Stream Restoration Benefits

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More than 1 billion dollars is spent annually restoring degraded streams and rivers in the United States alone because of the perceived value that healthy streams and rivers provide. Despite this immense investment, quantifying the benefits from these projects is often neglected. Without this step, it is difficult to compare restoration alternatives, prioritize projects, and determine the real returns on investment. While there are many factors that make quantification difficult, a more rigid adherence to and acceptance of the benefits assessments process will improve the ability of practitioners and sponsors to assess the value of their investment. Further, current practice can be improved with the explicit use of conceptual models, establishment of clear objectives and associated metrics, better predictive tools, quantification of uncertainty, more structured decision methods, and adaptive management. This chapter provides both a theoretical foundation and a practical framework for the vital process of assessing the benefits of stream restoration projects.

1. STATE OF THE PRACTICE

Recent studies and the development of a comprehensive database of more than 37,000 projects show that although over 1 billion dollars is spent on restoration projects each year [*Bernhardt et al.*, 2005; *Wohl et al.*, 2005], the overwhelming majority of these projects do not have explicit success criteria, and even fewer projects have postconstruction validation to ensure that the intended project goals are being achieved [*Kondolf*, 1995; *Kondolf and Micheli*, 1995; *Thompson*, 2006; *Brooks and Lake*, 2007; *Palmer et al.*, 2007]. In the few cases where systematic project assessment and monitoring were performed, it was found that half or more of the projects failed to meet the intended goals and design criteria [*Kondolf and Downs*, 2004]. Reviews of habitat restoration efforts focusing on the emplacement of in-stream structures have generally found little evidence that these techniques are effective or sustainable over a significant period of time [*Frissell and Nawa*, 1992; *Roper et al.*, 1997; *Pretty et al.*, 2003; *Roni et al.*, 2005].

In light of the above findings, it is not surprising that we have yet to fully account for the return on investment for completed projects. However, several studies have been completed that provide an indication of some of the economic benefits that can be derived from stream restoration and stewardship. Valuation methods have been used to quantify the value of fisheries as a way of estimating restoration benefits [*Dalton et al.*, 1998; *Stevens et al.*, 2000; *Morey et al.*, 2002]. Studies have shown that urban stream restoration, riparian corridors, and storm water best management practices improve nearby property values [*Wiegand et al.*, 1986; *Paterson et al.*, 1993; *U.S. Environment Protection Agency (U.S. EPA)*, 1995; *Streiner and Loomis*, 1996; *Center for Watershed Protection*, 1997], while willingness to pay surveys shed light on the broader value of stream restoration [*McDonald and Johns*, 1999; *Basnyat et al.*, 2000; *Collins et al.*, 2005; *Weber and Stewart*, 2009].

Within the private sector, no standard of practice has emerged, and there are few requirements to identify, quantify, and present the benefits of stream restoration projects. Studies consistently demonstrate that most projects fail to

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articulate clear objectives [*Kondolf and Downs*, 2004; *Palmer et al.*, 2007], so it should come as no surprise that they also fail to quantify the anticipated benefits. Indeed, the nature of project formulation generally precludes the need for evaluating benefits; a funding entity decides a stream reach should be restored for whatever reason and engages a professional to develop and implement a design. There is little incentive for the professional to further justify the effort.

Current stream restoration practice usually proceeds with the identification of problem reaches of streams that can be "fixed" by applying methods that have demonstrated success in the past. Streams and riparian corridors are generally viewed as consisting of "good" sections interspersed with "poor" segments, and it is often believed that the system can be improved by making the poor segments good. Determining how best to stabilize a stream reach while concurrently affording the greatest habitat for the species of interest, and even the desired age cohort of the species of interest, has become the focus of most conventional restoration efforts.

Federal, state, and other public water resource projects are developed under a variety of laws, policies, and institutional directives that sometimes stipulate the application of certain methods for the quantification of benefits (or impacts). The principles and guidelines (P&G) of the *U.S. Water Resources Council* [1983] provide the main basis for evaluating potential federal water resource projects and their alternatives. The P&G has guided the U.S. Army Corps of Engineers (USACE), Bureau of Reclamation, Natural Resource Conservation Service, and Tennessee Valley Authority (TVA) in project formulation since 1983. The analyses of government-funded stream restoration projects depends upon the agency and program, but generally centers upon the manipulation of habitat or, occasionally, changes in water quality. In the case of restoration actions associated with mitigation, an assessment of the quantity and quality of habitat produced is usually required.

Habitat-based approaches generally have roots in the Habitat Evaluation Procedure (HEP). HEP was developed in 1980 in response to the need to document nonmonetary values of fish and wildlife resources. It is based on the fundamental assumption that habitat quality and quantity can be numerically described using Habitat Suitability Index (HSI) models. HSI models summarize the conceptual understanding of habitat preferences of a target species scaled between 0.0 (no habitat) and 1.0 (ideal habitat) as functions of selected environmental variables, based on various sources of information [*Storch*, 2002]. In-stream flow methods and tools (e.g., Instream Flow Incremental Methodology (IFIM) and Physical Habitat Simulation System (PHABSIM) [*Bovee*, 1982]) developed by biologists and hydrologists working for regulatory agencies quantify changes in habitat as a function of discharge, utilizing HSIs as a basis for determining habitat quality [*Annear et al.*, 2002].

HSI-based methods have received much criticism because they use arbitrary classification and narrow habitat preference schemes, are rarely validated with independent data, are not readily transferable across systems due to scale and behavioral issues, involve species of dubious relevance or importance, assume that populations respond in lockstep with habitat availability, or cause complicated trade-offs [*Roloff and Kernohan*, 1999; *Ferrier*, 2002; *Gurnell et al.*, 2002]. Two major flaws exist in the assumptions of HSI models [*Railsback et al.*, 2003]: first that a species uses the selected habitat type, even if other habitats were available and second that the selected habitat provides the resources for a population to reach a sustainable carrying capacity. Despite widespread use, controversy has also accompanied the IFIM, in particular, the hydraulic and habitat models (PHABSIM) [*Mathur et al.*, 1985; *Scott and Shirvell*, 1997; *Kondolf et al.*, 2000; *Hudson et al.*, 2003]. A multiauthored review produced divergent opinions regarding the scientific defensibility of PHABSIM [*Castleberry et al.*, 1996].

Methods for benefits analysis providing alternatives to the habitat-based tools described above have been developed, and others are emerging. Improvements have also been made to the habitat-based methods, especially in the use of community- rather than species-based index models and in applications that recognize serially changing needs in complex life histories or settings with distinct seasonality. Several federal agencies have invested heavily in research to develop tools and methods for valuing ecosystems and for conducting benefits analyses for aquatic ecosystem restoration projects. The gulf between the state of the science and practice in this area is indicative of the recent growth of the field and the interest in the topic.

2. ECOSYSTEM ORGANIZATION AND THE ASSIGNMENT OF VALUE

The *National Research Council (NRC)* [1992, p. 18] defined restoration as "the return of the form and function of an ecosystem to its pre-disturbance condition." While other definitions have been advanced that capture various nuances of restoration, the reference to form and function is a common theme and is useful for conceptually organizing ecosystems. Ecosystem form, or structure, refers to both the composition of the ecosystem and to its physical and biological organization [*NRC*, 2005]. Structural characteristics vary in time and space, are unique to each system, and include, for example, stream morphology, size and distribution of bed sediments, composition of the riparian vegetation community, and the stream's hydrodynamic signature.

Ecosystem functions are the physical, chemical, and biological processes that create and sustain an ecosystem [*Fischenich*, 2005]. Functions include, for example, movement of water and sediment, decay of organic matter and cycling of nutrients, and growth and development of the organisms utilizing the ecosystem. Functions are largely responsible for the "self-organizing" and dynamic characteristics of ecosystems. Structure and function are closely linked in river corridors such that change to one is likely to affect the other.

The term ecosystem services emerged in the early 1980s to describe human-valued uses of ecosystems [*Mooney and Ehrlich*, 1997]. These uses are a derivative of the system's functions and structural characteristics and can be direct (e.g., recreational fishing, potable water, and transportation) or indirect (e.g., nutrient retention, flood control, and habitat provision). Several efforts have been made to define ecosystem services for streams and other aquatic ecosystems, but a consensus has yet to emerge.

Values are an estimate, usually subjective, of worth, merit, quality, or importance. Values can be expressed in economic (monetary) terms or using other (generally qualitative) means. Ecosystem values can be related to directly consumed outputs, such as water, food, recreation, or timber; or indirect uses that arise from the functions occurring within the ecosystem, such as habitat, water quality, and flood control. Thus, values are derived from certain ecosystem characteristics that, in turn, are determined by the underlying functions. Values can thus be applied to the ecosystem itself, to one or more of its structural elements or functions, or to any of the derived uses (services).

Farber et al. [2002, p. 387] state, "As humans are only one of many species in an ecosystem, the values they place on ecosystem functions, structures and processes may differ significantly from the values of those ecosystem characteristics to species or the maintenance (health) of the ecosystem itself." The basis for those values can be instrumental, subjective, or intrinsic [*Sagoff*, 1996]. The instrumental value of streams stems from the fact that they provide products and services necessary for human well-being. Streams also have subjective value insofar as people happen to want, like, and enjoy them; at least this is the case for healthy streams.

