local information to a restoration planning process based on their experiences with a river and its biota [*Jacobson and Primm*, 1997; *McDonald et al.*, 2004; *Robertson and McGee*, 2003].

The sum of these trends has produced, for many restoration projects, a complex planning environment characterized by participation of people and institutions representing disparate technical understanding and diverse values. Although the trends are most apparent in large restoration projects involving many governmental and nongovernmental institutions, diverse values, and large sums of public money (Sacramento-San Joaquin Delta, Chesapeake Bay, Florida Everglades, Colorado River, Platte River, Upper Mississippi River, for example), the social drivers promoting these trends are present in any project when ecological outcomes are uncertain and when there is a perceived accountability for public funds or to off-site stakeholders. The thesis of this chapter is that river restoration planning in a multidisciplinary and stakeholder-driven environment will be aided by conceptual models that encourage effective communication of complex systems and enforce systematic thinking. Conceptual models have been used in this role in other restoration projects, notably the Kissimmee River, Florida [*Trexler*, 1995], the Sacramento-San Joaquin Delta [*Taylor and Short*, 2009], and the Elwha River, Washington [*Woodward et al.*, 2008].

The conceptual model presented here (Figure 1) is intended to provide a framework for understanding river restoration and many of the decisions common to river restoration processes. The salient parts of the model are (1) recognition of multiple drivers of the decision-making process and ecosystem characteristics; (2) implementation of an adaptive decision process incorporating managers, stakeholders, and independent scientists; (3) recognition of the role of historical legacy in shaping present-day river responses to management; (4) a three-tiered hierarchical conceptualization of ecosystem response; (5) an explicit incorporation of social-economic responses in parallel with ecosystem responses; and (6) an adaptive management feedback loop based on response measures, explicit reference conditions, and learning.

The model has evolved from an initial conceptualization used in understanding ecosystem restoration in the Everglades [*Harwell et al.*, 1999]. The Everglades example was used subsequently to craft a hierarchical response model to illustrate river restoration on the Upper Mississippi River [*Lubinski and Barko*, 2003]. While working with adaptive management of river restoration projects on the Lower Missouri River, the first author continued to elaborate the hierarchical model and place it within a broader framework that includes decision making and learning. An intermediate version of the hierarchical response model was used to illustrate concepts in flow-regime restoration on the Lower Missouri River [*Jacobson and Galat*, 2008]. While the model has evolved toward generality, it has inevitably grown in complexity. In the form presented here, it is intended to be generally applicable to river restoration processes where ecological uncertainties are acknowledged and the restoration process incorporates stakeholders with a diversity of backgrounds and values.

Each river restoration project may ultimately develop one or many conceptual models refined to communicate the specific characteristics of its project, its river, and its decision framework. The model presented here is intended to illustrate the general usefulness of conceptual modeling in the river restoration process and to introduce some specific characteristics of conceptual models that may increase their utility.

2. CONCEPTUAL MODELS

A conceptual model is simply an abstract mental image of important parts of a system and how they are related. In an ecosystem context, conceptual models are defined as "graphical representations of interactions among key ecosystems components, processes, and drivers" [*Woodward et al.*, 2008]. A conceptual model is usually displayed graphically for increased understanding.

Conceptual models vary broadly in their structure and complexity [*Gentile et al.*, 2001]. Those for ecosystems can get very complicated and often evolve into complex process-based [*Walters et al.*, 2000] or probabilistic [*Reiman et al.*, 2001; *Stewart-Koster et al.*, 2010] computational models. Conceptual models may also vary depending on perspective. For example, many conceptual models are focused on specific biota and may be structured to support population models [*Wildhaber et al.*, 2007]. The emphasis in such a model is to illustrate the influence of factors that determine probabilities of passing from one life stage to another. In contrast, the Grand Canyon Ecosystem conceptual model is focused on illustrating general ecosystem productivity with less focus on particular species [*Walters et al.*, 2000].

The model presented here is intended to illustrate the broad effects of management or restoration actions. As such, it has a bias toward management actions and how they propagate through a riverine ecosystem. Unlike the models cited above, this model is considerably more generic because it does not specify an endpoint but allows users to define their own biotic or abiotic interests.

