Some Suggested Guidelines for Geomorphic Aspects of Anadromous Salmonid Habitat Restoration Proposals

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Abstract

Proposals to improve fish habitat for anadromous salmonids by modifying channel form or substrate must be justified based on geomorphology as well as biology, because geomorphic factors often cause such projects to fail. Proposals should address the geomorphic setting at the watershed scale, by specifying changes in flow regime or sediment yield through tools such as a sediment budget. Proposals should also address geomorphic setting and process at the reach scale, indicating the basis for design channel form and dimensions, calculating the frequency of bed mobilization, and assessing existing gravel quality for spawning habitat enhancement projects. Proposals should include explicit provisions for post-project performance evaluation, including adequate baseline data to permit project-induced changes to be quantified. Restoration projects also require clear objectives and adequate funding for long-term monitoring, and generally would benefit from an adaptive management approach to implementation and evaluation.

Key words: stream restoration, salmonid habitat, Sacramento River, San Joaquin River.

Introduction

Aquatic and riparian habitat for salmon and other organisms is, in effect, a by-product of the channel geomorphology, which, in alluvial reaches, largely reflects the prevailing flow and sediment regimes, as well as effects of riparian vegetation and human modifications. Thus, it should come as no surprise to learn that many efforts to restore aquatic and riparian habitat have failed because their designs did not account for geomorphic influences (National Research Council 1992), including watershed scale influences such as increased or decreased sediment loads and runoff (Iversen et al. 1993; Kondolf & Downs 1996). Similarly, an adequate understanding of geomorphic processes at the reach scale is needed to design a site-specific restoration project (as opposed to generic approaches based on presumed attributes of the channel). The understanding should include changes in channel form, distribution of velocities in the project reach, and sediment transport patterns anticipated from the project. Just as geomorphic factors must be considered in project planning and design, biologically limiting factors must be understood, both on the reach and watershed scale, to develop specific objectives of restoration actions. Moreover, the size of investments in habitat restoration argues for careful evaluation of the actual effectiveness of the projects in achieving their objectives.

Failed projects that involved large amounts of in-stream construction have many bad consequences: waste of restoration funds, diversion of funds from projects that would be ecologically beneficial, and giving the public and decision-makers the wrong impression that restoration projects are inherently failure-prone and a poor public investment. The purpose of this paper is to help restoration designers propose, and decision-makers select, restoration projects likely to have a high success rate and make good use of resources. I use the term "restoration" for projects intended to restore a river's biological functions, whether or not they are intended to return the river to its pre-development state.

Salmonid Habitat Restoration in the Sacramento-San Joaquin River

In the Sacramento-San Joaquin River system of California, anadromous salmonids formerly occurred throughout the system. Spring, fall, and winter runs of *Oncorhynchus tshawytscha* (chinook salmon) were abundant, supporting large cannery industries, and runs of *Oncorhynchus kisutch* (coho salmon) and *Oncorhynchus mykiss* (steelhead trout) occurred in various parts of the river system (Fig. 1). However, the abundance and distribution of these fish underwent a severe decline as a result of hydraulic mining, dam construction, water diversions, altered flow regimes, deforestation, artificial bank protection, channelization, levee construction, increased predation, pollution, and over-fishing. Spring-run chinook salmon were extirpated from the San Joaquin system by the 1940s and their present distribution is con-