The intrinsic value of streams lies in the belief that they have value for their own sake, beyond that which can be ascribed to anthropocentric needs. This latter view has a cultural basis for Americans who, regardless of religious faith, tend to consider nature sacred and deserving protection [*Kempton et al.*, 1995]. Intrinsic values also have a pragmatic foundation; they promote ecological sustainability because they implicitly value future ecosystem uses that may not be highly valued in the present, but prove critical in time. Potential future values, spiritual qualities, aesthetics, the ability of exposure to natural settings to attenuate stress, inspire art, or catalyze maturation, as well as other, related roles cannot be easily monetized or quantified, but they are important and discussed by growing literatures [e.g., *Freeman*, 1993; *NRC*, 2005].

Figure 1 provides a schematic representation of the relationships among ecosystem structure and functions, ecosystem services, and the ways in which systems can be valued. The figure also introduces three fundamental strategies for organizing metrics used in benefits analyses. These include an approach based upon an assessment of the functional condition of the overall ecosystem, one based on an assessment of services, and an objective-based approach that focuses on functions and conditions directly related to the project objectives. These strategies are developed further in the following sections.

3. BENEFITS ASSESSMENT FRAMEWORK

Quantification of stream restoration benefits requires a prediction of changes in the state or condition of streams over time and assignment of a value to those changes. Motivation for assessing the benefits is generally one or more of the following: (1) to justify spending on restoration initiatives, (2) to prioritize restoration projects in the face of limited budgets; (3) to compare the benefits of different alternatives, projects, or programs; (4) to maximize the environmental benefits per dollar spent; and (5) to ensure that mitigation requirements are met or to calculate banking credits.

Results that emerge from a benefits assessment are fundamentally influenced by the way in which the benefits question is framed. To provide meaningful input to decision makers, it is important that computed benefits and costs reasonably reflect important changes that occur to the ecosystem as a consequence of the restoration actions. The general strategy best suited to characterizing the benefits and

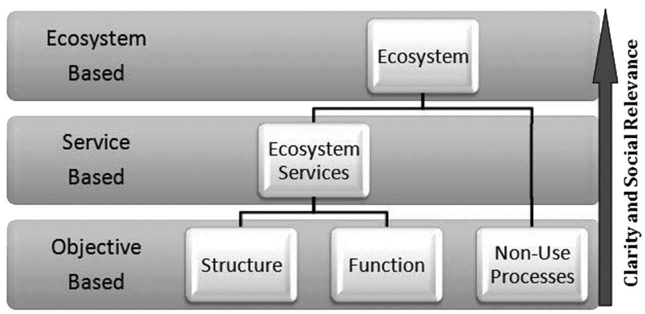

Figure 1. Organization of potential valuation metric sets and characterization strategies.

selection of the appropriate analysis scales are also important considerations that must be addressed for all projects.

3.1. Benefits Measure Change

Restoration does not create new ecosystems, but rather causes a change or changes in the condition or character of ecosystems over time. It is important to note also that ecosystems are not static; their condition changes over time in response to both natural and anthropocentric influences. Consequently, the appropriate basis for evaluating project benefits is the changes over time in the "state" of the ecosystem, as reflected by key metrics. Figure 2 shows the basis for comparison that serves as a benchmark for discussions in this chapter. The baseline is referred to as the future without-project (FWOP) condition and is represented by the projected system benefits over the planning time frame (50 years in this example) in the absence of any action. The incremental benefit afforded by each of the alternatives is the area between the benefit curve for a given alternative and the curve for the FWOP condition.

In cases for which benefits are monetized, the area under the curve in Figure 2 is a net economic benefit that can be expressed in terms of total dollars and can be converted to a present value, average annual value, etc., by applying basic economic formulae. In those instances, relative ranking of the alternatives is clear-cut, and determination of overall project worth can be made by dividing the project benefits by the costs, yielding a benefit/cost ratio or by calculating the net difference between benefits and costs. The latter approach is used for federal projects.

Difficulties in assignment of monetary values to ecosystems have limited the application of benefit cost methods for ecosystem restoration projects. When the units for metrics are not dollars, other decision support methods may be needed to evaluate alternatives. Techniques such as cost effectiveness evaluations and incremental cost assessments are often used as a way of comparing alternatives for which the benefits are described using a nonmonetary metric. Various Multi Criteria Decision Analysis (MCDA) methods can be helpful when there is not a common metric set for all alternatives.

An example of a nonmonetary metric commonly used for stream restoration projects is the expression of output in terms of the associated "habitat" created or restored. More specifically, the output is the product of the quantity of desired habitat (in acres or miles of stream) multiplied by a modifier (usually indexed from 0 to 1.0) representing the "quality" of the habitat. This habitat-quality metric is often referred to in terms of "habitat units." The same comparison strategy as shown in Figure 2 applies except that benefits are expressed as habitat units rather than dollars.

3.2. Metric Assessment Strategies

Figure 1 presents three alternative metrics strategies that can be used for benefits assessment. The lower two alternatives, objective-based and ecosystem service-based, are similar in that they rely upon identification and quantification of

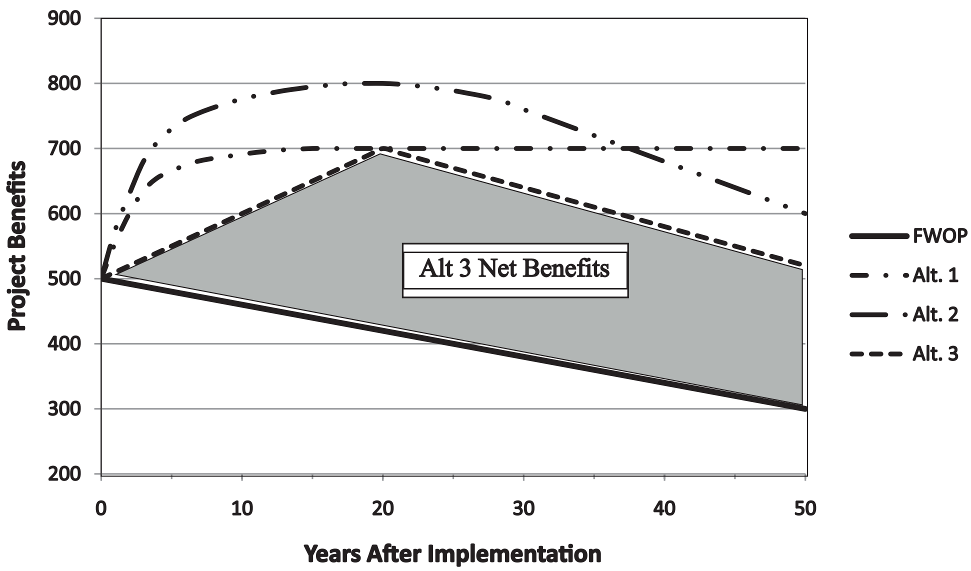

Figure 2. Schematic representation of benefit curves for restoration alternatives. The shaded area represents the net benefits for alternative 3.

key ecosystem functions or services as the basis for assessing benefits. These approaches are consistent with some existing practices for benefits quantification, and outputs can be expressed in monetary terms or in other nonmonetary units that convey ecosystem value or benefit. The third strategy, ecosystem-based, has its origins in mitigation practice and seeks to value changes from restoration in terms of overall ecosystem quality.

An important consideration for the objective- and service-based methods is identification of the ecosystem functions or services that are to be included in the analysis and those that are to be excluded. The valuation exercise, particularly when used to compare alternatives as opposed to broader analyses (such as the documentation of a program's value), may focus on only a subset of these factors, for example, habitat and water quality improvement, while ignoring all other factors. The ideal solution is to limit the considered factors to those that have a clear effect on decision making while omitting all others.

There has been a growing advocacy for the use of hydrologic and geomorphic metrics as a fundamental basis for evaluating aquatic ecosystem restoration projects. The concept stems from the realization that hydrology and geomorphic processes are overriding forces that influence almost all other functions. The Nature Conservancy (TNC), for example, advocates reestablishing or replicating the natural hydrologic variability in river systems as a necessary means to restore native biodiversity [*Richter et al.*, 2003]. The objective-based strategy is geared toward this basic approach, while acknowledging that specific objectives for each project might suggest the inclusion of additional metrics. While there is no consensus as to which specific hydrogeomorphic metrics are most ecologically relevant, methods exist to quantify many hydrologic and geomorphic parameters with reasonable certainty and replicability.

Both the objective-based and ecosystem service strategies can utilize biological metrics. Examples include community composition, species populations, provision of habitat, and maintenance of biodiversity. Most biological metrics are correlated to physical changes caused by restoration, requiring an understanding of the associated hydrogeomorphic processes but imposing additional data assessment, modeling, or other predictive techniques to translate these abiotic changes into the biological metric of interest. Furthermore, they are subject to many independent drivers outside the arena of restoration tools. This adds analytical complexity, uncertainty, and costs to most benefit evaluations. Biologically based metrics may be more socially or ecologically relevant and meaningful to decision makers in many cases, potentially justifying the added costs and uncertainties.

The use of service-based concepts for assessing ecosystems has gained considerable policy support in recent years. The Millennium Assessment, a formal effort by an international group of economists and ecologists to promote the consideration of services in decision making, illustrated the wide-ranging importance of ecosystem services [*Millennium Ecosystem Assessment*, 2005]. Most services can be monetized, providing consistent units for valuation. Services also tend to have more meaning to the general public, and decision makers then do basic ecosystem functions. In practice, however, services require the prediction of the supporting hydrologic, geomorphic, and biological processes, as well as analyses to impart a social value to those functions. Monetization adds yet an additional level of analysis and associated uncertainty. Significant advances are needed in relevant social, economic, and policy science for ecosystem services to move from a conceptual to an operational framework for decision making [*Brauman et al.*, 2007; *Daily et al.*, 2009].

