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Lessons learned from river restoration projects in California

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ABSTRACT

1. California is a tectonically active region with a Mediterranean climate, resulting in extreme spatial and temporal variability in river channel conditions. Restoration approaches that work in one part of the state may not succeed elsewhere.
2. Restoration projects should be planned and designed based on an understanding of geomorphological and ecological *processes*, rather than simply mimicry of *form*, as in blind application of a classification scheme.
3. Most rivers in California have been dammed, resulting in changed flow and sediment transport conditions downstream. If these changes are not recognized, restoration designs are likely to be ineffective or inappropriate.
4. Very few restoration projects in California have been subject to objective post-project evaluation. As a result, opportunities to learn from past experience to improve future project design have been lost.
5. A case study on Rush Creek illustrates the importance of geomorphologically and ecologically informed project objectives, and the need to account for dam-induced hydrologic changes in developing recommendations for flushing flows.

KEY WORDS: river restoration; California; effects of dams; episodic flow; flushing flows; performance evaluation

INTRODUCTION

River and stream 'restoration' projects have been undertaken in California for a wide variety of objectives. These objectives range from full restoration, in which riparian and aquatic habitats lost due to past human action are recreated, to projects that are motivated by flood defence or similar purpose, but which may involve enhancement of environmental values (Brookes and Shields, 1996). Many projects are undertaken to mitigate environmental impacts of development projects elsewhere.

In a region with relatively uniform geology, topography and channel characteristics such as Denmark, a restoration technique successful at one site may be successful in others. California, however, is a tectonically active region, with a wide range of rock types, elevations, erosion rates and strong orographic controls on precipitation. Elevations range from below sea level to over 4300 m, and annual precipitation

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ranges from under 100 mm to over 3 m. Moreover, there are extreme seasonal and inter-annual variations in precipitation. As a result, stream power and sediment transport vary enormously spatially and temporally.

In California, the spatial variability means that a technique successful in one locality may not work in another, depending upon how flow regime, stream power and sediment transport vary from site to site. The temporal variability means that a designer's intuition about likely future flows at the project site may be influenced by his experience over the previous several years—conditions which may be a poor guide to actual flows in the future. To forecast the performance of a restoration technique at a particular site requires that the geomorphology of the site (and catchment influences) be understood and that the stream power experienced at the site in the future be forecast from analysis of the hydrologic regime.

The recently increased popularity of river restoration projects in California has drawn many practitioners into the field, some of whom lack background in fluvial geomorphology and ecology but nonetheless design projects involving large manipulations of channel form. Despite the designers' good intentions, many projects have been unnecessary, unsuccessful, or actually detrimental to aquatic habitat. Most restoration projects have not been subject to objective post-project evaluation, so the actual rates of success are unknown, and lessons cannot be learned to improve the performance of future projects.

This paper presents a number of points drawn from a decade of research in the field of river restoration and research projects undertaken by graduate students at the University of California at Berkeley. Each point is supported with an example described here or previously published. These points are followed by a case study, illustrating some of these points.

LESSONS LEARNED

Objectives should be clearly stated and based on an understanding of geomorphological and ecological processes

It is only in the context of actual geomorphological and ecological processes that restoration goals can be sensibly formulated and evaluated. Some literature on restoration has addressed only social and institutional factors in successfully implementing projects, such as agreement among all participants in the planning process, assured funding and rapid implementation (Connin, 1991). While these factors are clearly important, they do not guarantee that the physical modifications undertaken are necessarily beneficial to the physical and biological processes in the channel.

To use a medical analogy, 18th century physicians might consult each other concerning the most effective method and rate of bleeding patients for a given ailment, but their agreement on this treatment (and the institutional arrangements that delivered such treatment to large numbers of patients) did not guarantee that the treatments were actually beneficial, because the underlying human biology was not properly understood.

Geomorphology is needed to plan and design restoration projects

A competent geomorphological analysis can shed light on the fluvial processes and controls at a catchment scale, and an historical analysis can document the evolution of the channel and catchment, providing the manager with insight into the underlying causes of the channel's current condition (Sear, 1994; Kondolf and Downs, 1996).

In its report *Restoration of Aquatic Ecosystems*, the National Research Council (1992) reviewed the status of ecological restoration of lakes and rivers in the United States and concluded that many river restoration projects had failed because the river's geomorphology and hydrology were poorly understood. Ironically, the report (written by a committee that did not include a geomorphologist) then recommended that geomorphology be taken into account by classifying the channel using the stream classification system of Rosgen (1994, 1996) and utilizing a table which specifies bed and bank structures suitable for each 'stream type' (Rosgen and Fittante, 1986).

To rely only on such a classification-based approach for project design can be viewed as a 'cookbook' approach. It does not yield fundamental information on how the river functions geomorphologically and ecologically, and what are the underlying causes of the present (degraded) river condition. These insights are needed as a basis for selecting restoration objectives and techniques. Nonetheless, a cookbook approach has exerted a strong attraction upon many non-geomorphologists, many of whom understand that geomorphology is important but have been frustrated by its complexity. Once the alpha-numeric codes have been mastered, a classification scheme may provide the illusion of understanding the specific river. It is perhaps a human trait that while we understand and appreciate the complexities in our own fields, we are often drawn to believe that another field can be reduced to a set of principles that we can easily apply.