Conceptual models are frequently cited as a necessary step in formal adaptive management in which stakeholders and scientists jointly develop a shared understanding of the river system and then apply the model to predictions of system behavior (hypotheses) under management scenarios [*Walters*, 1986]. Eventually, hypotheses are identified that are worthy of implementation as management experiments. While there is value in starting the conceptualizing process with a blank piece of paper so that no ideas are left out of consideration, provision of a general framework serves to increase the efficiency of discussion and to assure that essential structural components of restoration are included. The framework can be generic and flexible for adaptations yet still convey the relational interactions that should be addressed in most restoration projects.

The conceptual model also functions as a teaching tool for participants who may lack technical background or who are uncertain about the adaptive management process. The ecological relations illustrated in the model serve to convey a general understanding of the various factors associated with river restoration and management, including consideration of external factors that are not manageable like historical events and geologic context. The general structure additionally serves to show participants their role in decision making, how management actions are evaluated against reference conditions, and how learning is fed back into the decision-making process.

Conceptual models can also be used to communicate to an external audience for purposes of greater understanding and transparency of process. Graphical documentation of structural components of restoration projects supports the logic of restoration decisions and monitoring designs. Well-constructed conceptual models also support the credibility of a project and help justify the restoration investment.

Another key role of a conceptual model is to focus discussion among scientists who typically represent diverse disciplines in river restoration projects. These disciplines may bring different understandings of what is considered salient, credible, and legitimate information to the restoration process. The conceptual model can aid scientists in the development and negotiation of their roles through the common visualization of relations among their disciplinary perspectives and the placement of their science within the overall restoration management process.

3. MODEL FRAMEWORK

3.1. Simplified Version

Our experience supports the value of conceptual models in communicating restoration goals and strategies in a multidisciplinary and stakeholder-driven environment. The framework is intended to act as a guide for the design and development of river restoration actions across multiple disciplines and varying degrees of participant's knowledge about the ecosystem or decision-making process. In practice, the model framework would likely be introduced to participants incrementally, starting with broad overviews of the restoration and adaptive management process (Figure 1a).

The simplified version of the model (Figure 1a) has a circular form familiar in adaptive management models [*Lee*, 1993; *Walters*, 1986]. The broad components of the model are (1) the natural framework that determines the nature of the river, including flow, sediment, and chemical regimes and geologic constraints; (2) social-economic drivers that influence the ecosystem directly and also influence the decision-making process; (3) a restoration or management action that arises from the decision-making process and acts as a filter on the natural system; (4) the riverine ecosystem affected by both natural processes and constraints as well as the restoration action; (5) performance measures for how well restoration activity functions relevant to the objectives set in the decision-making process; and (6) an evaluation step in which performance measures are evaluated and learning is fed back to decision making.

This rendering of the conceptual model is useful as an introduction to the more complex model and serves to emphasize several key points:

1. The restoration framework is dominated by an adaptive management loop of implementation, response, evaluation, and learning.

2. Restoration actions occur as filters that mediate naturally dynamic processes or regimes. In this sense, reconfiguring a channel or changing reservoir operating rules are examples of actions that change the spatial or temporal distributions of river characteristics but that operate within a natural system with the capability of altering or overwhelming the restoration activity.

3. Social-economic changes may be imposed on the riverine ecosystem outside of the restoration decision-making process and are thereby uncontrolled in the design. An example of uncontrolled social-economic change might be emergence of a biofuel economy that increases land values for crop production, reduces land availability for wetland restoration, and increases competition for in-stream flows.

The overview version of the model helps to communicate concepts incrementally to participants and to emphasize the point that restoration occurs in an open system framework in which results can be altered by uncontrollable natural forces and unplanned social-economic forces.

3.2. Building Blocks of the Detailed Model

A more detailed version of the model is used to develop understanding of typical relations in river restoration (Figure 1b). The detailed version is based on the general idea of illustrating drivers, stressors, and effects on an hierarchically structured ecosystem [*Gentile et al.*, 2001; *Henderson and O'Neil*, 2004] (Figures 1b and 2–4).

