FORUM

Evaluating Stream Restoration Projects

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ABSTRACT / River and stream restoration projects are increasingly numerous but rarely subjected to systematic postproject evaluation. Without conducting such evaluation and widely disseminating the results, lessons will not be learned from successes and failures, and the field of river restoration cannot advance. Postproject evaluation must be incorporated into the initial design of each project, with the choice of evaluation technique based directly upon the specific project goals against which performance will be evaluated. We emphasize measurement of geomorphic characteristics, as these constitute the physical framework supporting riparian and aquatic ecosystems. Techniques for evaluating other components are briefly discussed, especially as they relate to geomorphic variables. Where possible, geomorphic, hydrologic, and ecological variables should be measured along the same transects. In general, postproject monitoring should continue for at least a decade, with surveys conducted after each flood above a predetermined threshold. Project design should be preceded by a historical study documenting former channel conditions to provide insights into the processes responsible for the present channel condition and to suggest earlier, potentially stable channel configurations as possible design models.

Despite the increasing commitment of resources to stream restoration, postproject evaluation of stream restoration projects has generally been neglected. In some cases no postproject evaluation has been conducted, while in others a lack of advance planning has caused evaluation results to be of little use in determining whether or not project objectives have been satisfied. To date, no general guidelines for the evaluation of stream restoration projects have been developed and implemented. Such guidelines are needed to facilitate the systematic study of past restoration success and failure so that the practice of stream restoration can be improved.

The need for improving approaches to postproject evaluation is illustrated by recent restoration surveys. The National Rivers Authority found that, of nearly 100 enhancement projects completed on British rivers, only five had been the subject of postproject evaluation reports (Holmes 1991). In North America, evaluations of aquatic and riparian restoration projects have been conducted on a regional basis. O'Neil and Fitch (1992) examined 400 in-stream aquatic habitat enhancement structures installed in southwestern Alberta between 1982 and 1990 and found that while 69% where structurally stable, 33% were of low or zero effectiveness in achieving habitat enhancement goals. Frissell and Nawa (1992) examined 161 aquatic habitat enhancement structures on 15 streams in western Oregon and Washington and found over 18% had failed outright, and 60% were damaged or ineffective. Riparian restoration projects were evaluated by Carothers and others (1990) (17 projects in the southwestern United States) and by Jensen and Platts (1990) (nine riparian restoration projects in the Great Basin and Snake River region). Approaches to evaluating generic or wetland restoration projects have been discussed (Erwin 1990, Berger 1991, Westman 1991), but the evaluation of properties unique to stream or river systems deserves further discussion.

The lack of systematic postproject evaluation may be due to inherent difficulties in measuring stream restoration success. This may be confounded by regional ecological variation. Restoration of a lowland river of Denmark, for example, may require different evaluation criteria than a high-energy river of Colorado. Often, postproject evaluation criteria and techniques are not considered until after the project is designed and implemented. Confounding these difficulties is the preference of sponsoring agencies to fund tangible construction projects rather than intangible monitoring and evaluation studies. Some fund-

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ing sources are for implementation of projects only; detailed monitoring and evaluation would be considered research or experimentation and would not be considered for funding (e.g., California Department of Fish and Game 1993). Consequently, the environmental manager who seeks to measure the success of a stream restoration is commonly faced with insufficient baseline data, inadequate funds for monitoring, and no guidance on how to proceed with an evaluation. Where postproject evaluation has been attempted, most success criteria applied have been biological, with little reference to channel geomorphology.

Our approach to evaluating stream restoration projects emphasizes measurement of the geomorphic characteristics of the restored reach. This emphasis is based on the understanding that interactions between the stream channel, floodplain, and stream flows provide the framework supporting aquatic and riparian structures and functions. This perspective concurs with recent studies in riparian ecology that argue for geomorphic factors as primary determinants of the spatial and successional patterns of biological communities (Gregory and others 1991, Statzner and others 1988). Likewise, recent studies in water quality monitoring have suggested that measurement of geomorphic channel characteristics may prove a cost-effective indicator of overall watershed condition (MacDonald and others 1991). Further, the National Research Council recently recommended that "the principles and analytical tools of hydrology and fluvial geomorphology need to be applied to a much greater extent than in the past to the planning and execution of [river and stream restoration] projects" (National Research Council 1992, pp. 172–173).

The purpose of this paper is to consider the problem of evaluating stream restoration projects and to provide: (1) general recommendations on how to incorporate evaluation considerations into project planning, and (2) specific recommendations regarding the application of evaluation techniques designed to capture changes in riverine processes. This approach emphasizes geomorphic measures as a framework into which evaluation for other factors can be integrated. The result is a first-cut at a procedure that will require adjustment to fit individual projects.

Postproject Evaluation: Planning

Defining Restoration Objectives

Restoration has been defined as "the return of an ecosystem to a close approximation of its condition prior to disturbance. In restoration, ecological damage to the resource is repaired. Both the structure and the functions of the ecosystem are recreated" (National Research Council 1992, p. 18). In practice, complete restoration is often precluded due to existing human settlement or other alterations of the independent variables of runoff and sediment yield. Stream restoration projects often seek to recreate lost channel and floodplain functions such as bank stabilization, pollutant filtering, or fish and wildlife habitat. Proposed measures may range from the removal of trash from urban channels to the replacement of artificially straightened canals with revegetated meandering channels. Restoration sponsors range from real estate developers forced to satisfy a regulatory mitigation requirement to volunteer community action organizations.

The term "restoration" is often applied to projects that mitigate for alterations of natural channels for flood control, even when the existing natural channel may be ecologically sound and in no need of "restoration" (Kondolf 1994). In such cases, restoration actually means "environmentally sensitive flood control," increasing flood conveyance without resort to engineered concrete channels (Williams 1990). Since the construction of these environmentally sensitive alternatives may entail restoring vegetation and wildlife habitat to the reconfigured channel, postproject evaluation concerns are identical to those for true restoration.