A channel classification system can be extremely useful for inventory over large regions, provide a geomorphologically stratified framework for more detailed observations, and provide an initial basis for suggesting restoration strategies once project objectives have been determined (Kondolf, 1995a,b). However, if such schemes are used to set objectives or to design projects, there is considerable risk of failure. This is especially true when used by non-geomorphologists, who would lack a rigorous foundation of knowledge and experience to provide a context for the recommendations from the cookbook approach. Thus, they may mistake the simplifications of a classification system for an understanding of the often complex geomorphology of the river.

There are many examples in California of restoration projects built by non-geomorphologists relying on a classification system. These projects sought to alter the existing channels into entirely different configurations based on preconceptions derived from a classification system, without adequately analysing catchment-level influences and the historical context. Many of these projects have failed, which has undermined public support for stream restoration in at least one case.

Coastal California rivers have high seasonal and inter-annual variability, so traditional concepts of equilibrium channels may apply poorly to some California rivers

California has a Mediterranean climate, with virtually all precipitation in the winter. Run-off is likewise concentrated in winter in rainfall-fed rivers at lower elevations, but rivers draining high elevations derive most flow from snowmelt, with most flows delayed until later spring or early summer. In addition, there is a large year-to-year variability. The greatest flow variability is on rivers fed by rainfall, such as the Eel River, whose flow at Scotia (drainage area 8060 km^2) has ranged from 0.3 to 22 000 $m^3 s^{-1}$ (Friebel *et al.*, 1996). Concepts of bankfull discharge and its common return period of 1.5–2 years (Leopold *et al.*, 1964) are derived mostly from studies in humid regions or on snowmelt rivers. In most arid climates, less frequent events are more geomorphologically effective (Wolman and Gerson, 1978).

In rivers of the southern and central California Coast Ranges, the channel may widen during floods, only to narrow progressively during years with lower discharge as vegetation is able to re-establish along the channel. This cyclical widening and narrowing is illustrated by sequential aerial photographs of the Carmel River above Los Padres Reservoir (Figure 1). In 1987, the channel was mostly bare sand and gravel, although with some patches of riparian vegetation, reflecting channel conditions 4 years after the 1983 flood, a 15-year flood (i.e. with a return period of 15 years) and 1 year after a 5-year flood in 1986. In 1993, after 6 years of drought, vegetation became well established in the channel because no high flows capable of scouring the bed had occurred. In 1995, immediately after a 40-year flood, the bed was mostly bare sand and gravel, the vegetation having once again been scoured from the surface. There have been proposals to 'restore' southern California rivers after large floods, proposals which evidently reflect a lack of understanding of the geomorphological and ecological processes of flood scour and recolonization.

The frequency of large floods has been reduced by extensive dam construction in California

The importance of floods as periodic disturbances in the aquatic and riparian ecosystem is now widely appreciated (Resh *et al*., 1988; Sparks *et al*., 1990). In California, fish communities in reaches downstream of dams are more often dominated by exotic species than unregulated reaches (Baltz and Moyle, 1993), evidently because the elimination of flood disturbance allows the exotic species to thrive. In many rivers, reduction or elimination of flooding downstream of reservoirs has resulted in reduced rates of channel migration and reduced connectivity between floodplain and channel, resulting in less diversity of riparian and aquatic habitat (Johnson, 1992; Ward and Stanford, 1995). Channel adjustments to reduced floods (and to reduced sediment supply) can be expected on alluvial rivers (Williams and Wolman, 1984). In California, channel narrowing is the most common adjustment, due to factors such as reduced sediment supply, incision, establishment of vegetation in the active channel, or deposition.

Because of reservoir regulation, the flow regime downstream of the dam comes, at least in part, under human control, and thus becomes a 'decision variable' in river management. The term *instream flows* has been used to designate flows deliberately released from a reservoir to maintain ecological functions (Loar and Sale, 1984). Most attention has been focused on minimum flow requirements, but deliberate high flow releases, termed *flushing flows*, are increasingly required to simulate some effects of natural floods (Reiser *et al*., 1989; Kondolf and Wilcock, 1996).