3.2.1. Drivers. Drivers are natural and social-economic forces that operate to provide the background context within which restoration occurs. For the purposes of this model, drivers are treated as boundary conditions or factors that are input to the model and not affected by model dynamics. Natural drivers are climatic, physiographic, land cover, and biogeographic factors that control natural fluxes of water, mass,

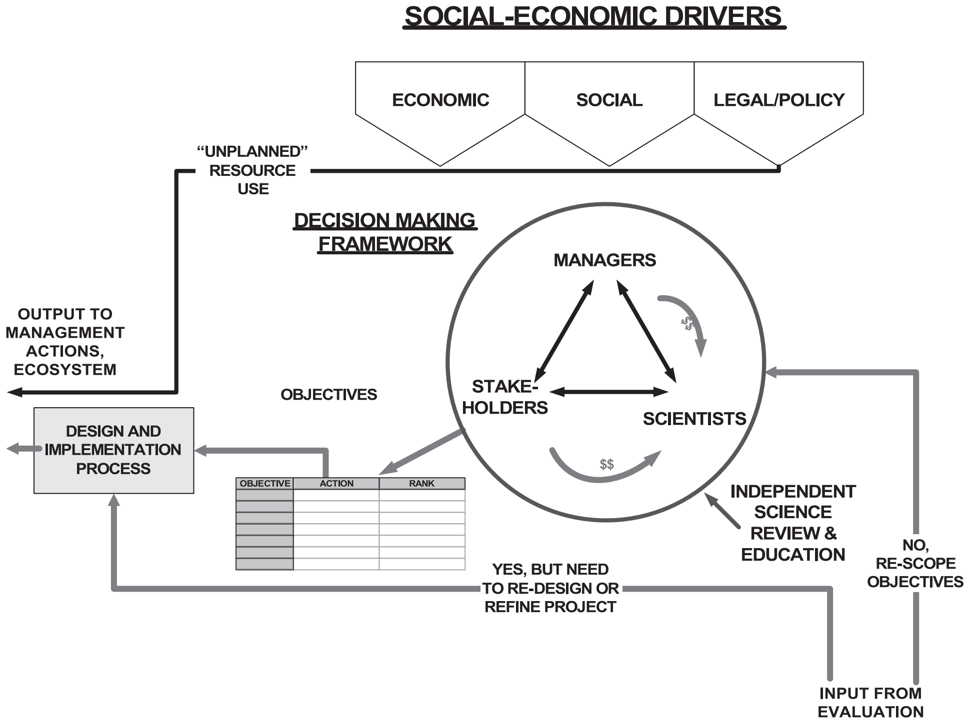

Figure 2. Upper right-hand quadrant of the conceptual model, showing the social-economic drivers and decision-making process.