Regardless of restoration context and objectives, thorough and clear documentation during the planning process is required to guide project implementation and to provide a detailed inventory of predicted environmental benefits for agency personnel, the public, and postproject evaluators. Sound documentation will also facilitate smooth transitions when personnel change or the overall plan needs to be revised. In addition, project documentation must integrate evaluation considerations into each phase of restoration plan development. Figure 1 is a simplified flow chart of the planning process to be referred to in the following discussion of how to achieve this integration.

Securing Resources

Although restoration projects are generally tailored to meet budget constraints, care must be taken to ensure that adequate funding is available to cover all components as the project plan is developed and refined. Frequently, a budget for postproject evaluation is not included in original cost estimates. Continual reevaluation of the relationship between available resources and plan components throughout the plan-

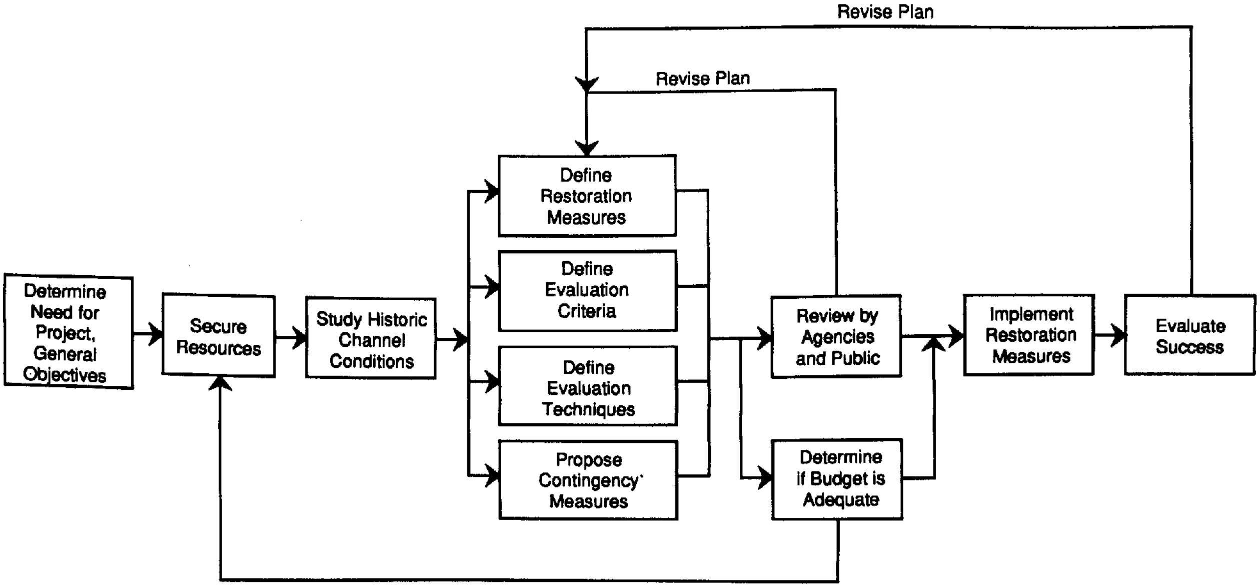

Figure 1. Simplified flow chart of the process of planning, implementing, and evaluating a stream restoration project. See text for discussion of components.

ning process (indicated by a feedback loop in Figure 1) is needed to ensure that all proposed evaluation costs may be covered.

Protecting the evaluation budget is required to avoid diversion of the monies to seemingly more pressing needs after project construction. Legal financial restrictions should be considered for this purpose. For example, in the United Kingdom the National Rivers Authority uses the mechanism of commuted sums to set aside funds for long-term maintenance of its projects (John Gardiner, National Rivers Authority, Thames Region, personal communication 1992), while the US Army Corps of Engineers requires bonds or letters of credit from developers to ensure permit mitigation and monitoring requirements are satisfied (Molly Martindale, US Army Corps of Engineers Regulatory Branch, San Francisco District, personal communication 1992).

Historical Channel Conditions Study

Project design and evaluation must be guided by as much knowledge as possible about past channel conditions. Changes in channel form and independent geomorphic watershed variables can be documented from analysis of historical maps, boundary lines, aerial photography, surveys for bridge and pipeline crossings, gauging records, field evidence, and archival sources (Kondolf and Sale 1985). Sources on vegetative cover and fish and wildlife use may include resource inventories, fishing and hunting records, environmental impact studies, habitat conservation plans, and written accounts.

Documenting the history of the channel and its watershed is essential to provide a temporal context in which to interpret evaluation results. Planners cannot assume that a river system is stable simply because no channel changes or fluctuations in river-dependent populations occurred during the design period. Likewise, long-term, ongoing changes from other causes must not be confused with effects of the project. For example, river channels below many reservoirs undergo a change in width in response to a reduction in peak flows and sediment supply (Williams and Wolman 1984). For a restoration project completed downstream of a reservoir, effects of the project must be distinguished from those of the reservoir.

The historical analysis should cover a large enough area to capture all events potentially influencing the project reach. The entire watershed upstream should be examined to identify events affecting the flow regime and sediment load, such as deforestation or dam construction. For channels in erodible alluvium, the study should include the channel downstream to the first stable grade control to capture events whose effects may propagate upstream, such as channelization or base-level lowering.