The altered hydrology and sediment supply below reservoirs has implications for restoration channel design and minimum instream flow requirements. Flow requirements are often set based on the distribution of water depths and velocities in the channel, assuming fixed channel boundaries. However, if the channel is adjusting to changed conditions (such as the dam), the relation between flow and hydraulic conditions is likely to change. These changes must be understood in setting instream flows and

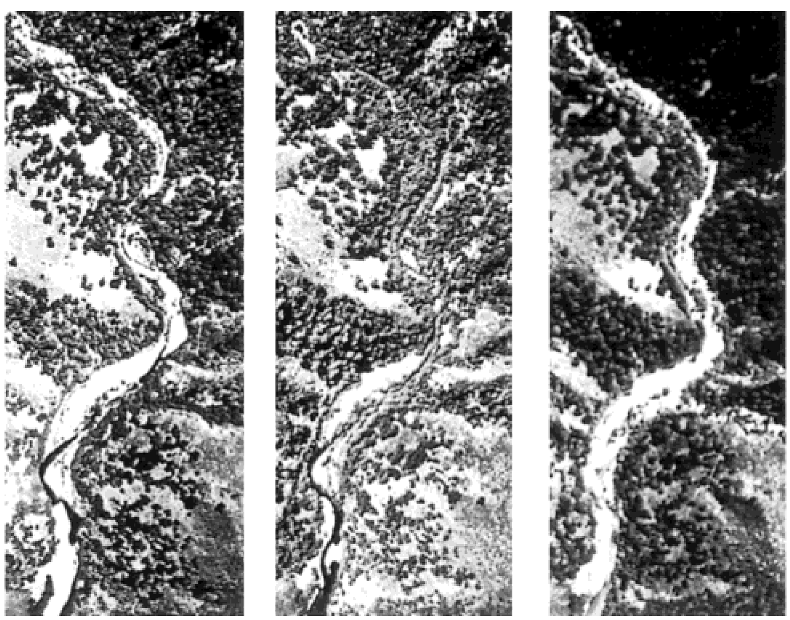

Figure 1. Sequential aerial photographs of the Carmel River above Los Padres Reservoir. In 1987, following a 15-year flood in 1983 and a 5-year flood in 1986, the channel was mostly open sand and gravel. In 1992, following 6 years of drought, riparian vegetation had established along the new low-flow channel and elsewhere in the formerly open active channel. After a 40-year flood in 1995, the channel was once again mostly open sand and gravel, reflecting extensive scour and removal of vegetation by the 1995 flood. Photographs used by permission of the California-American Water Company, Monterey, California.

designing (and evaluating) restoration projects (Kondolf and Larson, 1995). Moreover, flushing flows may complicate the picture further, as they may prevent some dam-induced channel change such as narrowing through vegetation encroachment.

In California, most rivers are dammed: 1400 dams over 7.5 m in height and 60 000 m^3 in reservoir capacity (and many smaller ones) impound over 60% of the state's run-off (California Department of Water Resources, 1984; Mount, 1995). Restoration projects are likely to be located below dams, but the implications of the altered hydrology and sediment supply have not always been appreciated by project designers. The case study describes the basis for setting flushing flows for Rush Creek.

Changes in sediment supply must be understood for restoration design

Many channels in California are sediment-starved because rates of sediment supply have been reduced by upstream dams, extraction of sand and gravel from the channel, bank protection works and other influences. Other rivers have experienced increased sediment supply as a result of land-use effects. In the Trinity River, California, the supply of coarse sediment has been reduced by upstream dams, while the supply of fine sediment from tributary catchments has increased due to timber harvest and road construction. The delivery of fine sediment to the channel below the dam, combined with reduction in flood flows capable of transporting the sediment downstream, resulted in extensive deposition of fine sediment over gravel and cobble substrates important for salmon spawning and invertebrate production. High-flow releases have been proposed to flush fine sediment from the gravels and maintain a more dynamic channel regime (Wilcock *et al*., 1996), in conjunction with a programme of physical alterations to river banks and pools (US Fish and Wildlife Service, 1995).

To mitigate the effects of upstream dams in reducing the supply of gravel, spawning riffle restoration projects have been undertaken in at least 15 rivers and streams in California (Kondolf and Matthews, 1993; Kondolf *et al*., 1996). These projects have involved artificial importation of spawning-sized gravel to the channel, either placed in constructed riffles or dumped below dams for redistribution by the currents. Some of these riffle restoration projects have been undertaken without an appreciation for the sediment transport regime downstream of dams. Riffle restoration projects on the Merced, Stanislaus and Tuolumne Rivers have washed out in flows with return periods as low as 1.5 years (Kondolf *et al*., 1996).

Restoration should be based on understanding of process, not simply mimicry of form

Many of the problems described above can be viewed through a distinction between *process* and *form*. A restoration project is more likely to be successful if its design is based on an understanding of geomorphological and ecological processes, rather than an imitation of channel forms believed to be suitable or prescribed by adherence to a classification scheme. Commonly, run-off and sediment load in the catchment have been altered (e.g. by land use changes or dam construction) such that historical channel forms or channel forms from nearby 'reference reaches' (reaches believed to reflect pre-disturbance conditions at the project site) may not be in equilibrium with present, changed conditions.

Post-project performance evaluation is needed to avoid repeating mistakes and to develop an understanding of how rivers respond to restoration actions

It is often assumed that restoration projects are beneficial, but many well-intentioned projects are actually ineffective or detrimental (e.g. Frissell and Nawa, 1992; Iversen *et al*., 1993; Kondolf *et al*., 1996). River geomorphology and ecology are complex, and we cannot predict precisely how the river will respond to a given treatment. Our restoration efforts are best viewed as experiments, from which we can learn valuable lessons to improve future project design (Kondolf, 1995a). Post-project evaluation can entail repeat ground and/or aerial photography, cross-section surveys, bed material size sampling, vegetation surveys, and sampling of invertebrate, bird and fish populations (Kondolf and Micheli, 1995).