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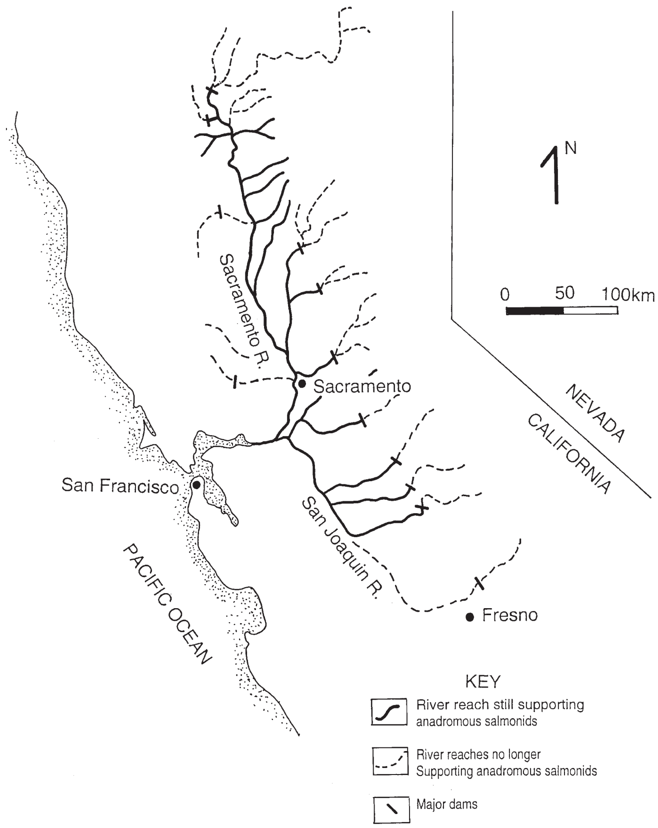

Figure 1. Map of the Sacramento-San Joaquin River system, showing reaches that still support anadromous salmonids (solid lines), and reaches in which anadromous salmonids no longer occur (dashed lines) as a result of migration barriers, dewatering, or other factors. (Adapted from California Department of Water Resources 1982).

fined to three principal tributaries of the Sacramento River. Winter-run chinook salmon are threatened with extinction, as are coho salmon and steelhead trout.

In response to the dramatic declines in threatened or endangered fish populations, a number of large state and federal efforts are now underway to restore salmonid habitat in the Sacramento-San Joaquin River system. With over $100 million available annually for habitat restoration, funding agencies such as the U. S. Fish and Wildlife Service, the California Department of Fish and Game, and the CALFED Bay-Delta Program are now receiving numerous proposals to fund specific habitat restoration and rehabilitation projects. Most of these projects involve physical changes to the channel and, thus, their success will depend largely on geomorphic processes. Experience with habitat restoration projects funded from 1990 to 1994 under the "Four-Pumps Agreement" has demonstrated that, despite good intentions, some of the projects have been ineffective or detrimental because project planning did not adequately consider geomorphic setting on the reach or watershed scale (Kondolf et al. 1996*a*, 1996*b*).

Purpose and Scope

The purpose of this paper is to suggest some guidelines for preparation and evaluation of salmonid habitat restoration proposals, based on geomorphic principles and the review of a number of salmon habitat restoration proposals for the Sacramento-San Joaquin River system from 1994 to 1997. Although these guidelines were developed in response to salmon habitat restoration proposals in this region, the basic approach should be applicable elsewhere. The paper emphasizes geomorphic attributes, but many other considerations, geomorphic and otherwise, might be important in preparing or evaluating restoration proposals, especially for other resources and in other regions. Some of the components recommended here can be drawn from existing geomorphic studies, but to develop an adequate database for reach-level project design will typically require original field surveys.

The Biological Context: Limiting Factors

To understand how the proposed project will improve overall survival and natural reproduction of salmonids, the proposal should summarize existing information on the target species and run, the role of different reaches in life history of target fish, and the factors likely to be limiting the population. Because of the complex nature of anadromous fish production, its linkage with watershed processes, and the importance of marine influences, biologists often have little information about limiting factors. Nonetheless, the analysis may identify life stages that are not limiting populations, and for which enhancement projects would be less beneficial than projects addressing different life stages (Reeves et al. 1989; Beechie et al. 1994).

Geomorphic Considerations

Geomorphology must be considered at both the watershed and reach scales. The issues of particular importance to a project will depend on the local conditions, and for many projects altered flow and sediment transport regimes figure prominently as constraints on channel behavior. Thus, proposals should include basic information on alterations in flow, and sediment supply and transport (Appendix 1). In particular, gravel supply and intragravel flow must be addressed for projects to create spawning habitat. Bank vegetation and large woody debris would be important for habitat restoration in many stream restoration projects.