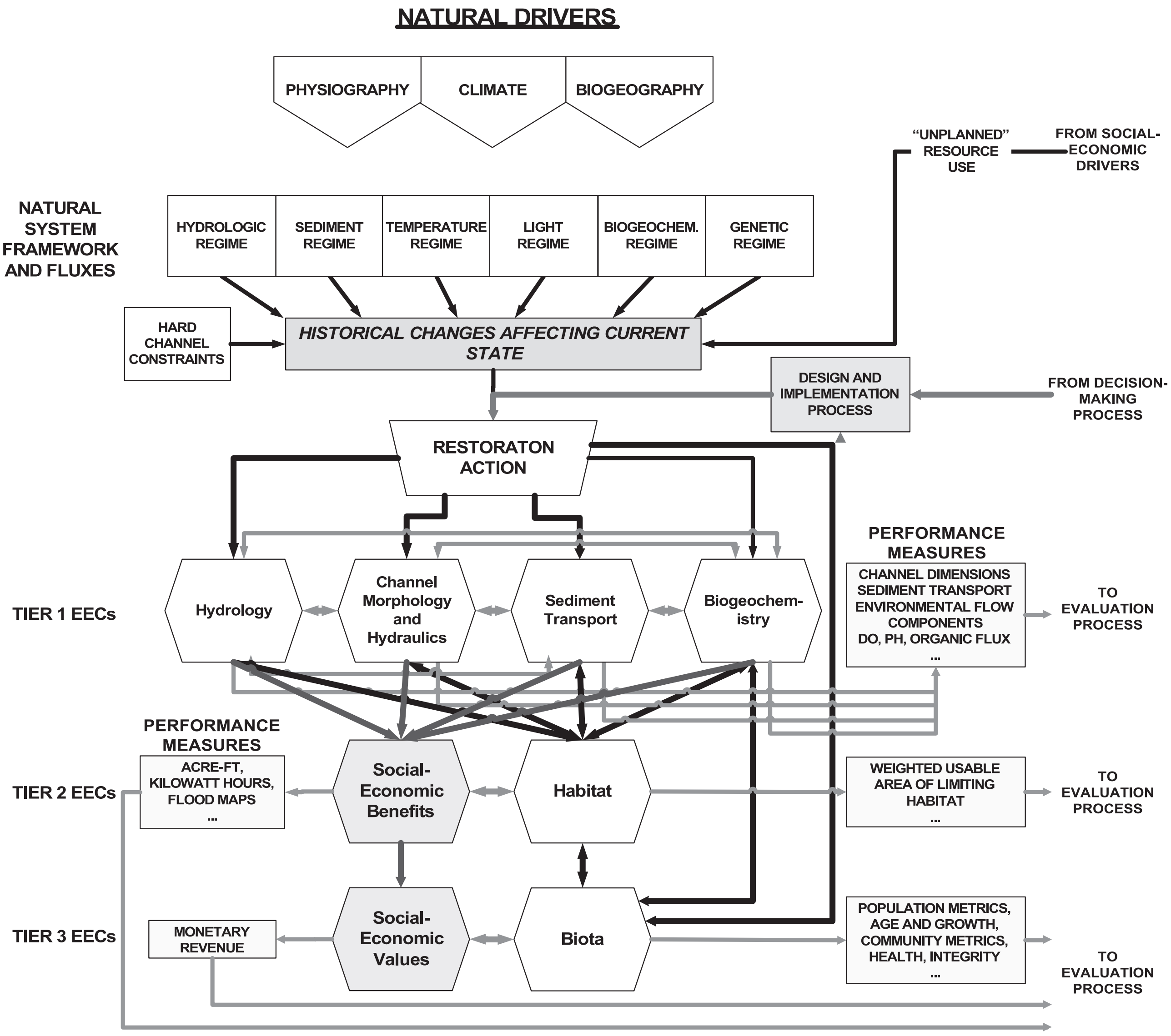

Figure 3. Left side of conceptual model showing natural system framework and regimes, filter of historical changes, and the three-tiered riverine ecosystem consisting of ecologic and social-economic essential ecosystem characteristics (EECs).

energy, and genetic information in a watershed. Social-economic drivers are economic, social, and legal/policy factors that influence human decisions about river restoration, including factors that act to limit restoration actions, for example, costs, laws, or prevailing management philosophies.

Social-economic drivers are depicted separately from the natural drivers and are treated as boundary conditions to the model as they impose constraints on ecosystem performance and the decision-making process (Figure 2). Economic benefits, social learning, and new policies may be generated internal to the system in the decision-making part of the model, but the drivers shown are considered external. The economic driver includes external market-driven forces that would alter monetary valuation of goods and services provided by a river ecosystem. The social driver includes social movements that may change values recognized in goods and services provided by rivers. The legal/policy driver is the framework of laws within which restoration occurs.

The physiography driver (Figure 3) includes geology, soils, and topography of the watershed, factors that exert controls on water, sediment, and geochemical fluxes into the river corridor. In large watersheds, physiography generally can be considered invariant over planning time frames of decades to centuries. However, as smaller watersheds are considered, or