Unfortunately, objective post-product evaluation is rarely undertaken by agencies constructing or funding restoration, perhaps because it is felt that limited funds should be used to 'do something' rather than for 'more studies'. For example, the guidelines for a grant programme funding local projects to improve fish habitat conditions explicitly states that funds are for 'implementation' only, not for 'studies', evidently precluding funding for post-project evaluation to the grantee (California Department of Fish and Game, 1996). However, the agency itself does not conduct objective evaluation of the performance of the projects it funds.[1]

One proposal recently funded under the programme called for installation of numerous artificial habitat enhancement structures in a reach of stream channel that had been previously reported as excellent habitat by the California Department of Fish and Game, the funding agency. The proposal failed to present any evidence that the channel needed the supposed enhancements, nor any explanation as to how the structures were expected to address factors limiting the populations of fish. These facts alone suggest that this 'restoration' work is as likely to be harmful as beneficial to the integrity of the channel and thus to aquatic habitat, but the explicit avoidance of project performance evaluation virtually ensures that potential negative effects of projects such as this will go undetected. The local agency that proposed the project is unlikely to evaluate objectively the project's performance because it cannot use any portion of the project budget for 'studies'. Moreover, these (and similar) funds support a restoration programme within the local agency, employing a number of people. There may be a disinclination within this agency to evaluate projects for fear that exposing 'failures' might threaten future funding.

In some cases, such as the spawning riffle restoration projects in the Merced, Tuolumne and Stanislaus rivers mentioned above (Kondolf *et al*., 1996), it has been only through academic research (largely done as graduate student team projects and theses) that lessons could be drawn from restoration projects and disseminated to the community involved in constructing and funding such projects.

Even when an agency constructing a project seeks to conduct objective evaluation, a lack of in-house expertise may lead to an ineffective evaluation study design. One large and well-publicized restoration project in northern California (Hamilton, 1993) included enormous effort (mostly by high school students) to measure channel habitat conditions and sample invertebrates. Unfortunately, it was subsequently impossible to determine if the project objectives had been achieved because the pre-project baseline data collected were not appropriate for evaluation of performance (Swenson and Manning, 1992).

As argued above, many restoration projects in California have not benefited ecological resources because their design was not based on sound geomorphological and ecological understanding, clearly thought out objectives, and catchment-level and historical study specific to the rivers proposed for restoration. Several of the points elaborated above are illustrated in the case study below.

CASE STUDY: BANK PROTECTION, AQUATIC HABITAT ENHANCEMENT, AND FLUSHING FLOWS ON RUSH CREEK

Background

Rush Creek drains 133 km^2 (above Grant Lake Reservoir) on the steep, eastern slope of the Sierra Nevada range in California, debouching into Mono Lake, a saline, terminal lake (Figure 2). Flow derives from snowmelt in the upper catchment, with lower reaches of the stream flowing through a semi-arid climate in the rain shadow of the Sierra Nevada. From 1941–1982, the Los Angeles Department of Water and Power diverted nearly all flow from the main tributaries to Mono Lake, drying out Rush Creek below

[1] Postcript: In its October 1997 Request for Proposals, the California Department of Fish and Game announced that its grant programme would henceforth consider funding proposals for, 'project evaluation', monitoring, and maintenance following project implementation', a positive step to encourage post-project performance evaluation.