The ecosystem-based strategy is founded on the notion that ecosystems form a convenient scale of organization that is understandable by the scientific community, decision makers, and the public. Under this strategy, restoration benefits can be expressed in terms of the type of the ecosystem and the degree to which its potential functionality is restored. In the simplest terms, a system's health or functionality can be expressed as a percentage of some reference condition, for example, the restoration action might improve a stream condition from 70% to 90% functional. One basis for determining functionality would be to evaluate key structure or process metrics or ecosystem services, in much the same way that the hydrogeomorphic (HGM) approach is applied to wetlands for mitigation [*Smith et al.*, 1995].

An additional modifier can be applied to assign a value to various ecosystems allowing for an easier comparison of benefits across diverse project settings (e.g., a stream, a wetland, and an estuary). The value modifier can be based upon the regional or national significance of the resource and might be established as a matter of policy. For example, recent studies emphasizing the value of headwater streams might suggest that they receive a higher significance rating as a matter of national policy than third- to fifth-order urban streams. Some classification scheme(s) sensitive to scale hierarchies would be necessary to apply this approach. Significance ratings for various ecosystems do not presently exist, although the USACE does have a method for considering significance when evaluating ecosystem restoration projects.

Figure 3 provides systematic representation of these various metric strategies and relative analytical complexity, uncertainty, and study costs for each. It demonstrates that almost all ecosystem restoration projects build from assessment of geomorphic and hydrologic conditions and that additional uncertainty, complexity, and cost is associated with metric sets that become

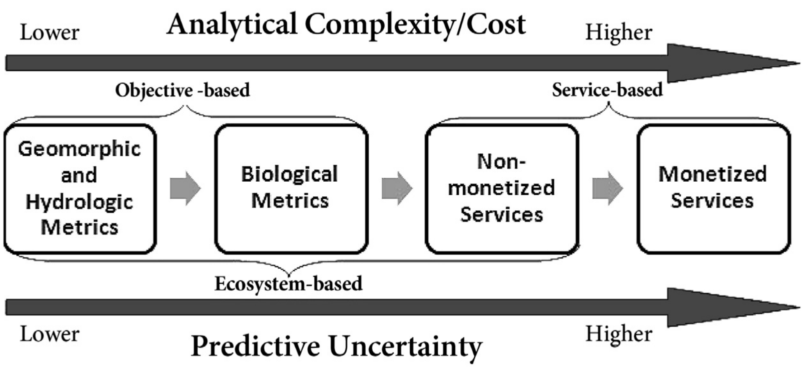

Figure 3. Metric formulation strategies and associated uncertainty, complexity, and cost.

further removed from these foundational factors. Exceptions exist: the restoration of riparian systems as a means of addressing energy, nutrient, or other water quality problems being a notable example. The evaluation of a biological metric typically involves assessing hydrologic or geomorphic consequences of restoration actions (e.g., depth, velocity, and substrate size), then converting these to some biologically relevant metric (e.g., habitat quality, diversity, and community structure). Conversion of these factors into services (e.g., recreational fishing) involves yet another level of effort with associated uncertainty, complexity, cost, and independent variables intrinsic to resource utilization. Monetizing goods and services represents yet a higher level of complexity.

Comprehensive valuation of aquatic ecosystems should be viewed as a practical improbability. The recognition that our knowledge is imperfect is at the root of issues with aggregation of assessments to higher scales and composite valuation of whole ecosystems. Multiplying one range of uncertain values by another, perhaps iteratively, let alone critical interdependencies and unforeseen behaviors of processes, services, and valuations, create the need for caveats regarding the state of the science. This does not imply no ecosystem valuation can be accomplished, simply that comprehensive valuation and summation of ecosystem goods and services to arrive at a total value is both unlikely and unnecessary.

3.3. Scalar Considerations

Identification of the spatial scale of the restoration effects is a key factor in the analysis independent from the metric set used for the analysis. The direct footprint of the project is obviously included, but projects affect ecosystem processes such that both direct and indirect impacts may extend beyond this footprint. Consideration of these impacts will yield a more inclusive analysis, but may be more difficult to accurately quantify. The study limits should extend beyond areas of direct impact to incorporate areas with indirect or secondary effects likely to affect management decisions.

The temporal scale of the analysis (the period of time over which benefits and costs are distributed) can play a crucial role in determining the results. Most restoration measures cause long-term (and potentially irreversible) changes to the ecosystem such that the project "life" is effectively indefinite. However, both benefits and costs become more uncertain and less meaningful with time from the present, suggesting practical limits for the analysis period. For federal water resource projects, 50 years has become the norm. Twenty years may be a reasonable time frame for some stream restoration projects, but the long time required for riparian system development and the equally slow response to some disturbances suggest that longer periods might provide better estimates of benefit.

Costs and benefits from stream restoration projects are unlikely to be constant over time. In order to accurately calculate benefits, the annual time streams of estimated benefits and costs must be translated into total values at a common point in time. A common and accepted practice is to establish a "base year" (usually when a project becomes operational) then use appropriate methods to convert future benefits and costs to a "present value" for the base year. If projects or alternatives with different project lives must be compared, values are often amortized over the project time horizon, yielding annualized benefits and costs.

Empirical evidence suggests that humans value immediate or near-term resources at higher levels than those acquired in the distant future [*NOAA*, 1999]. Thus, discounting has been introduced to address this time preference. The present value of a future benefit or cost is computed from:

$$PV = FV/(1+i)^n, \tag{1}$$

where PV is the present value of a benefit or cost, FV is its future value, i is the discount rate, and n is the number of periods (generally years) between the base year and when the benefit or cost occurs. For example, assume that a future benefit of a stream restoration project is an expanded catch of salmon valued at $1,000,000 in year 10. The present value of that benefit, assuming a 4% discount rate, is

$$PV = \$1{,}000{,}000/(1 + 0.04)^{10}$$

$$PV = \$675{,}584.$$

Discounting is mechanically easy, but is not without its critics. No agreement exists on the correct discount rate, and some object to the application of discounting to nonmonetary metrics. Discount rate selection can profoundly influence benefit-cost analyses. The Congressional Budget Office recommends a 2% rate based on the long-term cost of borrowing for the federal government. Since 1992, the Office of Management and Budget has recommended 7%, based on the marginal pretax rate of return on an average investment in the private sector in recent years. These figures roughly bound prevailing opinions regarding appropriate rates.

4. CONDUCTING BENEFIT ANALYSES

Benefits analysis involves multiple steps, many of which are common to all assessments and some that depend upon the specific project characteristics, metric set, and valuation techniques that are applied. These steps are summarized here:

1. Determine the purpose of the assessment. The assessment scope depends upon the potential use of the results. Common applications include the following: (1) relative comparison of different alternatives, (2) meeting mitigation requirements, and (3) determining if the benefits warrant overall costs.
2. Ensure a sound qualitative understanding of the ecosystem. This may require the development of a conceptual model representing a clear understanding of the causal mechanisms for degradation and the means to achieve restoration objectives.
3. Characterize the restoration alternatives under consideration. Specifically, define (1) how the various actions influence the ecosystem processes or condition to yield desired improvements, (2) adaptive management opportunities and how they may affect outcomes, and (3) life cycle costs for each alternative (including any adverse impacts).
4. Determine the general metric strategy and select specific metrics. This decision is based on results of previous steps, an understanding of the advantages and limitations of each strategy, available resources, policies, and so on.
5. Determine the spatial and temporal scopes of the analysis.
6. Forecast the parameters of interest. This may be the most complex and critical step in the process, potentially involving different models and analytical tools as well as the application of professional judgment.
7. Conduct any needed sensitivity and uncertainty analyses.
8. Apply any additional valuation approaches, if necessary (e.g., monetization of outputs, application of significance modifiers, etc.).
9. Make any needed comparisons and carefully document the process and results.
10. Monitor and adaptively manage the project.

4.1. Metric Selection Factors

Metrics can be (1) measurable system properties that quantify the degree of objective achievement [*Reichert et al.*, 2007], (2) mathematical functions developed for the purpose of assigning a value, as in the case of the ecosystem-based approach, or (3) ecological indicators. Metrics that can be directly measured relate to the physical, chemical, biological, or even social system attributes needed to affect the desired system response. The *U.S. EPA* [1991] distinguishes indicators on the basis of whether they best measure stresses, exposures, or responses. An accurate portrayal of the condition of a system when using indirect measures requires the use of suites of indicators, each in their appropriate role [*Schulze*, 1999].

No universally applicable metric set has been developed for stream restoration projects. Appropriate metrics for restoration projects heavily depend upon the project objectives, benefits assessment strategy, and other factors unique to the individual project. Direct measures are preferred to indicators for the purpose of quantifying benefits because the direct measures are more specific and more easily correlated to restoration actions. However, multiple metrics including both direct measures and indicators are often needed to characterize benefits, especially given the long response and recovery times for some systems. Table 1 provides examples of indicators and direct measures for a few ecosystem services and processes.

Good metrics should measure the level of performance, raise awareness and understanding, measure progress toward programmatic goals and objectives, and support decision making. The best metrics possess the following attributes:

1. They are *scientifically verifiable*. Two independent assessments would yield similar results.
2. They are *cost-effective*. The technology required to generate data for the metrics is economically feasible and does not require an intensive deployment of labor.