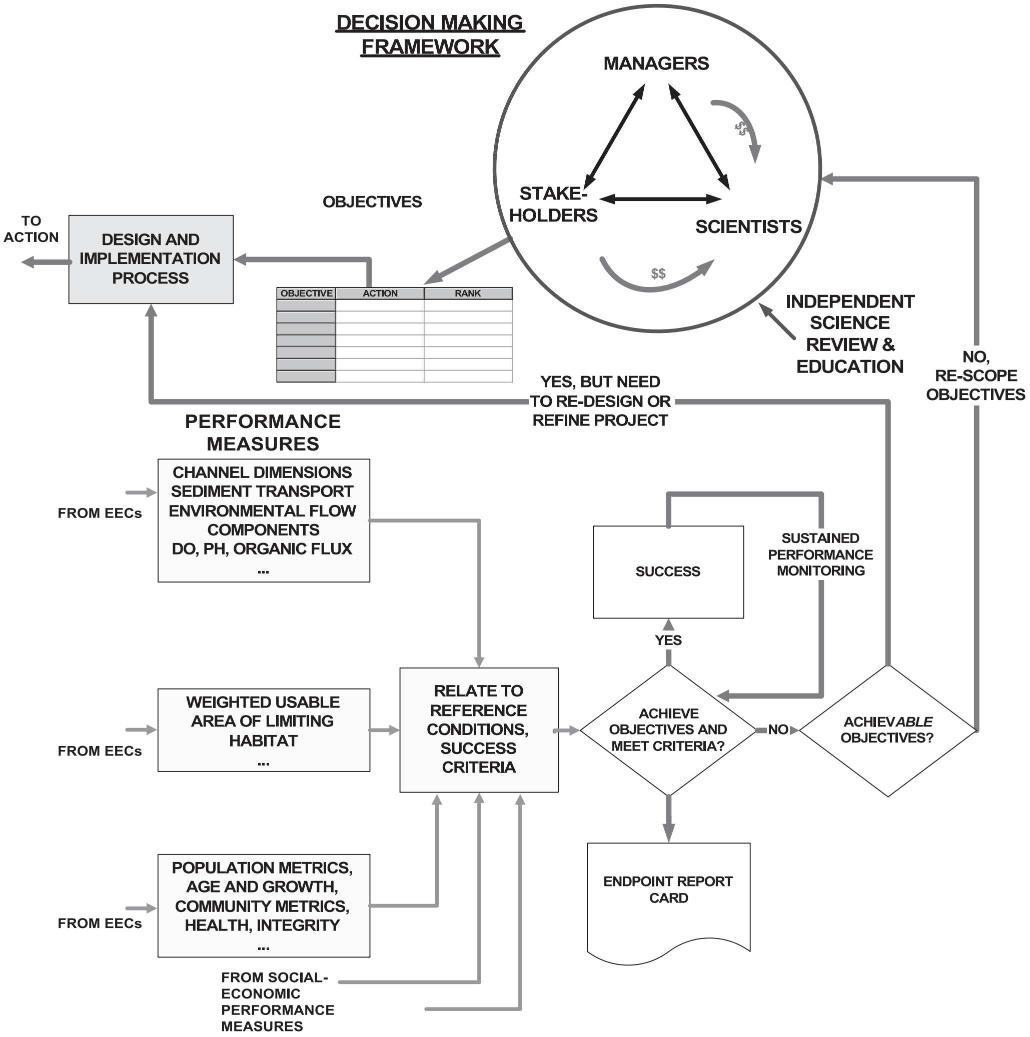

Figure 4. Lower right quadrant of conceptual model showing evaluation of metrics against reference conditions or other success criteria, decisions, and adaptive feedback to redesign or to the decision-making process.

tectonism increases, topography and surficial materials may change considerably over a time frame of years, especially with urbanization. The climate driver is the broadscale climatic context of a watershed that controls fluxes of atmospheric energy and moisture into the watershed. Unlike physiography, climate is more likely to vary dynamically within a planning time frame, for example, due to multidecadal climatic shifts. The biogeography driver describes the pool of organisms available in the watershed, and the natural flux of genetic information due to immigrations, emigrations, mutations, and extinctions. The biogeography driver includes the spatial distribution of organisms within the watershed, which may influence fluxes into the river corridor. For example, natural variation of the type and distribution of vegetation can affect the time series of runoff events.

3.2.2. Decision making. The upper right-hand corner of the model depicts the decision-making process, in this case, symbolized as the interaction among action agency (managers), stakeholders, and scientists (Figure 2). These three roles are generic to decision-making processes in river restoration and management, although the venue for interaction and the engagement in roles certainly varies among projects. In large, multipurpose river systems, restoration decisions typically involve institutions and agencies that are fully engaged in these three roles. In a small project, for example, a reach-scale restoration of a low-order stream, the main participants may be limited to a funding agency (manager) and a landowner (a stakeholder). To the extent that controversy arises, however, other stakeholders (downstream neighbors, regulatory agencies, and watershed councils) may become involved. Conflict often engenders additional independent scientific input to decision making.

The three roles can be conceptually distinguished, although in practice, their boundaries may be somewhat blurred. The action agency is primarily responsible for funding, planning, and carrying out the restoration action. Although labeled as an agency, this role can also be carried out by a partnership, a nongovernmental organization, or a private entity.