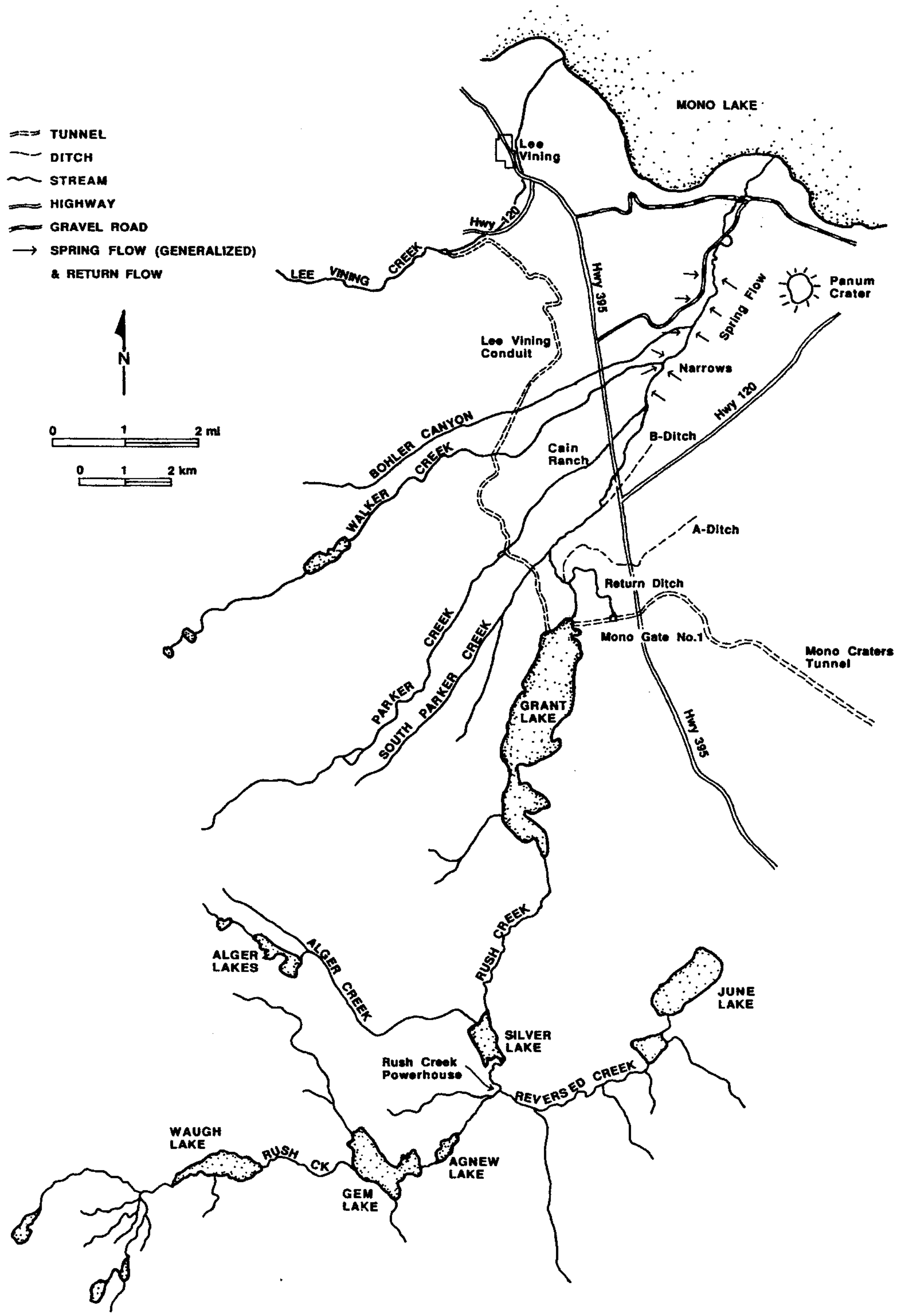

Figure 2. Location map of Rush Creek, showing localities referred to in the text. The 'Meadows' reach lies between the Narrows and the northern gravel road crossing.

Grant Lake Reservoir (Kondolf and Vorster, 1993), and eliminating a formerly productive brown trout (*Salmo trutta*) fishery (Vestal, 1954). By 1982 Mono Lake had dropped 7 m because stream inflows were so much less than evaporation (Stine, 1991). During wet years (1967, 1969, 1982 and 1983), high flows spilled from Grant Lake Reservoir, and the channel of Rush Creek incised to the lower lake level, its new base level (Kondolf and Vorster, 1993; Trihey & Associates, 1993). A series of legal actions and water rights hearings have established minimum flow requirements, including flushing flows, and initiated a court-mandated programme of restoration projects to enhance aquatic and riparian habitat (Dunning, 1994). The restoration work was carried out in the context of litigation and contentious evidentiary hearings before the State of California Water Resources Control Board (the State Board).

Riparian revegetation and bank erosion

Prior to 1941, Rush Creek was flanked by extensive riparian vegetation, especially in a lower gradient floodplain reach known as 'The Meadows' (Figure 2). Virtually all of the riparian vegetation was killed by dewatering of the channel and consequent drop in the alluvial water table (Stine *et al*., 1984). One objective of the restoration programme has been to restore riparian vegetation, but re-establishment of riparian vegetation in the incised reach has been limited because the surfaces flanking the present channel (former floodplain and channel) are now too high above the water table for seedlings to survive. Moreover, these surfaces are no longer inundated by floods (which would increase soil moisture and disperse seeds) because of their height above the channel and reduction in flood flows by Grant Lake Reservoir. The bottomlands along Rush Creek were formerly vegetated with willows (*Salix* sp.) and other riparian plants, but are now vegetated mostly with xeric species such as sagebrush (*Artemisia tridentata*).

In reaches where the incised channel has widened at the expense of former floodplain surface, riparian vegetation has been re-establishing naturally on gravel bars, whose surfaces are close to the alluvial water table. About 3.5 km upstream of the mouth, the channel is incised about 0.8 m below the adjacent terrace, into which it has been migrating and eroding, depositing a point bar on the inside of the bend. The point bar surface, less than 0.2 m above the summer water level, is hydrologically connected to the present channel; it has a shallow water table, is inundated frequently, and is densely vegetated with young willows and other riparian plants (Figure 3). The natural process of eroding the high terrace (supporting only xeric plants) and replacing it with a point bar (supporting dense riparian vegetation) has the effect of 'restoring' the channel.