Table 1. Example Indicators and Measures for Select Functions[a]

Function	Description	Indicators	Measures
Maintain water quality	Water quality parameters are directly tied to support of biologic community. Riparian communities trap, retain, and remove constituents of surface and overland flow, improving water quality. Water quality influences potential use for consumption, irrigation, and other purposes.	watershed conditions (% impervious surface) stream order presence/absence/abundance of key indicator biota abnormal forms or behaviors; unusual mortalities of indicator species plant, fish, and invertebrate density, diversity, distribution, and health riparian buffer condition	conventional water quality measures (e.g., d.o., ph, conductivity, turbidity, tds, salinity, temperature, suspended sediment) bacterial counts metals and trace element sampling nutrient (n, p) tests rates of sediment deposition in channel and riparian corridor
Quality and quantity of sediments	Organisms often evolve under specific sediment regimes, and these must be preserved for the ecological health of the system. Sediment yield and character are primary variables in determining the physical character of the system.	change in banks, pools, and bars acceptable relative to other similar streams distribution, abundance, health, and diversity of aquatic biota presence of indicator species macroinvertebrate survey Redd counts Secchi depth	sediment grain size distribution embeddedness sediment yield sediment concentration and load by type/fraction armor layer size and thickness depth to bedrock sediment mineralogy
Maintain surface/ subsurface water connections and processes	Provides bidirectional flow pathways from open channel to subsurface soils, mitigating flood and draught impacts, maintaining base flow. Allows exchange of chemicals and nutrients. Provides habitat and pathways for organisms. Maintains subsurface capacity to store water.	invertebrates found in the hyporheic zone moist soil conditions, hydrophytic vegetation adjacent wetlands, hydric soil indicators groundwater elevation fluctuations watershed % impervious surface soil porosity	flux in groundwater levels stream base flow hyporheic macroinvertebrate distribution, density, and diversity isotope dating water chemistry profiles temperature recording texture, structure, moisture, redox, and porosity of adjacent soils
Regulate chemical processes and nutrient cycles	Provides for complex chemical reactions to maintain equilibrium and supply required elements to biota. Provides for acquisition, breakdown, storage, conversion, and transformation of nutrients within recurrent patterns.	presence of seasonal debris in riparian area presence/absence of indicator species and their health presence/absence of photosynthesis, fecal matter, biofilms, and decomposition products riparian vegetation composition and vigor changes in algae, periphyton, or macrophyte communities changes in trophic indicators	BOD (CBOD and NBOD) and DOC. stable carbon isotope analyses cell counts, atp concentration, respiration rates, uptake of labeled substances redox potential ion exchange capacity adsorption capacity dissolution/precipitation rates decomposition rates plant growth rates, biomass production

[a]From *Fischenich* [2005].

3. They are *easy to communicate to a wide audience*. The public would understand the scale and context and be able to interpret the metric with little additional explanation.

4. They are *changeable by human intervention*. The metric would have a causal relationship between the state of the system and the variables that are under a decision maker's control. Metrics that are independent of human action do not inform a management, policy-making, or design process.

5. They are *credible*. It would be perceived by most of the stakeholders as accurately measuring what it is intended to measure.

6. They are *scalable*. It would be directional, whether qualitative (best, good, or worst) or quantitative, as appropriate.

7. They are *relevant*. It would reflect the priorities of the public and other stakeholders and enhance the ability of managers and/or regulators to faithfully execute their stewardship responsibilities. There is no point assembling a metric no one cares about.

8. They are *sensitive* enough to capture the minimum meaningful level of change or make the smallest distinctions that are still significant, and it would have uncertainty bounds that are easy to communicate.

9. They are *minimally redundant* in that what it measures is not essentially reflected by another metric in the set being used.

10. They are *transparent* such that use of the metric avoids "readily unapparent and/or known agendas."

4.2. Ecosystem-Based Approach

The ecosystem-based approach is intended to provide a mechanism for assigning benefits that allows for comparisons across ecosystem types, facilitating prioritization and trade-off decisions in the face of limited budgets. It also offers the advantage of presenting benefits in terms that are relevant to and easily understood by scientists and the general public alike: the ecosystem itself. People generally understand the intrinsic value and importance of streams, wetlands, lakes, and estuaries. By scaling the system based upon the degree to which it functions or its overall integrity, and further delineating ecosystem types by more refined classifications, this method can integrate a variety of factors that contribute to decisions regarding the benefits or value of restoration actions.

The ecosystem-based approach requires three steps: (1) classification of the stream, (2) assignment of a value to each stream class, and (3) determination of the functionality of the stream relative to reference standards for the range of conditions to be evaluated. The ecosystem-based approach is not presently developed for stream systems and is presented herein as a concept that can serve as a basis for conducting benefits analyses, recognizing that considerable work is needed before it can be practically implemented. Many of the concepts draw upon the HGM approach to assessing wetland function [*Smith et al.*, 1995].

The development phase is carried out by an interdisciplinary team of experts (Team) and begins with the classification of streams into regional subclasses. Alternatively, an existing classification scheme [e.g., *Rosgen*, 1994] can be used provided it adequately delineates streams by function and value. The Team then develops a functional profile that describes the physical, chemical, and biological characteristics (functions) of the regional subclass, identifies which functions are most important, and determines ecosystem and landscape attributes and processes that influence each function. The functional profile is based on the experience and expertise of the Team and information collected from reference streams. Reference streams are selected from a reference domain (a defined geographic area) and represent sites that exhibit a range of variation within a particular stream type including sites that have been degraded or disturbed as well as those sites that have had little disturbance.

The Team next develops assessment models and calibrates them based on data collected from the reference streams. These models define the relationship between critical attributes and processes of the ecosystem and surrounding landscape and the capacity of a stream to perform a function. The assessment model results in a functional capacity index (FCI) (0–1.0), which estimates the capacity of a stream to perform a function relative to other streams from the same regional subclass in the reference domain. The standards used to scale functional indices are reference standards or the conditions under which the highest, sustainable level of function is achieved across the suite of functions performed by reference streams in a regional subclass.

In the implementation of this method, the assessment model is applied to the FWOP as well as to each restoration alternative to determine the FCI at various points in time over the planning period. The frequency of computation depends upon the anticipated change in the condition of the system and the need to accurately portray the changes in the quality of the system over time. If changes are linear, calculating an FCI at the beginning and end of the study period is adequate. Nonlinear response, thresholds, and variable implementation schedules may demand calculation of time steps on the order of decades or years. If the quantity of stream length or area differs among the alternatives and the FWOP, then it should be calculated at each time step as well.

Calculation of overall benefit proceeds as described for Figure 2. The stream length or ecosystem area is multiplied by the FCI and by the value for that particular system for both the alternatives and the FWOP. The benefits are the difference between the computed product for the alternative and FWOP. The value term could be expressed any number of ways ranging from an overall monetary value determined from detailed data collection and analysis to a simple semi-quantitative scale based upon factors related to ecosystem significance, public utilization, production of services, etc. The value term can be eliminated in circumstances where it does not affect decisions, for example, when simply comparing alternatives in the same ecosystem type.

4.3. Objective-Based Approach

The objective-based approach to assessing benefits of ecosystem restoration is very closely linked to the restoration process itself. Specifically, metrics that have ecological significance and are closely related to restoration objectives are used to assess project effectiveness or as a proxy for the benefits. The method relies upon a careful assessment of the conditions and processes for the ecosystem in order to evaluate causal mechanisms for degradation, critical limiting factors, and likely effects of management actions relative to the physical, chemical, and biological condition of the system. Without this sound theoretical understanding, it would be difficult, if not impossible, to develop performance criteria and meaningful measures of ecological condition.

Selected metrics should meet the criteria presented in section 4.1 and should be the most efficient way of reflecting the ecological effects of the proposed restoration work. They should be geared toward measuring change, generally in terms of both quantity and quality of some key physical, chemical, or biological condition or process. The objective-based strategy is generally consistent with the current state of practice in that it promotes identification of specific metrics related to ecological quality. These include, for example, (1) natural processes and dynamic properties that drive ecosystem self-design (i.e., hydrology and geomorphology) and (2) desired ecological end points (e.g., wildlife habitat).

Scientists have increasingly emphasized the need to focus upon processes rather than structure or form when developing stream restoration designs [*Kondolf*, 1998; *Bain et al.*, 2000; *Bennett et al.*, 2009]. The concept stems from recognition that habitat restoration will not be effective in the long term unless the ecological processes that sustain habitats are also maintained. Because habitat and biological health are closely aligned with watershed hydrology and geomorphology, proxy metrics for the effects of alternatives on these ecological services can be based on predicted hydrologic and geomorphic changes. Changes in these attributes are more directly linked to typical stream restoration actions and thus can be more readily and accurately predicted with an acceptable degree of uncertainty within study budget and time constraints. Metrics based on hydrologic and geomorphic outcomes must be ecologically meaningful, however, and thus would necessarily be place-specific and based on the central issues of concern.

Hydrologic metrics include measures of frequency, duration, magnitude, timing, and rate of change of flow. Each of these aspects of flow is an important determinant of the chemical and biological features and functions of stream ecosystems. The magnitude of flow is important for channel formation, sediment transport, and solute flux [*Doyle et al.*, 2005]. Flow duration is critical to biological processes and communities, while the timing of high and low flows exerts strong influence on biological community structure [*Poff and Ward*, 1989]. It must be recognized explicitly that rivers may respond to disturbance in episodic, complex, and unpredictable ways, especially if certain threshold conditions are crossed.