Geomorphic Setting at the Watershed Scale

A good understanding of the geomorphic setting at the watershed scale is needed to put the project site in a larger context, with respect to watershed-wide changes. Without the larger picture, local conditions might be attributed to local influences, which appear fixable with local treatments, such as biotechnical bank stabilization. Information on the geomorphic setting at the watershed scale can provide insights into trends in channel changes and supply of water, sediment, and in-stream woody material. For example, events such as recent fires, large floods, mass wasting, dam construction, or timber harvest can affect channel form directly or through changes in flow and sediment load. The information needed for restoration planning is similar to that needed for watershed analysis for forest management in the Pacific Northwest as described by Reid et al. (1996).

Watershed Map. The project site should be shown in the context of upstream influences. In some cases, where dams have hydrologically isolated the project reach from some upstream influences, a small-scale map of the entire watershed can be augmented by a larger-scale map of the river downstream of the dams. The watershed map(s) should indicate information on areas with high erosion rates or pollution sources, land-use changes likely to have altered runoff or sediment supply, reaches important for spawning and rearing habitat, gravel pits, levees, stream gauges, towns, roads, etc.

Flow Regime. The flow regime, and any hydrologic changes resulting from land-use change or reservoir construction, should be quantified. Specifically, the high flows, which have the greatest geomorphic effect on channel form, should be described with a histogram of peak annual flows and flood frequency analysis (Dunne & Leopold 1978). For reaches downstream of dams, dam effects on the flood frequency regime can be quantified by comparing: (1) pre- and post-dam conditions, if sufficient pre-dam and post-dam gauging records are available (Fig. 2); (2) gauges upstream and downstream of the reservoir for simultaneous periods of operation; or (3) measured flows below the reservoir with inflows calculated from reservoir storage changes. Where good gauge records are available pre- and post-dam, changes in other ecologically significant attributes of the flow regime can be described using the indices of hydrologic alteration proposed by Richter et al. (1996).

Depending on the biological role of the project reach, presentation of information such as changes in the frequency duration of flood recession flows or baseflows may be appropriate. Potential implications of changes in the flow regime should also be discussed. For example, reduced summer low flows from lowered groundwater levels can affect riparian vegetation, which in turn can affect channel stability.