The historical analysis may generate design alternatives. For example, when highway improvements necessitated realignment of the River Neath near Glynneath, Wales, the original proposal called for me-

Table 1. Relating general objectives to specific evaluation criteria

General objectives	Potential evaluation tools and criteria
Channel capacity and stability	Channel cross sections; flood stage surveys; width-to-depth ratio; rates of bank or bed erosion; longitudinal profile; aerial photography interpretation
Improve aquatic habitat	Water depths; water velocities; percent overhang, cover, shading; pool/riffle composition; stream temperatures; bed material composition; population assessments for fish, invertebrates, macrophytes
Improve riparian habitat	Percent vegetative cover; species densities; size distribution; age class distribution; plantings survival; reproductive vigor; bird and wildlife use; aerial photography
Improve water quality	Temperature; pH level; dissolved oxygen; conductivity; nitrogen; phosphorus; herbicides/pesticides; turbidity/opacity; suspended/floating matter; trash loading; odor
Recreation and community involvement	Visual resource improvement based on landscape control point surveys; recreational use surveys; community participation in management

ander cutoff and construction of a trapezoidal channel. However, parish boundaries, which were drawn centuries ago down the former river course, suggested an alternative route for the diversion. This route avoided shortening the river, created more diversity in plan form, and incorporated more variation in bed elevation (Halcrow 1989).

Project Design: Defining Evaluation Criteria

During the design process, the relationships between project objectives, restoration measures, evaluation success criteria, contingency measures, and evaluation techniques should be fully explored and defined. Thus, Figure 1 displays these elements of project design proceeding in parallel.

Clearly defining project objectives is central to postproject evaluation because it enables managers to translate restoration objectives into measurable evaluation criteria. These criteria are a means of keying specific objectives into measuring techniques. For example, the objective to improve fish habitat should be translated into specific changes in pool depths or bed material composition; the objective to increase riparian vegetation should be translated into specific percentages of cover or species densities. Evaluation criteria may also be stated in indices of ecological diversity, such as the biotic condition index of Winget (1985). More examples of relationships between project objectives and potential evaluation criteria are provided in Table 1.

Evaluation success criteria should be developed based on historical information and data gathered from the project site and applicable reference sites using proposed evaluation techniques. In some cases, one criterion may serve as an indicator for multiple objectives.

Although evaluation criteria constitute restoration targets, the experimental nature of the practice and the dynamics of aquatic systems may require defining a range of acceptable variation or developing a process for reviewing criteria suitability once the project is underway. In these cases, it will be necessary to try to distinguish clearly between an unexpected variation on success versus failure. In addition, the project design should define contingency measures (or a process to develop them) for implementation if the project fails to meet objectives.

The need for evaluation criteria to address project objectives directly is illustrated by the difficulties encountered recently when Kondolf's graduate seminar in stream restoration attempted to evaluate a stream restoration project completed in 1990 in the northern Sierra Nevada. Although extensive preproject documentation had been prepared for this project, success in meeting some key project goals could not be evaluated because the preproject data collected were not appropriate. The goal of increasing average pool depth by 50% could not be evaluated because preproject data consisted of depths measured at regular intervals along the channel, without regard for habitat type and without reference to permanent benchmarks. Another project goal was to achieve a pool–riffle ratio of 40:60. The 1992 postproject survey measured 55% pool, 39% riffle, and 6% glide (an intermediate category), but the project proposal had not addressed whether exceeding the target pool percentage was to be considered failure or success. Moreover, the preproject pool–riffle ratio had not been measured, so the effect of the project on pool–riffle ratio could not be determined (term project files for Landscape Architecture 254, University of California, Berkeley, Fall 1992).

Evaluation Technique Selection

Evaluation techniques should generate the most meaningful information possible at least cost and should be coordinated whenever feasible. For example, the same transects may be used for evaluating a number of characteristics, such as geomorphology, vegetation, and wildlife use. Statistical considerations will need to be addressed once a sampling framework has been proposed (Platts and others 1987).

Collection of baseline data at the project reach or reference sites can serve as a pilot study, ensuring that proposed evaluation procedures can be accomplished within budget and staff constraints and that the procedures will provide meaningful information regarding ecological structures and functions. These pilot studies can also serve to train personnel responsible for implementing postproject evaluation.

Reproducible techniques must be used for collection of preproject (baseline) and postproject data. Methods should be specified in sufficient detail (and transects permanently monumented) so that an outside person could confidently replicate the procedure. Reproducibility preserves the integrity of the data collection in the face of staff turnover and permits comparison with data collected from other projects.

The need to apply reproducible techniques to the collection of evaluation data is illustrated by a recent fish habitat enhancement project in north coastal California reviewed by Kondolf's graduate seminar in stream restoration. Aquatic habitat types (as defined by Bisson and others 1981) were inventoried before and after project construction, in 1987 and 1988, respectively. However, the boundaries between these distinct units were not referenced to permanent features, and the total length of the project reach derived from summing lengths of individual units was inconsistent, so the inventory could not be replicated. Cross sections could not be accurately replicated because they were not permanently monumented, and the preproject surveys included only three survey points on the channel bed, providing insufficient detail to show subtle changes (term project files, Landscape Architecture 254, University of California, Berkeley, Fall 1992).

Postproject Evaluation: Techniques

Fluvial Geomorphology

Channel capacity and floodplain inundation. Channel capacity adequate to contain the design flood is a principal goal of flood control-related restoration projects, but to restore dynamic flood disturbance-driven riparian succession on the floodplain, frequent overbank flooding is a goal. The two goals may conflict, with true ecological restoration of a floodplain precluded by the threat to human settlements if the natural floodplain hydrology (i.e., overbank flooding) were restored.