Potentially relevant geomorphic metrics include those ecologically relevant processes and structural characteristics affected by restoration measures. Examples of geomorphic processes included erosion, sediment transport and deposition, evolution of channel form, and changes in the channel morphology. Structural metrics include composition of bed material, presence of important floodplain features, riparian zone organization, channel cross section, planform, and slope. It is important that the selected metrics relate directly to relevant degradation and restoration processes as well as the ecological health of the system.

4.4. Service-Based Approach

Ecosystem services have been defined as “the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life” [*Daily*, 1997, p. 3]. As this definition implies, ecosystem services can be viewed as the link between the natural properties of ecosystems and human welfare. That is, the service concept connects an ecological focus on “what ecosystems do” with an economic focus on how ecosystems satisfy human needs. As such, the concept embodies both an ecological and human dimensions. Table 2 provides a list of example ecosystem services and the various ways in which they can benefit society. Information in Table 2 is extracted from more comprehensive listings given by *Daily et al.* [2000], *Stakhiv et al.* [2003], *Fischenich* [2005], and the *Millennium Ecosystem Assessment* [2005].

The concept of using ecosystem services as a basis for decision making, especially within the public sector, has gained considerable momentum in recent years. Significant investment in service research by the U.S. EPA, USACE, and Department of Agriculture demonstrate both interest in the topic and the need to advance scientific understanding and

Table 2. Examples of Ecosystem Services Relevant to Streams[a]

Services	Comments and Examples
Provisioning	
Food	production of fish, wild game, and nuts and grains
Freshwater	storage and delivery of water for domestic, industrial, and agricultural use
Fiber and fuel	production of logs, fuel wood, peat, fodder
Transport	waterborne movement of goods and people, animal movement, etc.
Power	Hydroelectrical supply
Regulating	
Flow regulation	groundwater recharge/discharge; surface storage
Water purification	retention, recovery, and removal of excess nutrients and pollutants
Sediment processes	erosion, transport, sorting and retention of soils and sediments
Natural hazard regulation	mitigation of droughts, flood attenuation
Climate regulation	influence local and regional temperature, precipitation
Cultural	
Recreation	fishing, hunting, birding, swimming, boating, etc.
Aesthetic	subjective value associated with pleasure derived from viewscapes
Educational	opportunities for formal and informal education and training
Spiritual	inspirational or religious values
Supporting	
Soil formation	sediment retention and accumulation of organic matter
Nutrient cycling	storage, recycling, processing, and acquisition of nutrients

[a]Adapted from *Daily et al.* [2000], *Stakhiv et al.* [2003], *Fischenich* [2005], and *Millennium Ecosystem Assessment* [2005].

develop tools before it can be operational. The Council on Environmental Quality (CEQ) in its draft revision of the principles and standards for Federal water resource development (P&S) says that "consideration of ecosystem services can play a key role in evaluating water resource alternatives" [*Council on Environmental Quality*, 2009]. Accordingly, it advises that planning studies identify ecosystem services associated with the study area and account for any changes in the quantity or quality of those services in plan formulation, evaluation, and selection.

Despite considerable interest in utilizing service-based approaches for characterizing restoration benefits, several key challenges remain. First, there is no consensus regarding the scope of ecosystem services and little agreement upon which services are most significant for streams. Second, service-based approaches face the same challenge as objective-based approaches with regard to the integration of multiple metrics; the issues of interdependencies, double counting, and variable units must somehow be addressed. Third, in addition to these challenges, tools to quantify ecosystem service production functions are lacking, and analyses must build upon predictions of the structural and functional conditions of the system. This adds to the uncertainty of the predictions as well as the cost and complexity of the analysis.

The process for conducting a benefits analysis using service-based approaches essentially mirrors the objective-based approach. The primary differences lie in the added effort of linking the structural and functional changes to the service outputs, computing those outputs, and the fixing an economic value. The additional step of monetizing service benefits is optional, but provides the convenience of common units for the cost of the benefits, and consistency among the services. This facilitates the trade-off and overall investment decision making, but it can lead to the compromise of overall ecosystem integrity or sustainability if individual services are optimized at the expense of other important ecosystem functions only because they are more easily monetized or have more immediate value. Thus, the application of the service-based approach should include additional analyses as necessary to ensure ecosystem integrity.

5. TECHNIQUES FOR PREDICTING AND VALUING ECOSYSTEM OUTPUTS

Methods for characterizing the benefits of ecosystem restoration efforts can be classified in numerous ways. One division is to separate those benefits that can be monetized from those that cannot or should not. The distinction is not always clear because an economic value can theoretically be placed upon any benefit, although practical limits exist in available methods and acceptable uncertainty. In this section, approaches for predicting outputs are described in terms of the types of models typically used. Model outputs sometimes have sufficient meaning for decision making, and no further action is needed. In other cases, the outputs require valuation, usually in monetary terms. Monetizing benefits facilitates trade-offs and other difficult decisions, but the techniques for monetization of ecological outputs are often contentious.

5.1. Predictive Models

Many types of quantitative models have been developed to indicate ecological response (outputs) to natural and managed changes in ecosystem conditions. They vary widely in structure, assumptions, data and expertise requirements, and utility. While the emphasis here is on numerical models, ecological models useful for this purpose can also include statistical models, which develop relationships between and among variables based on sampled-data distributions. Statistical models can be particularly useful in close conjunction with natural reference conditions, which can be regarded as a form of physical model often useful in restoration.

Numerical models fall into two basically different output categories: index models and actual output estimation models [*Stakhiv et al.*, 2003]. Index models typically use species habitat, community habitat, biotic integrity, and functional capacity indexes to reflect relative quality of a system anchored in some optimal condition of maximum quality and varying downward toward zero as conditions change from optimum. Quality indices and geographical area are typically "integrated" by multiplying unit area (e.g., 1 acre) by the unit quality index and summing the multiples. One example of the product of this multiplication is the habitat unit of HEP [*U.S. Fish and Wildlife Service (U.S. FWS)*, 1981], which in ideal circumstances can be compared directly to other habitat units of different spatial quantities and quality index values. Alternatively, Index of Biotic Integrity (IBI) [*Karr*, 1981] and some other multimetric index models scale over a broader range and are intended to reflect biological health relative to unimpacted reference conditions independent of stream length or area. Examples of index models are listed in Table 3.

Actual output estimation models include statistical and process simulation models that are typically developed from theoretical mathematical descriptors of process and form but may be hybrid models including both theoretical and empirical elements (statistical equations). Their common intent is to simulate natural process rates and output amounts as closely as needed for the model purpose. They generate model outputs in physical units matching the actual ecosystem output measured in the field. Examples include number of days per year of floodplain inundation, numbers of fish per mile, or average input of organic matter per acre of riparian habitat per year. Of the model types, the physical process models are most common and useful for predicting restoration benefits, while statistical models may be most robust.

The number of process-based models with potential application to a stream restoration projects is far too great to permit a summary in this document. Included are various hydrologic, hydraulic, water quality, sediment transport, and geomorphic models that are useful in predicting relevant physical and chemical characteristics over time. A number of biological process models have relevance including those focusing on trophic structure, community composition and interaction, species populations, nutrient and energy utilization, growth and succession, and similar important processes.

Determining the "best" models to use for evaluating restoration of stream ecosystems is situational, depending on a number of factors including the specific processes or conditions needing evaluation, required accuracy, available resources (expertise, time, funding), needed data, and institutional acceptability. In many cases, the "correct" model does not exist, and a model must be developed or adapted to meet the needs of the specific project and circumstances. An examination of existing models by *Stakhiv et al.* [2003] yielded the following conclusions:

1. Species-habitat models are sensitive to significant effects at the species level but are not inclusive enough to formulate for restored natural ecosystem integrity.
2. Community-habitat models are inclusive enough to formulate for more natural ecosystem integrity but may be insensitive to significant effects at the species level.
3. Index models (e.g., HEP/HSI, IBI, and HGM) are most widely available but tend to exclude important systems context, require greater planner and stakeholder interpretation, and may require both community and species level index models for analysis.
4. Process simulation models (e.g., Hydrologic Engineering Center (HEC) River Analysis System (RAS) and Comprehensive Aquatic Systems Model (CASM)) are less available but more output and process explicit. They can incorporate complete systems contexts, can provide simultaneous output for conditions of naturalness and significant resources, and are superior for organizing lessons learned into improved model structure.
5. As ecosystem planning conditions grow more complicated and the science improves, the advantages of process simulation models outweigh the expediency and lower-cost advantages of index models.