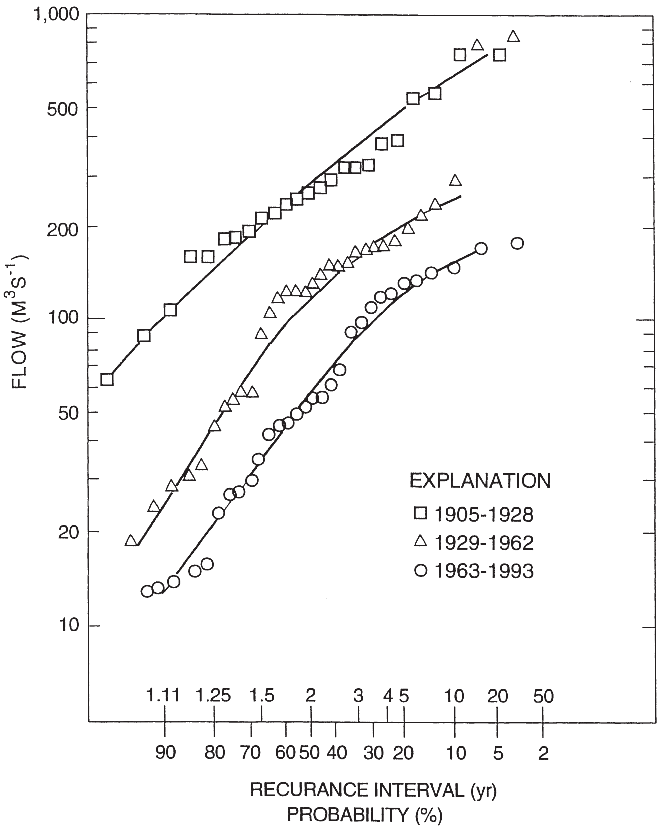

Figure 2. Reductions in flood regime induced by reservoirs, illustrated by flood frequency analysis for the Mokelumne River below the Camanche Dam (U. S. Geological Survey gauge No. 11323500), for three time periods: before the Pardee Dam (1905–1928), after the Pardee Dam but before the Camanche Dam (1929–1962), and after the Camanche Dam (1963–1993). Mean annual runoff is 932×10^6 m^3; Pardee impounds 259×10^6 m^3 (28% of annual runoff); and Camanche 532×10^6 m^3 (54% of annual runoff). (Source of data: U.S. Geological Survey published data, California Department of Water Resources 1984).

Sediment Budgets. Sediment budgets can vary widely in their level of detail and in the components measured and reported with the appropriate scale and scope depending upon the research questions asked. I refer the reader to the excellent treatment of the subject of sediment budgets by Reid and Dunne (1996). Many sediment budgets in the geomorphic literature were developed to better understand the relative importance of different erosional and sediment transport processes operating in the watershed. These budgets have typically included direct measurements or historical assessments of geomorphic processes such as fluvial erosion of hillslopes, mass wasting, bank erosion, and floodplain sedimentation (Swanson et al. 1982; Reid & Dunne 1996). For most habitat restoration projects, we are more interested in the runoff and sediment produced by the geomorphic processes, and their temporal and spatial patterns. The sediment budgets are used to place the project reach in a larger context of sediment supply and transport. In this case, estimation of natural sediment supply from upstream, historical changes in magnitude or caliber of sediment, or changes in sediment transport capacity at the site would be particularly important.

There is a widespread misconception that constructing sediment budgets is lengthy, expensive, and not necessarily useful in making management decisions. As demonstrated by Reid and Dunne (1996), budgets can often be constructed rapidly, yielding information sufficiently precise for most management needs. Sediment budgets rarely balance because of errors in measuring or estimating terms. It is worth bearing in mind that when one term is obtained by subtraction from measured or estimated components, errors in other components are masked, giving an impression that the budget balances (Kondolf & Matthews 1991).

Gravel Supply. For spawning habitat enhancement, the sediment budgets should include estimates of gravel supply from upstream. In many rivers, the supply of gravel from upstream changed dramatically this century with widespread construction of dams (Kondolf 1997). Reservoir sedimentation data (if available) can be used to estimate the pre-dam sediment supply (i.e., the sediment supply to which the pre-dam channel was adjusted and which is no longer supplied because it is trapped in the reservoir). Potential changes in sediment yield from the land-use in the catchment or trapping of sediment by upstream reservoirs must be considered. Most of the sediment deposited in the reservoir is usually fine grained, so the percentage of spawning-sized gravel must be estimated from the total (Collins & Dunne 1990). Probable rates of natural sediment supply can also be estimated using data from other rivers in the region (Reid & Dunne 1996). Gravel supply from bank erosion and tributaries should be identified and, to the extent possible, quantified. Rates of bank erosion can often be estimated from changes visible on aerial photographs or estimated from changes relative to known landmarks such as buildings or fences.

Gravel Transport and Losses. The sediment budget should include estimates of potential transport rates under pre- and post-dam flow regimes based on field measurements, observations of tracer gravel movement, or calculations of sediment transport competence and capacity (Kondolf et al. 1996*b*; Reid & Dunne 1996). Pre-dam sediment transport rates were usually higher because of greater sediment supply and greater transport capacity by higher, pre-dam flood flows. Most sediment transport formulae yield only potential sediment transport, with actual rates limited by supply. In addition, the budget should include estimates of losses, notably direct losses to aggregate extraction and subsequent trapping of gravel in upstream pits.