Because overbank flooding is an essential process in maintenance of floodplain ecology (Statzner and others 1988), unregulated rivers with frequent overbank flooding have been selected by conservation organizations as promising sites for restoration of floodplain forests (Tom Griggs, The Nature Conservancy, personal communication 1992). Channels deeply incised into their floodplains may have such increased channel capacity that overbank flooding is virtually precluded, typical of channels incised because of sand and gravel extraction (Sandecki 1989).

Whether the project goal is to encourage or prevent overbank flooding, the capacity of the restored channel is an important design variable. Channel capacity is typically calculated from standard engineering formulae or using computer models based on these formulae. In North America, the Manning equation (Chow 1959) is the most widely used:

$$Q = \frac{bAR^{0.67}\,S^{0.50}}{n}$$

where Q is discharge (flow, in cubic feet or meters per second), b is a coefficient (1.49 in imperial units, 1.0 in SI units), A is channel cross sectional area (square feet or meters), R is the hydraulic radius (approximated by mean depth in wide channels (feet or meters), s is water surface slope (dimensionless), and n is the coefficient of roughness (Chow 1959). This equation is at the heart of HEC-2, the step-backwater flow model most widely used in the United States (US ACE 1990a). The Manning equation, and models based upon it, are extremely sensitive to the coefficients of roughness, n, which cannot be measured directly. The n value can be back-calculated from measurements of discharge, water surface slope, and channel cross-sectional area. However, for floods not directly measured, and for channels not yet built, n must be estimated, an exercise that is more art than science and prone to wide variation among practitioners (Chow 1959). The uncertainties associated with estimating n (and to a lesser extent, other variables) lead to potentially large errors in calculation of flood stage for a given discharge, or conversely, to calculation of the channel dimensions needed to accommodate that discharge.

The ability of a restored channel to accommodate the design flood can usually be known only after it is tested in the design flood. For flood-control projects, the design flood is typically the 50- or 100-year flood, so the chance of obtaining a proper test of project performance within the first several years is low. However, much can be learned from observation of stage heights in floods less than the design discharge. High-water marks (such as accumulations of trash, or lines below which the bank has been washed clear of terrestrial debris) should be surveyed so that actual flood elevations can be compared with those predicted by the hydraulic model for that discharge. From the observed channel cross-sectional area and water surface slope, the n value can be back-calculated and compared with the estimates used in the model. (Note that n can change with flow, so the value measured at one flow may not apply to another.) Furthermore, if a flood control channel is grossly underdesigned, this may become obvious when its capacity is exceeded at a discharge much lower than the design flood.

An adaptive management approach has been implemented on a US ACE flood control project on Wildcat Creek near Richmond, California, where vegetation is permitted to grow within the flood control levees until it reaches a density at which the estimated n value exceeds 0.07, at which time the vegetation is cleared to reduce the n value to an acceptable level (US ACE 1990b).

Channel stability. Channel stability is a principal goal of some stream restoration projects (e.g., to stabilize eroding banks), a secondary goal of others (e.g., to ensure that habitat enhancement structures survive floods). In either case, a design flood for the project must be specified. It is usually impractical to design for all conceivable floods (such as the 500-year flood), so some flood (such as the 10-year, 20-year, or 100-year flood) must be selected.

Evaluation criteria for channel stability must be selected in light of project goals and geomorphic setting. Maximum bank erosion rates might be suitable in some cases. However, on meandering channels some lateral migration is natural: the channel location may shift, while the dimensions remain roughly constant. In such cases, the channel may be permitted to migrate, but evaluation criteria may be set to ensure that channel dimensions remain within an acceptable range.

Although the stability of a restored channel can be conclusively evaluated only after the design flood, the channel should be surveyed after smaller flows as well. Channel instability (e.g., unanticipated bank erosion) at lower flows indicates potential trouble at the design flood, although stability at those lower flows does not necessarily indicate the channel will perform successfully at the design flood. Besides bank erosion and bed degradation, more subtle types of project failure may be evident at lower flows, such as filling of pools or riffle gravels with fine sediment.

Riparian vegetation employed for bank stabilization may not perform its desired function until after several years of growth to establish its root network. Seedlings 1–2 years old are highly vulnerable to scour by floods. Vegetation becomes more resistant to erosion as the root network establishes, so that the chances of successful establishment increase with each year that the young plants are not scoured. Put another way, a flood that might cause a bank stabilization project to fail by scour of vegetation in the first year would leave the project unscathed in the sixth year.

Cross-section surveys. Repeated cross-section surveys are a well-tested tool to detect changes in channel form. Definition of the evaluation reach and selection of cross-section sites are influenced by project characteristics, but as a rule a study reach 20–50 channel widths (width at bankfull flow) should serve well. A sufficient network may consist of 10–15 cross sections located two to five channel widths apart. Preferably, cross sections would be sited in response to pool–riffle or meander bend spacing with replicates for similar morphological units. For example, on a meandering channel, cross sections could be located at the apex and crossover points of each meander bend (Figure 2). On meandering channels, it is frequently possible to use one benchmark as an end point for more than one cross section (Figure 2).

Individual cross sections should be surveyed relative to permanently monumented end points or base lines. Ideally, the preproject cross section end points should be located so they will not be disrupted by project construction. Effective cross-section monuments include short (1 m or less) lengths of rebar or metal fence posts pounded into the ground to nearly flush with the surface, brass plates set in concrete, nails hammered vertically into exposed horizontal tree roots, or marks chiseled into boulders, bedrock, or concrete. Since it is often difficult to relocate end-point pins or benchmarks after a year or more, the survey monuments should be photographed in relation to distinctive features (e.g., trees, buildings) and located on a simple sketch map showing the position of the monument relative to nearby features and annotated with distances along compass bearings from the features (Figure 2).