5.2. Economic Valuation

The concept of economic value rests squarely on the "utilitarian" premise that human welfare derives from the satisfaction of preferences. For the purposes of assessing the economic value of ecosystem functions or services, it is important to note that measuring the value of something using dollars does not require its purchase and selling in markets. It

Table 3. Example Index Models and Methods

Method	Description	Applicability
Habitat Evaluation Procedures (HEP) *U.S. FWS* [1980, 1981]	Procedure for assessing habitat based upon habitat quality as reflected by suitability indices multiplied by habitat quantity.	Broadly used for a variety of ecosystems, but widely criticized as overly simplistic. Results are not transferrable across systems or scales.
Hydrogeomorphic Approach for Assessing Wetland Functions (HGM) *Smith et al.* [1995]	Functional capacity determined by size of wetland. Capacity of a wetland to perform a function relative to other wetlands within a regional wetland subclass in a reference domain.	Developed for wetlands and questions remain regarding the applicability to other systems and across different classifications. Sound statistical basis but requires significant investment in time to develop models.
Index of Biotic Integrity (IBI) *Karr* [1981]	Determination of integrity of a particular reach compared to a reference site based upon multiple metrics. Several variants have been developed for regional applications.	Has been applied to various systems. Scores can be compared with similar habitat types in the same region, with regions defined as part of the assessment process. Simplicity is a benefit and a limitation. May be less robust in simple, species-poor or guild-poor contexts.
Instream Flow Incremental Methodology (IFIM) *Bovee* [1982]	Index model that calculates the amount of microhabitat available for different fish life stages at varying flow levels for selected fish species.	Primarily applicable to situations involving changes clearly related to discharge or stage. Results are theoretically comparable across classes. Most widely used method for streams despite numerous criticisms.
Riverine Community Habitat Assessment and Restoration Concept (RCHARC) *Nestler et al.* [1995]	Measures habitat based upon velocity-depth distributions as compared to a reference condition standard. Variants of the method include other parameters.	Underlying concept is broadly applicable to streams, but existing models are limited to situations where model variables are applicable. Results not transferable across ecosystems or scales.
Rapid Bioassessment Protocols (RBP) *Plafkin et al.* [1989]	Subjective score of the quality of conditions for taxonomic groups.	RBP is applied within the classification of low or high gradient streams and not for comparison across stream types. Extremely subjective, but quick and easy to apply.
Wildlife Community Habitat Evaluation (WCHE) *Schroeder* [1996]	Index based on the relationship of native vertebrate species richness to several habitat variables including habitat edge and isolation	WCHE is applied to forested wetland types and is not intended for comparison across systems. Applicability for streams may be limited regionally and topically.

can be measured by estimating how much purchasing power (dollars) people would be willing to give up to obtain it (or would need to be paid to give it up), if they were forced to make a choice. Thus, economic value defined in strict economic terms is the aggregate willingness to pay (WTP) in dollars for services expected from an ecosystem or the willingness to accept the loss of those services [*NRC*, 2005].

Methods for assigning economic value to environmental outputs can be classified in terms of the way in which preferences are expressed by an individual and by the availability of supporting markets (see Figure 4). Preferences that serve as the basis for economic valuation can be revealed (e.g., in purchasing decisions) or stated (e.g., through surveys). Revealed and stated preference methods within surrogate and hypothetical markets are used to capture values of ecosystem goods and services that are not incorporated in existing market values. Table 4 provides a summary of the more common valuation methods used for ecosystem restoration.

Conducting site-specific valuation studies using these valuation approaches can be time consuming and expensive [*McComb et al.*, 2006]. Benefits transfer techniques are methods used to infer a value for an ecosystem or service based upon data collected from another similar ecosystem [*Wilson and Hoehn*, 2006]. Benefit transfer offers an economical approach to assess ecosystem services values in decision making. Although problems with the method persist and criticisms are common, benefit transfer techniques have become more accurate for estimating ecosystem services values as valuation studies have grown over the years and through the application of simple guidelines, developed by economists, for improving validity and accuracy [*Wilson and Hoehn*, 2006; *Plummer*, 2009].

Adequate data, let alone complete data, are often not available when making decisions. In these cases, more informed decisions are promoted by using alternative analytical strategies. Qualitative discussions of the benefits could be

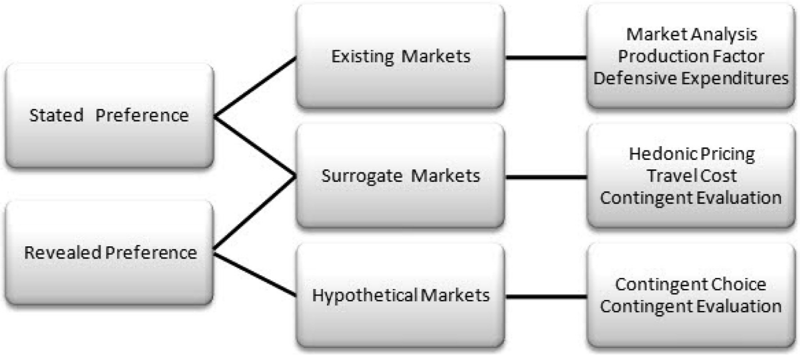

Figure 4. Economic valuation methods.

included in cases where quantitative analysis is not possible. Such discussions should address specifically why such quantitative analysis is not feasible and the reasons why the qualitative data is relevant. Breakeven analysis can be used in cases where risk or valuation data is lacking to estimate the number of units affected or willingness-to-pay value required to "break even" on a given project. Decision makers can determine whether the breakeven estimate is reasonable or not. Bounded analysis could be used when values are available for high-end and low-end scenarios for ecosystem services and environmental quality to create upper and lower bounds for the value [*University of Washington*, 2009].

There are many challenges to ecosystem valuation. Those who affirm the intrinsic value of ecosystems often object to the very idea of quantifying the value of environmental goods and services, comparing this to trying to value human life [*NRC*, 2005]. Environmental resources are particularly hard to quantify due to their broad range of intangible benefits and multiple value options [*Hussen*, 2001]. Accounting for the full range of values from aquatic ecosystems without "double counting" can be difficult, especially when multiple valuation methods are used [*Randall*, 1991]. The lack of markets make valuation in economic terms reliant upon methods that are often criticized [*Freeman*, 1993]. The selection of appropriate metrics for nonmonetary benefits is difficult and contentious, and there are no generally accepted standards.

6. OTHER ANALYTICAL METHODS

6.1. Benefit Cost Analysis

The key to all complex decisions is a skillful evaluation of trade-offs, in this case between various restoration alternatives and doing nothing. No existing decision-making protocol will establish, by itself, which of these choices to make, although protocols can certainly help organize the information [*Cairns*, 2006]. One common strategy is to evaluate the potential return on the investment in terms of benefits (monetary or otherwise) relative to the costs.

The formal process for this evaluation when the investment is a public expenditure is often referred to as benefit-cost analysis (BCA). The 1936 U.S. Flood Control Act, which required that the benefits of flood-control projects exceed their costs, caused the USACE to develop and adopt BCA as a basis for evaluating projects. Since then, cost-benefit techniques have gradually developed to the extent that substantial guidance now exists on how public projects should be appraised, and BCA methods are employed by agencies in many countries around the world [*Tevfik*, 1996].

Economic valuation plays a central role in the application of BCA, since BCA requires an estimate of the benefits and costs of each alternative using a common method (economic valuation) and metric (dollars) so that the two can be compared [*NRC*, 2005]. Comparison of costs and benefits allows an explicit consideration of trade-offs that are almost inevitably involved in restoration projects. These evaluations are particularly useful for (1) comparing the relative benefits and costs of different alternatives to select the preferred alternative and (2) determining whether the benefits are "worth" the costs.

Ideally, BCA provides objective information to a decision maker about quantifiable costs and benefits in common terms (dollars). The decision maker may then compare the costs and benefits of the decision and make a more informed decision than possible without them. In practice, the application of BCA is quite complicated. Benefits and costs are often difficult to identify, difficult to measure or monetize, and highly uncertain [*NRC*, 1999]. Additionally, although the BCA process aims for objectivity, analysts must make many subjective decisions and assumptions. These might include the choice of discount rate, whether and how to value environmental amenities (which are not traded in a marketplace), and what categories of benefits and costs to use. For

Table 4. Methods for Economic Valuation[a]

Method	Applicable To	Description and Importance	Constraints and Limitations
		Market Techniques	
Market price	Direct use values, especially wetland products.	The value is estimated from the price in commercial markets (law of supply and demand)	Market imperfections (subsidies, lack of transparency) and policy distort the market price.
Damage cost avoided, replacement cost or substitute cost	Indirect use values: flood protection, avoided erosion, pollution control, water retention, etc.,	Value of organic pollutant's removal estimated from the cost of building\ running treatment plant (substitute cost). Value of flood control derived from damage if flooding would occur (damage cost avoided).	Assumes that cost of avoided damage or substitutes match the original benefit. External circumstances may change the value of the original expected benefit and the method may therefore lead to under- or overestimates. Insurance companies interested in this method.
Productivity method	For specific wetland goods and services: water, soils, humidity in the air . . .	Estimates economic values for wetland products\services that contribute to the production of commercially marketed goods	Although methodology is straightforward and data requirements are limited, the method only works for some goods or services.
		Nonmarket Techniques	
Travel cost	Recreation and tourism	The recreational value of a site is estimated from the amount of money that people spend on reaching the site.	Only provides an estimate. Overestimates stem from other reasons for traveling to that area. Requires a large amount of quantitative data.
Hedonic pricing	Some aspects of indirect use, future use and nonuse values	Used when wetland values influence the price of marketed goods. Clean air, large surface of water or aesthetic views increase price of houses or land.	Captures people's willingness to pay for perceived benefits. Requires awareness of the link between the environmental attributes and benefits, else value not reflected in price. Very data intensive.
Contingent valuation	Recreation, tourism and nonuse values	Asks people directly how much they are willing to pay for specific services. It is often the only way to estimate nonuse values. Also referred to as a "stated preference method."	Possible bias in interview techniques. The most controversial of the nonmarket methods but one of the only ways to assign monetary values to nonuse values of ecosystems that do not involve market purchases.
Contingent choice method	For all wetland goods and services	Estimate values based on asking people to make trade-offs among sets of ecosystem or environmental services	Willingness to pay is inferred from trade-offs that include cost attribute. This is a very good method to help decision makers to rank policy options.
Benefit transfer method	For ecosystem services in general and recreational uses in particular	Estimates economic values by transferring existing benefit estimates from studies already completed for another location or context.	Used if it is too expensive to conduct a new full economic valuation for a specific site. Only as accurate as the initial study. Extrapolation limited to sites with the same characteristics.