Fine Sediment Sources and Transport. If fine-sediment deposition in gravel/cobble substrates or in pools is believed to have affected invertebrate habitat or reduced incubation success of salmonid embryos (Everest et al. 1987), the sediment budget can be expanded to address fine sediment. The seasonal timing of fine sediment delivery to the channel is particularly important because fine sediment delivered during summer baseflows (e.g., from agricultural erosion and irrigation return flow) is likely to deposit on the bed, whereas fine sediment contributed during high flows will likely be washed downstream without depositing.

Large Woody Debris Supply and Transport. The importance of large woody debris (LWD) in aquatic habitat has become increasingly recognized at reach scale and also at the river basin scale, at which LWD supply and transport can be studied (Malanson & Butler 1990; Nakamura & Swanson 1993; Abbe & Montgomery 1996). Many artificial habitat structures are constructed of logs and, in effect, are attempts to replicate some of the functions of natural LWD by increasing channel roughness, providing high flow refuge and cover for fish, forming scour pools, and regulating the transport of gravel through the river system. Before installing artificial structures, we should ask if some of the intended effects of the structures could be achieved on a more sustainable basis by encouraging riparian trees to topple into the channel and move downstream. Similarly, by increasing channel roughness, large woody debris can increase the potential retention of spawning gravel within the channel (Buffington et al. 1997) without resorting to artificial structures. On a large, active, gravel-bed river, much of the instream habitat may be created by LWD, which moves downstream with each flood. Thus, the overall area of habitat may remain constant, but the actual locations of the habitat units may change. In these active systems, artificial habitat structures installed to improve habitat on a reach scale are unlikely to be stable. However, if the supply and transport of large woody debris from upstream can be maintained, aquatic habitat can be enhanced in the local reach and throughout the river system.

Existing and potential sources of large woody debris should be mapped and evaluated as context for the proposed restoration projects, and opportunities for reinstating natural woody debris supply and transport should be considered as alternatives to expensive, artificial structures, whose lifetimes are typically short (Frissell & Nawa 1992).

Geomorphic Setting at the Reach Scale

Site-specific geomorphic information is needed to assess existing and post-project conditions. What are the existing channel geometry, substrate, depth, and velocity conditions? How are these less than optimal for salmon habitat? How will the project improve these conditions? Answering these questions also contributes to developing specific objectives for the project.

Channel Form. If a new channel form is to be constructed, the project proposal should clearly state the basis for the channel form and dimensions (e.g., the design discharge, its basis, and how the effects of upstream dams, if any, were factored in). Plan and section views alone may not indicate whether a flat or undulating channel bed is proposed, so a longitudinal profile of existing and proposed conditions may be needed.

In some proposals, channel form and choice of enhancement structures have been based on application of a channel classification system, such as the Rosgen classification system (Rosgen 1994). Although there is nothing wrong with classifying a channel per se, this level of analysis is not an adequate basis for restoration channel design, as acknowledged by Rosgen (1996). Many restoration projects based on classification in Maryland and California have failed during subsequent high flows, with the channel reverting from the idealized meandering form dictated by the classification system to a pattern more similar to its pre-project or historical condition. This was illustrated by a project in Deep Run, Maryland described by Smith (1997), and by a project in California (Fig. 3) described by Kondolf et al. (In press). Because the geomorphic processes influencing the pre-project channel form had not been altered by the projects, these processes tend to drive the channel back to its pre-project form. Thus, as observed by Sear (1994), it is better that restoration design be based on a real understanding of geomorphic process at the catchment scale, rather than application of "cookbook" rules or classification at the reach scale.

Spawning Gravel Quality. Proposals to import gravel into the channel or rip existing gravels should provide reasonable justification that the existing gravels are actually unsuitable, either because the framework sizes are too large for the salmon to move, too much fine sediment is present, or gravels have become compacted and immobile. Size distributions for existing gravels should be presented and the proposal should compare framework size with the maximum sizes movable by the fish present, and compare fine sediment content (e.g., percentage finer than 1 mm) with maximum acceptable levels of fine sediment (Kondolf 2000).