Cross sections can be surveyed with an automatic

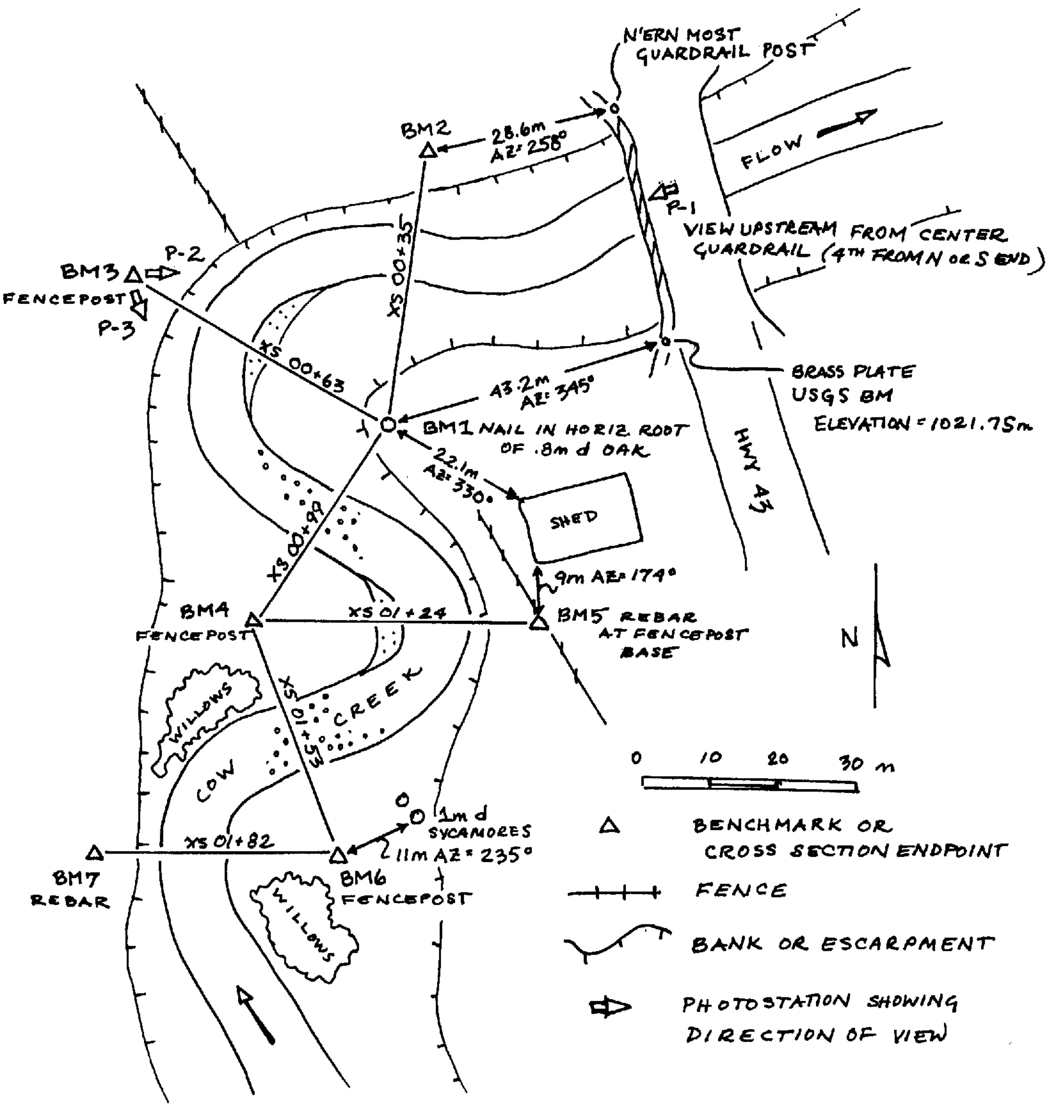

Figure 2. Sketch map of hypothetical stream reach showing placement of channel cross sections and permanent end points, recording location of benchmarks in distances and compass bearings from nearby landmarks, and location of photostations.

level or total station laser theodolite. In channels with irregular beds, replicate surveys using different measurement points may show apparent changes. To avoid this, the same set of points should be surveyed each time a cross section is measured to accurately detect changes over time. This is most easily achieved by stretching a tape across the channel and surveying at regularly spaced intervals (e.g., every 1 m) as well as surveying slope breaks (points where the channel bed changes slope such as the bank tops). If the channel undergoes large channel changes between surveys, apparent changes resulting only from different survey points can generally be ignored.

Survey data may provide the basis for construction of a topographic map of the project reach. The total station theodolite is particularly well suited for this task, producing a data set of points in three-dimensional coordinates. However, repeat surveys may not be suitable for documenting subtle changes over time because interpolation of contour lines may involve some judgement or subjectivity. This subjectivity can be reduced by ensuring that the same points are resurveyed and by using a computer program to draw contour lines.

Channel surveys should include an assessment of bed material size. Rough visual characteristics (e.g., "gravel" or "sand") can be recorded at each point on the surveyed cross section, or a more reproducible measure can be obtained using the pebble count approach (Wolman 1954, Kondolf and Li 1992).

Frequency of postproject cross-section surveys. The scheduling of evaluation site visits is commonly based on proposed restoration measures, project scale, and regulatory context. Flood events should also be used to guide the timing of project evaluation. Postproject conditions should be monitored after each flood above a threshold selected on the basis of the overall project design. This threshold should be less than the maximum design flood so that potential shortcomings in project performance can be recognized early.

Years may elapse after implementing restoration measures before a major flood tests channel capacity and stability and before aquatic and riparian structures and functions become established. Consequently, the postproject evaluation must extend over a period of years. On average, a decade is long enough to capture multiple occurrences of floods with a two-year return interval, as well as less frequent events (five- to ten-year return intervals) that are more influential in semiarid environments. A longer monitoring period would be scientifically desirable, but a decade should be considered the minimum time required to judge project performance and should be a feasible study period.