Curiously, one of the first 'restoration' projects undertaken on Rush Creek was to stop bank erosion at one of these meander bends in 1991. The project description reported the bank to be 'severely eroded' and 'the creek was actively eroding the banks laterally' (English and Skibinski, 1991). The designers had no data on actual bank erosion rates, being unaware of two cross sections surveyed from 1989 to 1991 at this meander bend for academic research, which showed erosion of 0.15 and 0.85 m year^{-1}, respectively (Figure 4). The project involved protecting the toe of the outside bend with rock, and planting willow above, a treatment termed 'soft armouring' (Figure 3). The project was evidently considered 'restoration' because the ' "soft armouring", using native vegetation, was used in place of traditional engineered solutions (rock rip-rap, gabians [sic], etc.)' (English and Skibinski, 1991).

No structures or other resources were threatened by the bank erosion, only a former wet meadow, now a sparsely vegetated sagebrush flat that had been 'heavily used in the recent past as a sheep holding area' (English and Skibinski, 1991). No evidence was presented or cited to show that bank protection was needed or beneficial at this site. In part, there may have been an assumption that bank erosion was inherently bad. Regulators had expressed general concerns about erosion and water quality, and there was a concern that if the valley flat were permitted to erode, the opportunity to restore it to a wet meadow in the future would be lost. (Restoration to meadow would probably have been impossible because the springs that had maintained the wet meadow had dried up after reduction in irrigated acreage up-gradi-

Figure 3. Photograph looking downstream to meander bend on Rush Creek about 3.5 km upstream of Mono Lake. Note dense growth of willows (*Salix* sp.) on the point bar on the right bank, contrasted with the high left bank supporting only sagebrush (*Artemisia tridentata*) and other xeric vegetation. Until the toe of the left bank was protected, this reach of Rush Creek was re-establishing a healthy riparian corridor on its own by eroding the left bank terrace and depositing a fresh point bar surface, which is hydrologically connected with the modern channel and thus supports riparian vegetation. (Photograph by the author, October 1994)

ent.) Moreover, there was political pressure to get a restoration programme under way. As a result, the project was approved by the Restoration Technical Committee, consisting of technical representatives from government agencies, environmental and fishery groups, and the Los Angeles Department of Water and Power (LADWP) (T. Taylor, Ilene Mandelbaum, and Gary Smith, personal communications, 1996).

Ironically, the bank erosion here can be seen as an essential part of the stream's natural process of recovery and revegetation. Implementation of an erosion control project (in part to preserve the potential for meadow restoration) can be viewed as counterproductive to the goal of re-establishing a healthy riparian corridor along Lower Rush Creek.

Aquatic habitat enhancement efforts

Efforts to enhance aquatic habitat for fish have included excavation of large pools, placement of boulders and other large roughness elements in the channel, and importation of gravel to create spawning habitat (English and Skibinski, 1991). Although utilization of artificially created pools and cover elements was documented by snorkel survey on neighbouring Lee Vining Creek (Taylor, 1994), the only post-project evaluations on Rush Creek concerned availability and utilization of artificially enhanced spawning sites (Taylor, 1993). In field surveys conducted in fall 1992, 1 year following gravel importation projects in 1991, spawning habitat (visually identified as sites with suitable gravel sizes, water depths and velocities) was found to be six times greater, and redd density 3.5 times greater, in treated reaches (i.e. with artificial gravel importation) than in untreated reaches. Populations of Age-0 fish in 1992 throughout Rush Creek were generally double (or greater) that those observed in 1990 or 1991, with the highest densities in treated reaches (Taylor, 1993). These observations were not continued after 1992 into years of higher flow, when the stability of the gravel placements could be tested, because the LADWP (the agency responsible for the restoration work) did not fund continued evaluation (T. Taylor, personal communication, 1996).

LADWP subsequently funded a qualitative, third-party review of the entire restoration programme on Rush and Lee Vining Creeks, which concluded that the programme lacked a coherent recovery strategy based on clear goals and objectives, and that the projects were not subject to critical design analysis (Interfluve, 1995). The restoration programme was also criticized during evidentiary hearings before the State Board and in court testimony. Unfortunately, the setting for these critiques was highly contentious, and the lack of detailed, quantitative data made objective evaluation of project performance elusive.

Flushing flow releases

With restoration of perennial flow to Lower Rush Creek, it became necessary to specify instream flows to support aquatic and riparian life. Setting minimum flow requirements throughout the year (to ensure adequate flow for spawning, juvenile rearing, etc.) is essentially a question of how given flows fill the channel, what distributions of depths and velocities they produce, and how these match the habitat requirements of the target species. Setting flushing flow requirements is somewhat more complex because these high flows maintain or influence channel form itself.