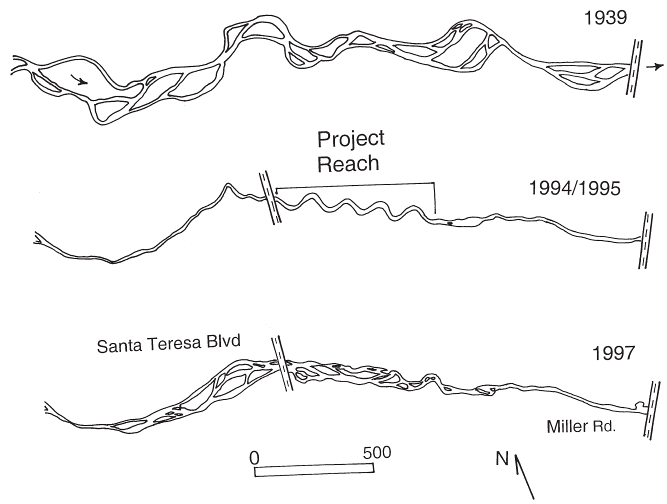

Figure 3. Channels of Uras Creek, near Gilroy, California, mapped from aerial photographs of 1939, 1995, and 1997. A 1995 channel reconstruction project to improve salmonid habitat constructed a meandering channel, based on application of a stream classification system. The design channel washed out in 1996, and the channel returned to the braided form more typical of streams in this setting (Mediterranean climate, episodic flow regime, and high bedload transport).

Bed Mobility. In cases where the channel is designed to be rearranged by high flows, the mobilizing flows should be stated and supporting calculations summarized. Similarly, proposals to import gravel should indicate the critical shear stress for the imported gravel, the shear stresses anticipated under post-project conditions, anticipated gravel mobility, and the planned management response to gravel loss. In some cases, the benefits of created spawning habitat may justify continued gravel placement. This is perfectly reasonable, provided the losses are anticipated and a decision is consciously made to add gravel on a frequent basis.

Intragravel Flow in Redds. For riffle reconstruction projects, the project must create the substrate, water depth, and velocity conditions suitable for spawning salmon, and also create channel bed geometries that induce intragravel flows of oxygenated water into and out of the bed. Many seemingly excellent spawning gravels are not utilized by spawning fish (Burner 1951), often owing to the absence of downwelling or upwelling currents (Healey 1991). Intragravel flow is also influenced by gravel permeability, which can be measured in situ using standpipes (Terhune 1958) as illustrated in a recent study in the lower American River (Vyverberg et al. 1997). Ideally, the restoration proposals should include a detailed longitudinal profile of the reach, showing expected groundwater circulation pathways and indicating anticipated permeabilities.

Bank, Floodplain, and Terrace Revegetation. If the project involves establishing riparian vegetation on an existing or newly created surface, the factors influencing vegetation success should be quantified and stated. Hydrologic and geomorphic factors include inundation frequencies of the surfaces, depth to water table during fall baseflow, and soil texture. Biological aspects should also be described, such as source of plantings, depth to which cuttings will be planted and relation of this elevation to the fall water table, seasonal timing of plantings, and strategies to control weeds.

Post-Project Evaluation of Geomorphic Conditions

Although post-project evaluation has not been common in the past and some grant programs have specifically prohibited use of funds for evaluation studies (Cantara Trustee Council 1998), other programs have added post-project performance evaluation as activities eligible for funding (California Department of Fish and Game 1999). The CALFED Bay-Delta Program recognized that evaluation must be designed into future habitat restoration proposals in the Sacramento-San Joaquin River basin (Healey et al. 1998). For projects involving channel modifications, physical as well as biological conditions need to be monitored to document evolution of channel form, substrate, and resulting habitat and biological use (Kondolf & Micheli 1995). Some important geomorphic monitoring elements related to habitat enhancement projects include: channel form, bed material size, streamflow data, and depth to water table and groundwater interactions.