Surveys of channel geomorphology should be conducted more frequently immediately after project construction to capture the period of most rapid change. For example, in the absence of major floods, over a ten-year period the surveys might be conducted in the first, second, fourth, sixth, and tenth year after project completion. If a ten-year flood occurred in the seventh year, the channel should be surveyed immediately after that flood as well.

Streamflow data and flood frequency. Streamflow records are commonly available from public resource agencies (and occasionally from private utilities) for larger rivers and some streams. In the United States, the US Geological Survey (USGS) publishes annual "Water Resources Data" volumes for each state that summarize annual peak flows and mean daily flows recorded at USGS stream-gauging stations. For ungauged streams, streamflow estimates can be generated using regional runoff relations (e.g., Rantz 1971) and other similar approaches (Dunne and Leopold 1978). In addition, direct measurements of streamflow for as long a period as possible prior to restoration will provide valuable baseline information. We recommend installation of a staff gauge at a site upstream of a hydraulic control and periodic current meter measurements to develop a relation between river stage and streamflow (Rantz and others 1982).

An indirect discharge measurement should be used to estimate peak discharge for any observed preproject flood events. The indirect measurement is based on using the channel cross section and water surface slope at flood flow from surveyed high-water marks and a roughness estimate [using guidance from sources such as Chow (1959), Barnes (1967), and Hicks and Mason (1991)] to compute peak flow using the Manning equation (Rantz and others 1982). The return period of the observed flood can be estimated from return periods for the same event in nearby gauged drainages or, for rainfall-generated floods, from the return period of the rainfall event.

The frequency of channel and floodplain inundation is a function of the flood regime and the local stage–discharge relation (the relation between elevation of the water surface and streamflow). Elevation of floods of various recurrence intervals can be plotted on the channel cross section to indicate the extent and frequency of inundation of surfaces adjacent to the channel, thereby characterizing the hydrologic framework within which restoration measures can be designed. The stage–discharge relation and extent of inundation should be verified from high-water marks in postproject evaluation.

Depth to water table and groundwater interactions. Depth to water table is an important variable controlling the distribution of riparian plants, especially in semiarid environments with limited rainfall during the growing season. Depth to water table can be monitored with shallow wells installed along monitoring transects so that water table depth can be related to vegetation species composition, density, and vigor. Shallow wells can be installed in sandy alluvium using a hand auger. Alluvial deposits with cobbles and boulders may require drill rigs or power augers (MacDonald 1988).

Water table elevations can be monitored manually by use of simple electric well probes (available for under US$200). For most purposes, this approach is entirely adequate. During periods of slowly changing water table elevations, weekly, biweekly, or monthly observations may suffice, while hourly observations may be needed to track changes during floods or rainstorms. Monitoring water table response to rapid stage changes or diurnal evapotranspirative demand cycles requires continuous recording of water levels using analog strip-chart recorders or electronic data loggers. While the latter are more expensive at present, future reductions in price are likely for this rapidly evolving technology.

The unsaturated zone above the water table holds water in soil pores under tension. Pore water in this zone can be of enormous importance to plant vigor but its behavior is complex, and it is more difficult to measure than the water table (Freeze and Cherry 1979).

Stream–groundwater interactions have a significant impact on riparian vegetation, especially in semiarid environments where water table depth is a primary control on vegetation distribution. Where positive seepage exists, the stream gains water from groundwater and a wider riparian zone is frequently supported, while in reaches with negative seepage, the stream loses water to the groundwater and riparian vegetation is typically limited to the margins of the channel (Kondolf and others 1987). Lee and Cherry (1978) describe several simple techniques for field measurement of positive and negative seepage. Baseline and postproject data on seepage may be required to design and evaluate restorations (Kondolf and others 1990).

Integration of geomorphic cross sections into ecological monitoring. The cross-section network established to capture geomorphic changes can serve as a frame of reference for monitoring other evaluation factors. If monitoring of riparian and aquatic habitats can be accommodated along geomorphic transects, ecological factors can be better related to underlying geomorphic controls. However, monitoring riparian and aquatic habitat may require transects in addition to those established for geomorphic monitoring. For example, monitoring riparian vegetation may require transects parallel as well as perpendicular to the stream channel to obtain an adequate sample to characterize different plant communities (Joe McBride, University of California, Berkeley, personal communication 1992).

Water Quality

Stream restoration projects are being implemented more frequently as a component of a nonpoint source pollution control strategy (Karr and Dudley 1981). Potential water quality benefits of stream restoration include reducing bank erosion and filtering upland runoff. However, because of the myriad of nonpoint sources and the variability inherent to aquatic systems, it may be difficult to detect specific improvements in water quality from a single project of limited size.

Water quality benefits may be most effectively realized when stream restoration is incorporated into an overall watershed management approach, as reported for Rock Creek, Idaho, by the US Environmental Protection Agency (US EPA 1992). Improvements in water quality in Strawberry Creek, on the campus of the University of California at Berkeley, have been documented following a restoration program that identified and eliminated point sources of pollution, stabilized eroding banks, and increased public awareness of storm drains as a source of pollutants to the stream (Charbonneau and Resh 1992). The success of watershed-wide efforts can be monitored using long-term measurements of physical and chemical constituents such as: temperature; pH; concentrations of dissolved oxygen, nitrogen, phosphorus, herbicides, and insecticides; suspended and floating matter; odor; and opacity (MacDonald and others 1991, National Research Council 1992). The communities of macroinvertebrates present in a channel can provide a time-averaged indication of water quality conditions (Rosenberg and Resh 1993).