The role of stakeholder in river restoration is more fluid. The definition of stakeholder is a person or entity that is affected by or can affect the action [*Williams et al.*, 2007]; in the case of river restoration decisions, the influence can extend far beyond the piece of property or river reach involved. Transmission of restoration effects to downstream areas potentially involves large numbers of the public. For example, river restoration in the Midwestern United States that is effective in diminishing nitrogen loading to local streams may ultimately affect hypoxia conditions in the Gulf of Mexico [*O'Donnell and Galat*, 2007], hence shrimp fishermen in Louisiana may believe that they are stakeholders in small upland projects hundreds of miles away in Illinois. In some cases, there can be indeterminacy between the roles of manager and stakeholder. For example, an agency with a legislated mandate to protect endangered species may consider itself in an action agency role, whereas other participants may consider its role to be as a stakeholder, albeit a particularly powerful one.

The role envisioned for science emphasizes the need for credible and salient science information as the foundation of restoration, and the legitimate participation of scientists in decision making. "Credibility" [*Cash et al.*, 2003] refers to technical adequacy of scientific information, "salience" refers to relevance of the information to decision making, and "legitimacy" refers to perception that the science has been unbiased and respectful of stakeholders' divergent values [*Cash et al.*, 2003]. It has been argued that this role should be limited to individuals, institutions, and commercial interests that agree to participate under terms of policy-neutrality, transparency, peer review, and equal access to information [*Lackey*, 2007]. Working under these terms minimizes opportunities for bias and creates the best opportunity for independence from agency missions and stakeholder influences. This role differs from that of scientists who participate in decision making under the auspices of a management agency or a stakeholder group to advocate specific management objectives. Scientists who forego policy-neutrality, transparency, peer review, and equal access to information are best classified in the role of manager or stakeholder. A similar distinction between "research scientists" and "management scientists" has been proposed in the context of the CALFED program [*Taylor and Short*, 2009].

As rendered in the decision-making portion of the model, decisions are determined through an open, three-way interaction among these roles. Although governance and power sharing can take many different forms, in the ideal situation, individuals or institutions in the role of independent scientists will provide information but will not vote on objectives or policy, thus maintaining policy neutrality. In many cases, scientists involved with the decision-making process, or monitoring and evaluation of the process, are funded wholly or in part by action or stakeholder entities. As an additional check against bias, another layer of outside, independent science review may be justified (Figure 2).

The interaction of managers, stakeholders, and independent scientists determines and prioritizes restoration objectives within the context of the prevailing social-economic drivers and some form of analysis relating presumed restoration benefits to costs. The participants in the decision-making process would work closely with technical staff from the management agencies to design and implement the restoration, design the monitoring and evaluation process, determine reference conditions or other criteria for success, and institutionalize learning and feedback to the decision-making process. The conceptual model indicates how performance measures feed into evaluation and back to the decision-making process where the decision can be made to act, or not, on the generated information.

3.2.3. Stressors, regimes, and filters. In previous application of conceptual models to ecological risk assessments and ecosystem management, stressors have been identified as the physical, chemical, or biological changes that link drivers to ecological effects; the effects are usually considered deleterious [*Gentile et al.*, 2001; *Henderson and O'Neil*, 2004; *Rodier and Norton*, 1992]. For chemical contamination, a stressor is a harmful chemical introduced to the environment; for physical characteristics, a stressor is a harmful extreme of a physical process; a biological stressor might be a native or nonnative population that is out of balance with its resources. In this formulation, a driver (for example, a human action like draining of a wetland) produces a stressor (a change in hydroperiod) which is linked to an ecosystem effect (change in the composition of the plant community).

An alternative formulation emphasizes the natural background dynamics of riverine systems (Figure 3). Continuing with the wetland example, this formulation identifies the drivers as those that determined the wetland plant community in the natural system (climate, physiography, and biogeography). These natural drivers produce regimes, that is, time series of fluxes of water, energy, sediment, and other dissolved and transported materials characterized by their magnitude, duration, timing frequency, and rate of change. A natural wetland community is adjusted to the range of dynamic variation that regulates ecological processes and disturbances. Alteration of one or more of the regimes can be conceptualized as a filtering process that may dampen variability, remove some frequencies, or amplify others. For example, dams tend to decrease magnitude and frequency of floods, which combined with changes to the sediment regime, result in channel adjustment and alteration of habitat availability [*Schmidt and Wilcock*, 2008]. A restoration action then can be understood as a change to the filter, resulting in naturalization in the magnitude, frequency, duration, timing, or rate of change of the regime. The regimes identified in this conceptual model are flow, sediment, temperature, light, biogeochemistry, and genetics (Figure 3). The regimes are symbolized in separate boxes to emphasize that they may vary independently from one another. For example, water temperature, water quality, and sediment regime downstream of a dam may be decoupled from the flow regime, depending on how the system is engineered. In other cases, sediment, temperature, light, and biogeochemical regimes may be strongly controlled by the flow regime, and in these cases, flow regime could be considered the master restoration variable [*Poff et al.*, 1997]. The genetic regime refers to processes and rates of movement of genetic information in a river basin due to immigration, emigration, mutation, and extinction. The genetic regime may also be influenced by the other regimes, for example, in the case where flow-regime alteration is associated with competitive advantages for exotic species [*Olden and Poff*, 2006].