In the Meadows section of Rush Creek, the channel widened over 300% from 1941 to 1983, so that although flows were now perennial, the aquatic habitat was poor because flow was shallow and the channel unshaded. One objective of restoration efforts, and of flushing flows in particular, was to promote channel narrowing towards an equilibrium width. High flows were expected to promote channel

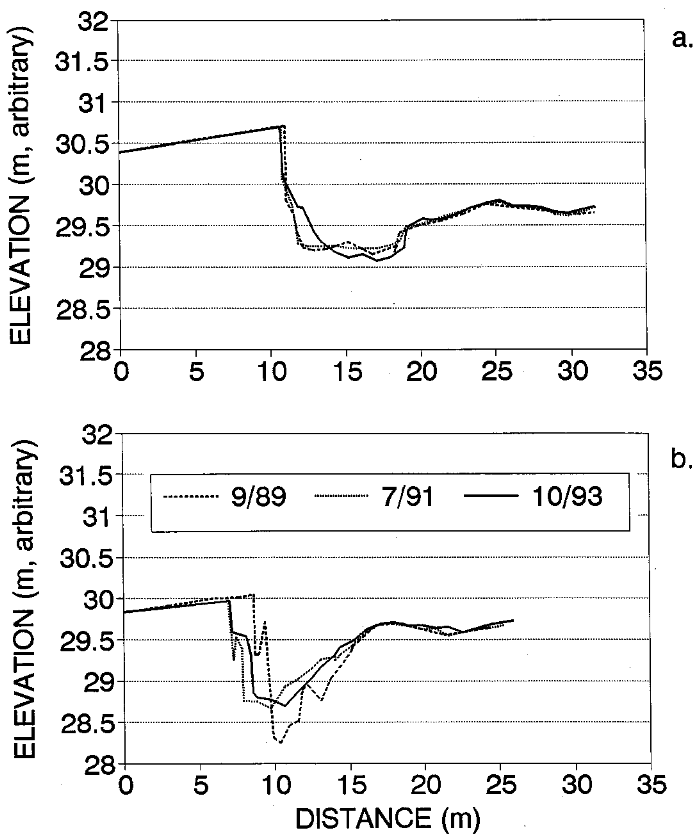

Figure 4. Channel cross sections of Rush Creek at the meander bend about 3.5 km upstream of Mono Lake, surveyed from 1989 to 1991. (a) Cross section at apex of meander bend; (b) cross section 26 m downstream. (Surveys by the author.)

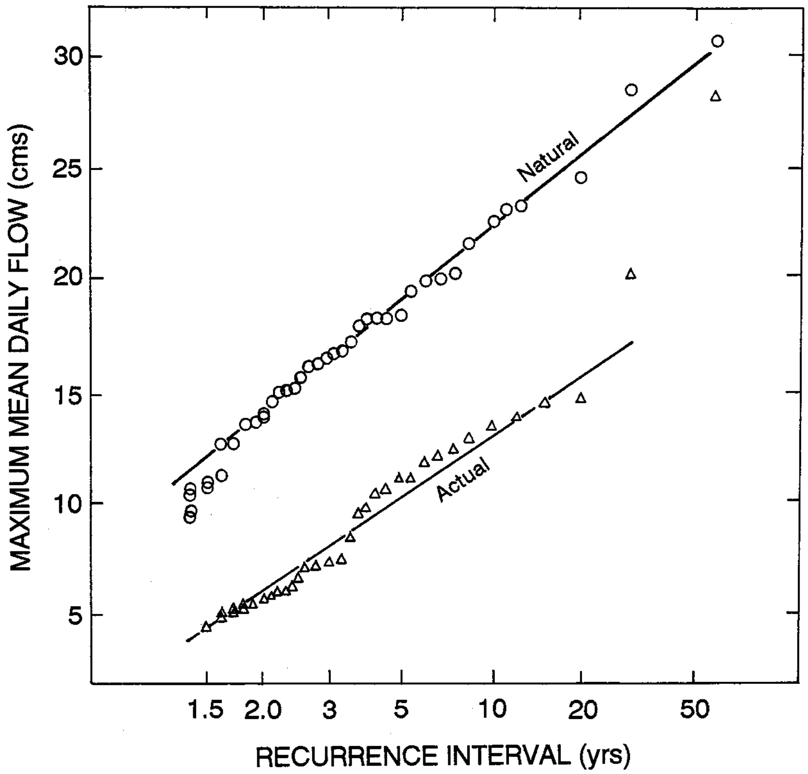

Figure 5. Flood frequency analysis of annual maximum mean daily flows (in $m^3 s^{-1}$, or cms) for Rush Creek at Damsite, directly upstream of Grant Lake Reservoir. Triangles are values from actual flow records, which reflect regulation by upstream hydroelectric impoundments. Circles are values for natural run-off computed from actual run-off and storage changes in upstream impoundments (adapted from Kondolf, in press).

narrowing by flooding bars and developing floodplains to permit deposition of suspended sediment on these surfaces within riparian vegetation established there. Another objective was flushing fine sediment from spawning gravels, which requires that gravels be mobilized to permit interstitial fine sediments to be exposed and transported away.

Flushing flow recommendations and other instream flow requirements adopted by the State Board (following extensive evidentiary hearings) were based on an analysis of flow records (mean daily values only) at the gauge Rush Creek at Damsite, upstream of Grant Lake Reservoir, for the period 1936–1993 (State Board, 1994). These flow records reflect the flow regime in Lower Rush Creek before diversion to Los Angeles in 1941, but they reflect regulation by upstream hydroelectric impoundments constructed since 1916, which have reduced flood peaks and prolonged snowmelt run-off. 'Natural' flows (without regulation by the hydroelectric impoundments) were calculated from the actual flow records and reservoir storage changes.