Channel Form. Channel form, and its changes over time, can be documented by channel cross sections and longitudinal profiles of the channel (MacDonald et al. 1991; Harrelson et al. 1994) to provide an objective basis for evaluating project performance. The channel should be surveyed before project construction to establish pre-project, baseline conditions, immediately after construction to establish as-built conditions, and afterwards over as long a period as possible, preferably at least a decade. The post-project channel surveys need not be done every year, but after floods large enough to move sediment and alter channel geometry ("pulsed monitoring") (Kondolf 1995).

Bed Material Size. Appropriate measures for bed material size depend upon the purpose of the project. To enhance pool-riffle morphology and provide riffle substrate for juvenile holding and invertebrate production, surficial bed material sampling is adequate. If spawning gravel quality is a concern, subsurface sampling is needed to determine the percentage of fine sediment within the gravel. To measure sediment size on the bed surface, the pebble count (Wolman 1954; Kondolf 1997) is a tried and tested method. The zig-zag count (Bevenger & King 1995) is not recommended because it does not yield an adequate sample size or reproducible particle size distributions, and it mixes sample points from a variety of habitat units.

Streamflow Data. An accurate record of streamflow through the project reach is essential to understand project performance and biological response. If a gauge record does not already exist, a recording gauge, or at least a crest-stage gauge, should be established to record stages of flows that will interact with the restoration project in the future (Rantz et al. 1982).

Depth to Water Table and Groundwater Interactions. Depth to water table and groundwater interactions are key controls on riparian vegetation establishment. Shallow monitoring wells can be installed in the banks and floodplain to document the water table conditions (MacDonald 1988). In addition, because seepage of water into or out of the streambed can be an important attribute of salmon spawning habitat, seepage meters (Lee & Cherry 1978), dye studies (Stuart 1953), or standpipes (Terhune 1958) may be useful in documenting intragravel circulation.

Other Considerations

Clear Statement of Objectives

Specific project objectives should be articulated, not only in biological terms, but also in terms of the specific, physical channel changes anticipated. The aquatic ecology depends upon physical channel conditions, so if natural geomorphic processes and conditions are re-initiated and recreated, there is a high probability that the associated organisms will return or respond to improved conditions (Brookes & Shields 1996). Most habitat restoration projects directly affect only the habitat itself; anadromous fish populations might increase or not for completely unrelated reasons (e.g., passage problems downstream, over-harvesting) (Kondolf & Micheli 1995). General restoration goals must be translated into specific, measurable objectives to evaluate the performance of the project and to gain insights for the design of future projects.

Adaptive Management

Uncertainties about the physical and ecological behavior of the complex riverine system imply that habitat management and restoration should be approached with flexibility to allow modifications in response to observed system responses. Adaptive management (Walters 1986) involves good monitoring data, ongoing evaluation of project performance, and deliberate experimental manipulations to test the system response. Perhaps most importantly, adaptive management used to test hypotheses about presumed limiting factors or channel function requires careful planning at the front end of the project.

The adaptive manager process is illustrated in Figure 4, from Healey et al. (1998). Conceptual models are, in effect, hypotheses about how the ecosystem works, how it is affected by environmental conditions, and how it may respond to restoration actions. Targeted research and pilot/demonstration projects are designed to maximize learning about the system before large-scale restoration is implemented. Results of the action are closely monitored to provide information that can inform our understanding of the problem, our goals, and conceptual models.

Funding for Project Planning

Pre-project studies to establish the site's larger context and establish baseline conditions are needed. The agency proposing the project can conduct them as a contribution to the effort, or funding can be requested for a Phase I planning study. It should be recognized that such planning studies might conclude that no project is needed at the site, or that the highest priority problems were elsewhere in the system. The planning study might indicate that gravel added to the channel (for spawning enhancement) would soon wash out in relatively modest floods, or that spawning habitat was not limiting a fish population. In any case, the funds for the planning study would be well spent because they would prevent larger expenditures on construction of projects that would prove to be ineffective or unnecessary.