3.2.4. Hard channel constraints. Self-formed alluvial rivers adjust to flow and sediment regimes to attain quasi-equilibrium channel morphology and associated physical habitat characteristics [*Langbein and Leopold*, 1964]. Many natural river channels, however, are also affected by what can be considered hard constraints, that is, geologic or engineering features that are resistant to erosion over decadal or longer time frames (also known as fixed local controls [*Schumm*, 2005]). Some features, like bedrock bluffs abutting a channel, are permanent natural influences on channel morphology. Other features, like debris fans, can be seen as externally imposed geologic features, but because they have some degree of erodibility, their effect on channel morphology is less permanent. For the purposes of this model, all geologic features that impinge directly on the channel and persist over a multiyear time frame are considered hard channel constraints (Figure 3). In addition, because engineering structures are persistent features that affect the channel in a similar way, we add engineering structures to the category of hard channel constraints. Hence, additions or removals of hard channel constraints are considered another type of management action that can transmit or diminish a stress to the river ecosystem. Bank stabilization is probably the most common example of engineered, hard channel constraint.

3.2.5. History, thresholds, and lags. The present state of a river can be strongly conditioned by its history, including alterations in the watershed and at the channel scale. Some alterations may be reversible and may therefore be candidates for restoration. Other alterations, like large dams or urban infrastructure, may not be practically reversible because of their presently perceived social-economic value; these values can change with time, but, as seen with dam removal [*Graf*, 2005], larger infrastructure is generally more permanent. Still other alterations of the watershed and channel will be persistent and resistant to reversal because they have surpassed biologic or geomorphic thresholds, that is, a state of disturbance beyond which the system has difficulty recovering to its predisturbance state. The box "Historical Changes Affecting Current State" communicates the need to understand how the history of river change constrains present-day restoration options (Figure 3).

Examples of threshold historical changes include accelerated erosion of upland soils, an alteration that will have a practically permanent effect on infiltration and runoff rates in some landscapes [*Trimble*, 1974]. A related example is accumulation of eroded soil in floodplain deposits, resulting in floodplain aggradation and disconnection of the floodplain from its channel [*Costa*, 1975; *Jacobson and Coleman*, 1986; *Walter and Merritts*, 2008]. Although the effects of floodplain aggradation can be reversed by extensive excavation, doing so may require efforts that outweigh the benefits [*Bain et al.*, 2008]. Yet another example is choking of stream channels with riparian vegetation when peak flows are diminished because of upstream dam operations [*Williams*, 1978]. Established woody riparian vegetation can impart threshold erosional resistance that requires greater energy to remove in order to restore channel dynamics than would have been necessary before the vegetation became established [*Johnson*, 2000; *Tal et al.*, 2004].

3.2.6. The riverine ecosystem: Essential ecosystem characteristics. The centerpiece of the conceptual model is a hierarchical arrangement of ecosystem components (Figure 3). The individual components are essential ecosystem characteristics (EECs), a unit that was developed originally in conceptual modeling in the Florida Everglades [*Harwell et al.*, 1999]. EECs are groupings of ecosystem characteristics that are ecologically meaningful, that facilitate communication to a broad audience, and that can be linked to management and to measurable endpoints. EECs may be useful in simulation modeling; however, because they are groupings of characteristics, it is more likely that simulation modeling would focus on specific characteristics within an EEC.

The arrangement of EECs is intended to convey several ideas that are important to river restoration. First, the EECs are linked by arrows that signify some level of causal influence. When the conceptual model is applied to a specific restoration action, these arrows can be rendered in weights or colors to show their hypothesized importance. Most of the arrows are double-ended, indicating that causal influence can move in two directions as an interaction among the EECs. In implementation, some arrows may be neglected, singled-ended, or double-ended depending on hypothesized system dynamics.