The maximum mean daily flow in each year was tabulated from both the actual and computed natural flow records, and a flood frequency analysis was conducted. The recommended flushing flows were estimated as a compromise between the actual and natural $Q_{1.5-2.0}$ (the flow with a return period of 1.5 to 2.0 years), based on scientific literature suggesting that in many snowmelt rivers such frequent floods are the geomorphologically effective, or 'channel-forming' discharge (e.g. Leopold *et al.*, 1964). As displayed in Figure 5, the historical $Q_{1.5-2.0}$ is about 4.5 $m^1 s^{-1}$, the $Q_{2.0}$ suggests a flushing flow of about

5.6 $m^3 s^{-1}$ for actual conditions, 12.8 $m^3 s^{-1}$ for natural conditions. The recommended flushing flow for years in 'wet' and 'wet–normal' years (i.e. with exceedence 0–40%) was 8.5 $m^3 s^{-1}$, a compromise between the flows suggested from the actual and natural flow regimes. In 'normal' years (with exceedence 40–60%), the recommended flushing flow was 5.6 $m^3 s^{-1}$, and in 'dry–normal' and 'dry' years, no flushing flow was recommended (Kondolf, in press). These flushing flows were expected to mobilize spawning gravels, based on observations of gravel movement during other studies over the period 1987–1991 (Tom Taylor, Trihey & Associates, personal communication, 1993). Indeed, as the active channel narrows in over-widened reaches of Rush Creek, it can be expected that gravel mobilization will occur with greater frequency as the minimum depth for gravel mobilization is achieved at lower flows.

A common dilemma in specifying flushing flows below dams is that there is often a narrow window of discharge between the flows required to mobilize gravels, and flows at which gravel and sand are transported at comparable rates—the latter condition being one in which the benefits of gravel cleaning may be cancelled by downstream transport and loss of the gravels themselves (Kondolf and Wilcock, 1996). On Rush Creek, however, the site of Grant Lake Reservoir was a large natural wetland, which probably trapped all gravel supplied from the catchment. Gravel supply to Lower Rush Creek was probably from lateral channel erosion into gravel-rich deposits of the Rush Creek delta in the Pleistocene Lake Russell (the ice-age enlarged lake ancestral to Mono Lake), a source which could be expected to continue during the flushing flows. In addition, restoration activities have included artificial additions of gravel to the channel.

Lessons from Rush Creek

The Rush Creek case study illustrates many of the lessons summarized earlier. First, the bank protection project reflected a choice of objectives inconsistent with geomorphological and ecological processes at the site. The bank erosion was stopped (at least in part) for the goal of restoring a wet meadow, which was probably unrealistic due to hydrologic changes. By stopping bank erosion, the project arrested the stream's natural process of recovery and re-establishment of woody riparian vegetation. At the least, these trade-offs could have been discussed in the project description but were not (English and Skibinski, 1991). The project can also be viewed as an attempt to control channel form rather than permit channel processes to create and maintain habitats through dynamic change and evolution.

The effects of dams and diversions on channel processes and stream ecology are illustrated on Rush Creek, through the history of dewatering and resultant channel change, and through the need to account for upstream reservoir regulation in setting flushing flows. Finally, the need for post-project evaluation is illustrated. Despite the large investment in these restoration projects, funding was not available to collect the data upon which an objective evaluation of project performance could be made. The evaluation subsequently conducted has been in a highly contentious setting of hearings and litigation.

CONCLUSION

The physical settings and objectives vary widely among river restoration projects in California, but some lessons emerge from experience and observations of many restoration projects.

Clear objectives, consistent with geomorphological and ecological processes, are a prerequisite to effective restoration, and to avoid constructing projects that are ineffective or actually harmful to aquatic and riparian resources. A real understanding of geomorphological and ecological processes (based on adequate study of the channel history, catchment-level influences for the site, and analysis of flow records) is needed, rather than application of 'cookbook' approaches based on mimicry of form. This is especially important given the wide range of conditions encountered in California streams. It is essential that the overall objectives for river management and restoration be clearly thought out to ensure that all restoration objectives are compatible and that proposed projects are consistent with the overall objectives for the channel.

Other important features of geomorphological processes in California are the extreme seasonal and inter-annual variability in flow, and the influence of infrequent large floods on channel form. Because most California rivers have been dammed, many channel reaches proposed for restoration are undergoing adjustments to reduced flood magnitudes and reduced supply of sand and gravel. Thus, many restoration programmes now include explicit requirements for periodic flushing flows to simulate some effects of natural floods. Lack of upstream sediment supply below dams, and the channel's competence to move artificially added sediment, must be considered in design of restoration projects below dams.

Perhaps most importantly, each restoration project is potentially an opportunity to learn more about the behaviour of these rivers and the effect of various treatments upon them. Thus, objective post-project evaluation is badly needed to permit the field to advance.

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