Water quality sampling stations should be located in relation to cross sections established for geomorphic and ecological monitoring. Specific approaches to conducting sampling and discussion of the use of channel cross sections as a cost-effective index to overall water quality are discussed by MacDonald and others (1991).

Biological Habitat

The principal focus of criteria applied to evaluate stream restorations to date have been biological, with an emphasis on measuring vegetation and fish and wildlife use. A proper treatment of the issues surrounding biological project success is beyond the scope of this paper. However, for purposes of establishing connections between geomorphic and biologic evaluation techniques, we suggest that two general approaches to the measurement of habitat enhancement can be distinguished. The first defines success as creation of physical habitat features, such as pools and riffles or riparian nesting areas. The second defines success as increases in populations of organisms in the project reach as a result of restoration.

For most restoration projects, the goal of restoring physical habitat may be more feasible than increasing biological populations. For example, fish populations are determined by numerous biological and abiotic factors besides physical habitat, such as disease, fishing pressure, and interspecific competition (Allen 1969, Platts and Nelson 1988). An increase or decrease in fish populations in a channel following a restoration project therefore may be completely unrelated to geomorphic changes effected by restoration. This is especially true of anadromous populations, which may be controlled in part by fishing pressure, impediments to passage, the availability of downstream rearing habitat, or conditions in the marine environment (Lawson 1993). The geomorphology-based evaluation techniques discussed above will be more applicable to evaluating changes in physical habitat than use of those habitats by organisms. However, as discussed below, opportunities to relate vegetation establishment and use by fish and wildlife to physical form should be taken wherever possible to improve our understanding of the links between physical habitat and ecological systems.

Aquatic habitat. Documenting changes in physical habitat requires information on how water depths, velocities, and temperature, as well as bed material size (substrate) and cover, have changed in the project reach following project construction. A clear nexus links the majority of these measurements to geomorphic factors.

The most simple approach is to directly compare field measurements of habitat before and after project construction. Water depth and bed material can be drawn from the standard geomorphic cross-section measurements. However, other habitat components (e.g., water velocity, temperature, cover) should be measured at the existing cross sections, and additional cross sections may be required to adequately characterize the range of habitat types such as pools, riffles, and runs. The total channel length falling into different habitat types can be compared (Bisson and others 1981), but unless the inventory is referenced to frequent benchmarks or other permanent features, habitat inventories may be impossible to replicate. Habitat types can change with flow (e.g., a riffle at low flow may become a run at higher stage), and different operators may be inconsistent in distinguishing between similar habitat types.

Variations in flow need to be taken into account when comparing measurements made on different dates. Cover and bed material size can be compared directly even if measured at different flows. However, to compare changes in water velocities, measurements must be made at the same flow or changes in habitat with flow must be modeled (e.g., Bovee 1982, Loar and Sale, 1981). Water depths can be compared from measurements at different flows if the relation between stage (elevation of the water surface) and discharge for the postproject channel has been established. Standard methods for measurement of velocity, depth, temperature, and cover for purposes of assessing aquatic habitat cover are described by Nielsen and Johnson (1983), Platts and others (1987) and Hunter (1991). Bed material size can be estimated visually, but applying the pebble count technique to habitat assessment provides a reproducible measure consistent with data collection in hydrology (Kondolf and Li 1992).

Aquatic organisms. Communities of concern may include aquatic vegetation, invertebrates, and fish. The greatest emphasis to date has been on enhancing fish habitat in streams, particularly for salmonids. The problem facing postproject evaluation design is how much and what type of biological sampling to include and how well the results may be correlated to physical factors, including geomorphic conditions. Sampling for aquatic vegetation and invertebrates is discussed by MacDonald and others (1991), The Nature Conservancy Council (1990), Holmes (1990), and Platts and others (1987). Sampling benthic macroinvertebrates can characterize community richness, diversity, and abundance and can be used to calculate biotic indices that serve as integrators of water quality (Rosenberg and Resh 1993, Plafkin and others 1989). Fish population estimates are discussed by Nielson and Johnson (1983).

Fish populations may be subject to natural fluctuations, and an increase in a fish population may lag behind improvement in habitat by years as the aquatic invertebrates and terrestrial food sources develop in response to improvements in bank and channel structure. Hunt (1976) monitored populations of brook trout (*Salvenis fontinalis*) in response to an enhancement project in Lawrence Creek, Wisconsin, by collecting three years of baseline data and seven years of postproject data. He found that the fish populations did not reach the stream's postproject carrying capacity until the fifth year after the project was implemented.

Because fish populations fluctuate widely in response to a broad range of human and natural factors, a limiting factor analysis is needed to shed light on the relative importance of all factors in limiting salmonid populations (Everest and others 1987). For example, it was discovered that large investments in habitat enhancement structures in the San Lorenzo River watershed could not pay off until another limiting factor (or bottleneck in fish production), the mortality of out-migrating smolts due to artificially opening the coastal mouth, was addressed (Philip Williams and Associates 1991).

Riparian vegetation. Changes in riparian vegetation can be measured with repeated plant surveys, the extent of which depends on the scale of the project and proposed restoration measures. For smaller projects where active revegetation is proposed, each planting may need to be monitored to determine survival rates. In cases where restoration may affect large areas of existing vegetation, a system of plots, transects, or quadrats may be applied to each strata to generate samples representative of the total plant populations.

Extending channel cross sections up the bank and onto the floodplain can provide a basis for vegetation transects, provided that care is taken not to disturb vegetation during the survey or when gaining access to the bank. Alternatively, vegetation transects could be defined as offset from geomorphic transects by a standard distance (e.g., 2 m) upstream or downstream of the cross-section lines. Transects aligned with stream cross-section transects will best display transitions in vegetation types due to differences in elevations and resultant depth to water table and inundation frequencies. Additional transects running parallel to the stream channel can provide more information about each vegetation type.