The EECs are arranged in tiers indicating a general hierarchy of groups of characteristics that are affected by restoration actions. The tiered structure communicates the idea that many, if not most, management actions propagate through a riverine ecosystem, from initial physical/chemical effects (tier 1), to an integrated habitat effect (tier 2), and then to a biotic effect (tier 3), following the right side of tiered arrangements. Hence, the structure of tiers reflects a cascade of measurable effects; placement does not necessarily denote importance or rank. Because of interactions among EECs, the ability to measure and predict the effects of management actions generally decreases from tier 1 to tier 3 (that is, uncertainty increases). Tiers could certainly be subdivided and increased in number, as would be appropriate for more complex models intended to describe complex cascades of cause and effect. For simplicity in this model, we have limited the cascade to three tiers.

Tier 1 EECs are fundamental measures of process and directly affected by restoration actions that involve altering watershed characteristics or dam operations or reconfiguring a channel. These characteristics are usually fairly easy to measure or predict with some confidence, although interactions can create uncertainty. For example, the Channel Morphology and Hydraulics EEC is intimately linked to the Flow Regime and Sediment Regime EECs; Channel Morphology and Hydraulics will adjust dynamically to flow and sediment management in a somewhat predictable way, although the details of adjustment are not always straightforward [*Sear et al.*, 1998].

At tier 2, EECs are split into those associated with conventional social-economic characteristics (left side) and those associated with ecological characteristics (right side). This split is somewhat arbitrary, as all EECs could be considered to measure ecosystem services as broadly defined [*de Groot et al.*, 2002]. Nevertheless, the split is useful in comparing the economic goods and services that arise from direct exploitation of a river to those that arise dominantly from ecological processes.

The tier 2 biotic EEC integrates effects from tier 1 EECs into Habitat, a broad category that encompasses temporal and spatial variation of the physical, chemical, and biological components of the environment that influence reproduction, growth, and survival of biotic communities. This definition assumes biological understanding informs what portion of the environment qualifies as functional habitat. That is, restoration could target habitat for fish spawning, habitat for benthic invertebrate growth, or habitat for shorebird nesting. This EEC is particularly important because of the large number of restoration projects that are intended to restore habitat [*Bernhardt et al.*, 2005]. The relation of the Habitat EEC as an intermediary between Physical and Chemical EECs and Biota EEC draws attention to the need to consider carefully what qualifies as functional habitat.

Habitat has a strong connection to the Biota tier 3 EEC indicating the potential role of habitat in creating bottlenecks for populations of many species. There is also a strong feedback from Biota to Habitat because of the role of some species in altering habitat for other species (and by extension, channel morphology, sediment transport, and biogeochemistry characteristics). Examples include (1) the role of vegetation in providing cover and shading and altering sediment transport; (2) alteration of substrate particle size distributions and sediment transport characteristics by nest-building activities of some fish species; and (3) alteration of hydraulics, sediment transport, nutrient cycling, and organic retention in beaver-dammed ponds. The Biota EEC is disarming in its size as it could conceivably contain a very wide range of biotic characteristics, including life stages of various species and community interactions. In practice, one of the challenges facing river restoration planning is to articulate practical biotic objectives and performance measures (see details in the Performance Measures section).

The left side of the diagram depicts Social-Economic EECs parallel to the Habitat and Biota EECs. The Social-Economic Functions EEC integrates tier 2 EECs into the functions that managed or unmanaged ecosystems provide, including, for example, water supply, flood control benefits, and denitrification of river water. The tier 3 EEC translates those functions into monetary Social-Economic Costs and Benefits. Similar to the right side of the diagram, uncertainty increases from tier 2 to tier 3. Inclusion of the Social-Economic EECs on the left side of the diagram, and connections to the right side of the diagram, emphasizes that humans are part of riverine ecosystems [*Rhoads et al.*, 1999] and that most restoration planning processes eventually need to confront the trade-off between ecological costs/benefits of a restoration project and its social-economic costs/benefits [*Jacobson and Galat*, 2008]. In some cases, benefits may exist for both sides because restoration for ecological goals results in increased ecosystem services that are valued by society, for example, when restoration of connectivity to floodplains