[a]Adapted from *U.S. Army Corps of Engineers* [2004].

federal water resource projects, guidance like the P&G is used to ensure that subjective decisions are made as consistently as possible across projects and agencies.

6.2. Cost Effectiveness and Incremental Cost Analysis (CE/ICA)

CE/ICA is a form of efficiency analysis that serves to refine and illustrate trade-offs among a set of alternatives for which the benefits are expressed in a single or aggregated nonmonetary metric. The combined use of CE/ICA allows the optimization of ecosystem restoration outputs, supply side (outputs) without consideration for the demand (measured by WTP). The approach is widely used on federal water resource development projects, and tools exist to help in its implementation (Institute for Water Resources Planning Suite (IWRPLAN), downloadable public domain model for conducting CE/ICA analyses, U.S. Army Corps of Engineers Institute for Water Resources, Washington, D. C., available at http://www.pmcl.com/iwrplan/GenInfoOverview.asp IWRPLAN 2010, site accessed 1 August 2010). Cost effectiveness (CE) analysis weighs the costs of each project plan against its nonmonetary measure of output. The CE analysis screens out plans that are not cost effective from further consideration to ensure that the least cost alternative plan is identified for each possible level of output. Any particular plan is not cost effective if the same or a larger output level could be produced by another plan at less cost, or if a larger output level could be produced by another plan at the same cost. The plans that remain after this screening process is performed define the "CE frontier," or the set of cost-effective (or "nondominated") plans associated with successively higher possible levels of ecosystem outputs.

Once all cost-effective plans have been identified, incremental cost (IC) analysis can be used to help answer "What level of restoration output is worth it?" The IC analysis identifies incremental costs per unit output gained from moving from one plan to the next higher-output plan. This information helps to identify plans that capture production efficiencies with respect to the predicted output along different segments of the CE frontier (i.e., output ranges). The technique may not identify a single "best" plan, but it does eliminate those plans that are demonstrably inferior to others, and it provides useful information to support decision making.

6.3. Techniques for Comparing Dissimilar Metrics

Given the multitude and diversity of ecosystem functions and services that could serve as a basis for evaluating restoration benefits, situations involving multiple metrics with different units of measure are not uncommon. Techniques facilitating comparisons and trade-offs have been well-studied and may be coarsely divided into four categories: (1) For simpler decision problems, direct comparison of dissimilar metrics may be straightforward, rapid, and require little or no analysis beyond a qualitative comparison and evaluation. (2) Dissimilar metrics may be converted into consistent units (e.g., dollars/acre, habitat units, etc.) for direct comparison [*Daily et al.*, 2000]. (3) Transformation or normalization of metrics to an equivalent scale represents a third option for metric comparison [*Yoe*, 2002]. (4) MCDA provides a useful framework for comparing dissimilar metrics to inform environmental decision making [*Gregory and Keeney*, 2002], where normalized metrics are combined with value judgments of those involved in the decision to create an alternative metric for decision making.

7. CRITICAL CONSIDERATIONS IN CONDUCTING BENEFITS ANALYSES

7.1. Conceptual Models

One of the greatest deficiencies in our endeavors to realize the potential benefits of stream restoration lies in the lack of quality and coherency of available data and our capacity to effectively communicate our understanding as a basis for informed decision making [*Hillman and Brierley*, 2005]. The range of responses of river systems to disturbance events, whether natural or man-made, induces an inordinate degree of complexity and uncertainty in our interpretation of trends and rates of change and likely future states/conditions. Such phenomena cannot be effectively appraised through black-box exercises. Rather, system-specific insights of the causal mechanisms for degradation and likely restoration trajectories over time are required. These must be communicated appropriately to key decision makers and stakeholders in the stream restoration process.

Conceptual models are descriptions of the general functional relationships among essential components of a system. They tell the story of "how the system works" with respect to key processes and attributes and, in the case of ecosystem restoration, how the proposed alternatives aim to alter those processes or attributes to benefit the system [*Fischenich*, 2008]. Conceptual models should be required as a first step in the planning process, as they provide a key link between early planning (e.g., an effective statement of problem, need, opportunity, and constraint) and later evaluation and implementation.

Conceptual models can be invaluable in supporting benefits analyses because they provide key linkages among ecosystem components and processes and help identify appropriate metrics for the measurement of project outcomes. They provide feedback to, and help formulate, goals and objectives, indicators, and management strategies. Conceptual models also play an important role in determining indicators for monitoring and are an invaluable tool to help interpret monitoring results and explore alternative courses of management. Detailed guidance on the development of conceptual models is given by *Fischenich* [2008], and a tool to assist the preparation of conceptual models is publicly available [*Dalyander and Fischenich*, 2010].

7.2. Nonlinearity and Thresholds

Natural processes tend to vary over time and space, as well as between species, communities, and geologic, physiographic, or ecological settings. The ecosystem services these natural processes provide are therefore also highly variable. Ecosystem services are also affected by thresholds and limiting functions that influence natural processes as well as changes in the values that might be applied as opinions and needs change over time. Improvements in the understanding and quantification of nonlinearities in ecosystem functions are likely to provide more realistic ecosystem service values.

Many ecological functions are likely to be characterized by a tendency to level off (i.e., asymptotic relationship) or change dramatically (i.e., ecological thresholds) over time and space, as is the case with certain ecological processes such as population growth, predator-prey interactions, and species-area relationships [*Cain et al.*, 2008]. However, such nonlinear relationships between ecological traits and ecosystem function, and ecosystem function and service delivery, have not been explored in depth, quantitatively or conceptually.

Stream and riparian habitats and conditions are highly variable and patchy. Efforts to restore riverine systems should seek to reinstate processes that create the variability in temporal regimes and spatial diversity that characterize healthy systems. Insofar as these characteristics are important to ecosystem function and health, they should be accounted for in the calculation of benefits. This might suggest the selection of metrics that quantify or at least capture the presence or absence of dynamism and key thresholds. Additionally, the "resolution" of forecasting efforts may need to be sufficiently fine that they capture important variability in benefit streams and certainly must capture the effects of thresholds.

7.3. Uncertainty

The natural variability of river systems, and the range of spatial and temporal scales over which processes interact, introduce complexity into ecosystem-based approaches to stream rehabilitation [*Everard and Powell*, 2002]. The emerging approach is essentially probabilistic rather than deterministic, recognizing the central place of disturbance-driven temporal and spatial variability in a nonequilibrium or multi-equilibrium view of ecosystem functioning [*Landres et al.*, 1999].

All stream restoration projects face uncertainties, with the principal sources including (1) incomplete description and understanding of relevant ecosystem structure and function, (2) imprecise relationships between restoration actions and corresponding outcomes, (3) variable opinions and weightings regarding the values of ecosystem services, and (4) unpredictable and highly stochastic events and interactions affecting key processes (e.g., flooding, fire, regional climate change, etc.).

Most components within benefit-cost analysis do not have one value but are best captured as being within a range of values (see Figure 5 for example). With enough information, benefits and costs can be expressed as probability distribution functions. Analytical tools can be used to provide benefit-cost information as probabilities to better account for uncertainty. There are a number of ways in which uncertainty and associated risks can be identified and addressed for steam restoration, providing decision makers with important information that can influence the selected alternative as well as expectations for the project's benefits: (1) identify and document study elements contributing to significant uncertainty, (2) employ scenario analyses to bound possible outcomes and assess the sensitivity of outcomes to judgments regarding key inputs, (3) use Monte Carlo analysis to provide probability estimates of outcomes when feasible, and (4) use confidence intervals or probability distributions as opposed to point estimates to describe uncertainty whenever possible.

A widely used criterion for decision making is to choose the alternative that yields the greatest net benefit. Using Figure 5 as an example, Alt 1 yields the maximum predicted net benefit. Decisions might change when uncertainty is quantified, however. For example, Alt 4 may be preferred over Alt 1 in Figure 5 because, although it has a lower predicted outcome, the

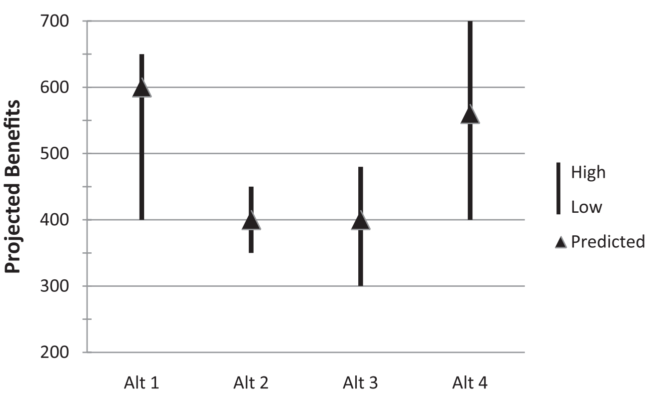

Figure 5. Influence of uncertainty on decision making.

range of likely outcomes may be regarded as more attractive. The uncertainty of the outcome of an alternative means that while the benefits could be excellent, they also have a chance of being poor. In general, faced with the choice between alternatives that generate the same expected value but with different ranges of outcomes, most people would choose the alternative with the lowest variability, implying that they are "risk averse" [*NRC*, 2005]. Alt 2 would be preferred to Alt 3 in Figure 5 following this logic.