Species presence, abundance, diversity, density, size, and vigor are important variables in determining the success of riparian vegetative restoration. Standard methods for quantitative sampling and measurement are reviewed by Platts and others (1987), Mueller-Dumbois and Ellenburg (1974), Bonham (1989), and Erwin (1990). Standard measurement procedures for riparian vegetation often include recording data on slope, elevation, soil, and hydrology and, thus, should be coordinated with geomorphic surveys and any water table observations. In addition, competition from nonnative species should be evaluated.

As noted above with respect to channel stability, successful establishment of vegetation depends in part on the climatic and flow characteristics of the years immediately following the restoration project. A large flood could wipe out recent plantings, while extreme drought could inhibit growth by virtue of water stress.

Wildlife and bird populations. Changes in populations of wildlife can be documented by repeated, systematic observation of sign, trapping, analysis of hunting records, and direct observation, as done for otter populations in Britain by Chanin and Jeffries (1978) and Green and Green (1987). For birds, direct observation and recognition of calls can be used (Morrison and others 1992).

Data collection programs must be designed based on seasonal distribution patterns and knowledge of habitat requirements for different life stages. The project reach must also be viewed in the broader context as part of a longer, linear habitat. This wildlife corridor serves not only as local habitat, but also as a route along which wildlife can migrate. Gaps in the corridor may leave large reaches of otherwise suitable habitat unpopulated. Thus, a restoration project may succeed in the creation of physical habitat, but repeated surveys may show no utilization because the site is not connected with other habitats.

Community Involvement and Recreational Use

Community support for public stream restoration projects has recently been recognized as an important determinant of long-term project success (Connin 1991, Neudorf 1989). In urban settings, neighborhood watches may be the best approach to control vandalism, litter, and crime (Walter Hood, Department of Landscape Architecture, U.C. Berkeley, personal communication 1992). In rural areas, community involvement may prevent damage caused by unauthorized off-road vehicles, litter, arson, and destruction of vegetation.

Standard social science techniques can be adapted to assess the success of community involvement efforts and any recreational use objectives. Procedures for "postoccupancy evaluations" of open space designs (Cooper-Marcus and Francis 1990) can be applied to stream restoration projects. Recreational use of restored banks and floodplain areas, including planned trail systems, can be documented by observations of use and by interviewing or surveying users. Individuals active during the public outreach components of the planning process could also be periodically interviewed during the postproject period to document attitudes towards the project.

Recreational uses are important benefits of many projects, but the potential conflict between recreational use and wildlife habitat and the potential for bank destabilization by concentrated human use (Madej and others 1992) must be recognized and planned for.

Photo Documentation and Visual Resource Assessment

Aerial photography provides an excellent complement to ground surveys of channel characteristics and vegetation. The appropriate scale depends upon the size of the river system, but a 1:2000 scale has proven useful in many applications on US Forest Service lands (Platts and others 1987). Aerial photography is generally more useful on larger rivers than small streams because on smaller systems the channel can be completely obscured from the air by trees, shrubs, or human structures. The scale of aerial photography required to provide adequate detail will depend on the size of the channel.

Techniques developed and applied extensively within the US Forest Service may be used to evaluate the impact of restoration on visual resources (Litton

1973, 1984). Visual elements of concern may include landforms, vegetation patterns, water presence and expression, and human uses and impacts. Preproject visual inventories may be developed based on topographic maps, high-altitude imagery, air and ground photography, and field work. The application of a system of landscape control points may be used to plot changes in the visible landscape from sensitive viewpoints, such as roads or trails adjacent to the project reach, or the stream channel itself (Litton 1973). To the extent that the restoration increases diversity of stream structure, the "uniqueness ratio" proposed by Leopold (1969) may be another useful measure of the project's visual impact.

Repeat ground photography can be used informally or with sufficient care that precise measurements of change can be made from the photographs (Malde 1973). Permanent photo stations should be established with views that will not be obscured by future vegetation growth (e.g., bridges).

Conclusion

As restoration of rivers and streams attracts increasing commitments of human and financial resources, a systematic approach to restoration evaluation is required to avoid repeating past mistakes. Evaluation of past project success has been largely lacking, probably because of logistical challenges, costs of conducting the studies, and a tendency for agencies to avoid publicizing failures. The development and implementation of standard guidelines for evaluation, in conjunction with publication of evaluation results, will enable restoration designers to learn from others' experience.

Recognizing channel geomorphology as the framework upon which ecological systems are developed, we recommend that postproject evaluation studies be designed with geomorphic cross sections as their foundation. Key to effective evaluation is the application of standardized, objective measures that can be reproduced despite changes in project personnel. Subjective judgements should be avoided to the greatest extent possible.

Postproject evaluation must be incorporated into project planning to ensure completion of appropriate baseline studies, careful selection of evaluation criteria based on clearly stated project objectives, consideration of historical channel conditions, and allocation of funds for at least a ten-year evaluation program.

Taken as a whole, administering a long-term postproject evaluation program, assuming that results are used to modify restoration measures if needed, is essentially equivalent to implementing a management plan for the restored reach. Walking away from a project after construction may lead to forfeiting the investment if the project is permitted to fail. Moreover, failure to evaluate success prevents the next generation of projects from benefiting from the effort. Thus, recognition of the need for long-term management of restored systems may constitute the next step in the development of restoration as a tool of land and water stewardship.

Given the wide range of stream restoration project goals and site conditions, it is probably not possible to devise a detailed universally applicable procedure for postproject evaluation. However, consideration of how to apply standard measurement techniques to capture changes in basic stream processes early in the restoration planning process may provide the best foundation for effective postproject evaluation.

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