Large package-deal projects with project planning and design included as part of the proposal are dangerous because the desirability of any project at the site has yet to be demonstrated. Once funds have been granted, the grantee agency may be inclined to justify some sort of project at the site (even if not really necessary) rather than give back the funds.

Conclusions

To be successful, river restoration projects must account for geomorphic processes at both the watershed and reach scales, so that ongoing changes in channel form are recognized and accounted for in project planning and design. The desirability of any project at a given site must be justified, based on large-scale considerations and reach-scale studies. In rivers with sufficient stream energy and sediment load to recreate a natural channel morphology during floods, a geomorphic study might indicate that aquatic habitat will be best served by no direct physical intervention beyond removing factors negatively influencing habitat (e.g., close levees, riprapped banks, etc). Funding should not be committed to a construction project before there is sound scientific information to support the need for a project. The conceptual design for a project must be worked out before the suitability and potential effectiveness of the project can truly be evaluated. Specific information is needed on how the project proposes to modify channel conditions and processes, and how the modified channel is likely to interact with future flows. This information is also needed to evaluate project performance in the future.

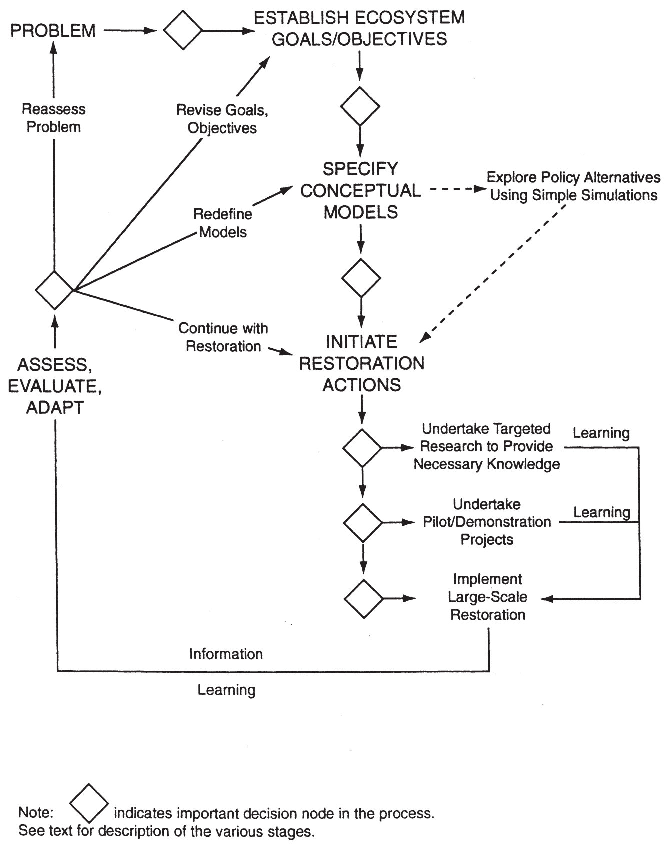

Figure 4. Model of applications of adaptive manager to ecosystem restoration. Diamonds indicate decision nodes. (From Healey et al. (1998), with permission.)

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Appendix 1. Geomorphic elements in salmonid habitat restoration proposals.

Geomorphic setting at watershed scale:
- Watershed map
- Flow regime
- Sediment budget
  - Gravel supply
  - Gravel losses and transport
  - Fine sediment sources and transport
  - Spatial relations
- Large woody debris

Geomorphic setting at reach scale:
- Channel form
- Spawning gravel quality
- Bed mobility
- Intragravel flow in redds
- Bank, floodplain, and terrace revegetation
  - Inundation frequency, water table depth, and substrate

Post-project evaluation of geomorphic conditions:
- Channel form
- Bed material size
- Stream flow data
- Depth to water table and groundwater interactions
- Period of monitoring