Although considerable uncertainty exists regarding the value of ecosystem services, there is often the possibility of reducing this uncertainty over time through learning. An adaptive management program can increase the likelihood of achieving desired project outcomes in the face of uncertainty. When adaptive management is employed, alternatives with a greater range of uncertainty in outcome may be attractive to decision makers because, in theory, the more poorly performing outcomes will be eliminated through the adaptive management actions, increasing the likelihood of attaining the maximum result. Thus, if either Alt 1 or Alt 4 in Figure 5 includes adaptive management, it would likely be preferred because of the elimination of the lower part of the uncertainty bar.

7.4. Monitoring and Adaptive Management

Adaptive management recognizes that decisions are based on the best available, yet often incomplete and imperfect scientific data, information, and understanding [*Walters*, 1997]. Importantly, adaptive management provides a decision-making framework that can adjust management actions based on newly acquired information and monitored outcomes of previous decisions. This adaptive decision-making process can increase the chances that management goals and objectives (e.g., ecosystem restoration or sustainability) will be achieved despite uncertainties.

There are many benefits to the development and implementation of an adaptive management program for stream restoration projects, virtually assuring a reasonable return on investment. For the purpose of benefits analyses, greatest return is an increased probability of achieving the maximum benefits from the ecosystem restoration action. From a probabilistic standpoint, these potential benefits can be described using Figure 6.

Each of the lines shown on the graph represents a potential project outcome over a given period, and each of these outcomes has an associated probability set shown to the right of each line. The first probability is for the full set of outcomes, while the second is for only the solid lines. The dashed lines represent outcomes that adaptive management practices will prevent. Thus, the total benefits can be regarded as the sum of the products of the benefits for each possible trajectory multiplied by their probability. By eliminating the poorly performing trajectories (dashed lines), the overall probabilistic project benefits will increase due to the elimination of poorly scoring outcomes as well as the restructuring of the probabilities for the higher scoring outcomes.

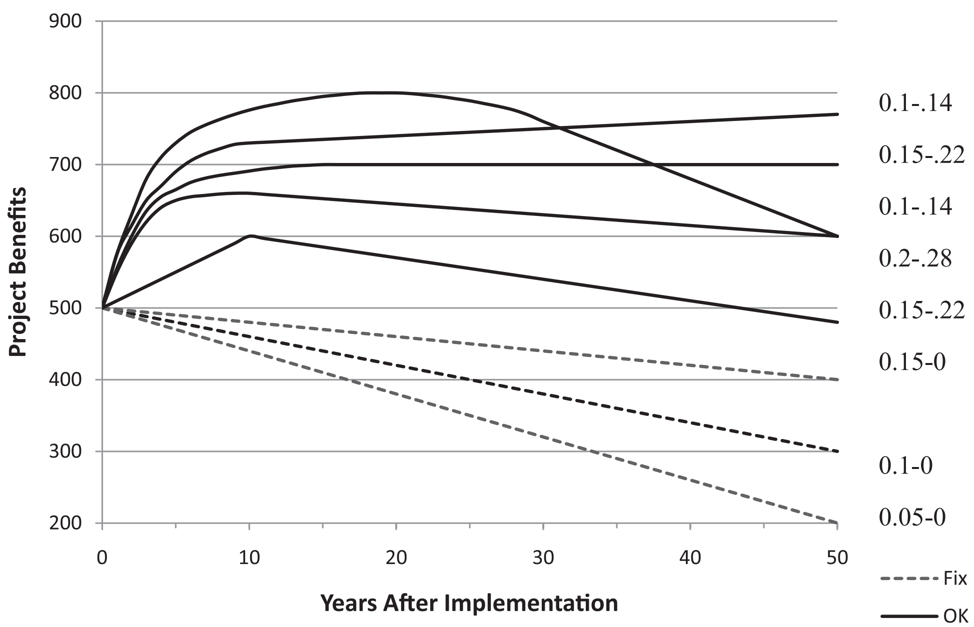

Figure 6. Quantification of the benefits of adaptive management.

Monitoring is a significant component of an adaptive management program. Additionally, project-level monitoring can (1) confirm that a project was implemented as intended, (2) provide feedback regarding the effects of the project relative to expectations, and (3) support management decisions based on trends and outcomes. Metascale monitoring can be used to document or increase program effectiveness in both ecosystem restoration (where multiple restoration actions or projects have occurred) and regulatory arenas (such as mitigation programs). To the extent practical, monitoring programs should be geared toward maximizing these benefits and contributing to a better understanding of the benefits of stream restoration.

8. DISCUSSION

Despite annual investments of over 1 billion U.S. dollars in aquatic habitat rehabilitation activities, very little is spent on monitoring or on evaluating these projects. Consequently, little information exists with which to assess project outcomes or determine if the benefits are worth the costs. Retrospective investigations of completed projects would provide useful information regarding the efficacy of various restoration strategies and possibly some indications as to the benefits derived from investments.

On a go forward basis, estimating benefits from stream restoration projects provides a useful means for comparing alternatives, prioritizing projects, and assessing overall return on investment. Critical factors in the estimation of benefits include identification of an appropriate strategy, selection of the most effective metrics, and a determination whether or not to monetize the benefits. Use of ecosystem service-based concepts for calculating benefits has gained considerable interest in recent years, and efforts are underway to develop new tools and data to support these approaches.

Interest has also grown in using more direct hydrologic and geomorphic metrics as indicators for ecological and service-based benefits sought from most stream restoration projects. The basis for this interest stems from the fact that management measures to achieve restoration objectives typically involve manipulation of hydrology or geomorphology, and tools to quantify and predict related metrics are much more developed than those for evaluating biological or service-based outputs. Decreased study cost and complexity along with the reduced uncertainty offset possible ambiguities due to the proxy nature of the metrics.

Table 5 presents a matrix that considers different classes of metrics for measuring the effects of alternatives on ecosystem support services and includes an assessment of how they compare relative to time and cost of implementation, associated uncertainty, and overall credibility. Of course, specific judgments made in any planning case would necessarily consider place- and situation-specific circumstances when selecting metrics.

Some economists argue that use and nonuse preferences for changes in ecosystem services can be directly estimated using stated preferences techniques such as "contingent valuation," which essentially involves sophisticated public surveys. These surveys elicit the choices that survey respondents would make if they had to pay for alternative states of nature. However,

Table 5. Options for Measuring Alternative Effects on Ecosystem Benefits

Basis for Evaluation	Example Performance Metrics	Time and Cost of Analysis	Uncertainty in Estimates	Scientific Credibility
Hydrologic and geomorphic structure and processes	Hydrograph shape; frequency of floodplain inundation; physical habitat distribution; sediment transport capacity	low	low to moderate	high
Biological structure and function	Index of Biotic Integrity; habitat suitability for a species or community; species richness; population estimates	low to moderate	moderate to high	moderate to high
Services rendered (non-monetized)	Recreation use-days; number of catchable fish; tons of cargo; tons of nitrogen removed	moderate to high	high	moderate to high
Ecosystem functional capacity	A classified ecosystem scaled by the functionality relative to reference conditions and (optionally) public significance	low to high	moderate to high	unknown
Economic value	Increase in property values adjacent to restored streams; commercial fishery yield; WTP for recreational opportunities	high	high	low to high

many objections to this approach have been articulated outside as well as within the economics profession. One important conceptual criticism argues that people do not view ecological services as individual consumers; instead, people view and express their preferences for such services collectively through environmental laws and other public policies.

Fischenich [2005] outlined principles necessary for the effective restoration of streams. A common theme of these principles is the understanding of key processes that occur within a system to create conditions important to the ecosystem's character and maintenance. In other words, we must know how the system operates, or functions, in order to make good management decisions. This concept is fundamental to restoring and managing ecosystems. It is equally fundamental to the assessment of the benefits from restoration projects. Selection of an appropriate method and associated metrics are largely influenced by this level of understanding.

Several measures can be employed to improve benefit analyses, independently of the method or metrics that are utilized. Quantifying and documenting the uncertainty associated with predicted conditions provides decision makers with valuable information. The considered development and use of specific conceptual ecological models guide not only decisions regarding ecosystem restoration process, but also metric selection and benefits quantification efforts. Monitoring and adaptive management programs are important not only as follow-ups to the project implementation, but also during the formulation process. Decisions regarding the potential for adaptive management actions can influence decisions and affect overall project benefits.

The principal and overarching output of ecosystem restoration should be improvement to the natural integrity of the system. In the narrow sense defined by *Karr* [1981], ecosystem integrity is the relative completeness of natural ecosystem function, structure, and associated complexity, which reflects the system's resilience and sustainability. Measuring this important and integrative characteristic would provide the best means by which to assess stream and other ecosystem restoration efforts. Some suggest that this can be accomplished by assessing the ecosystem structure and functions [e.g., *Schneider and Kay*, 1995], while others argue for a more socially based perspective such as critical ecosystem services [e.g., *Daily et al.*, 2000]. Considerable research is underway to evaluate the alternative existing methods and develop new approaches for assessing benefits. Ecosystem integrity might be a useful concept for assessing the various models and methods that are developed from these efforts.

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