Integrating Geomorphic Process Approach in Riparian and Stream Restoration: Past Experience and Future Opportunities

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ABSTRACT. Riparian and stream restoration efforts frequently focus on the restoration of desired channel forms within a stream corridor, often without consideration of the geomorphic processes that drive the development of those channel forms. As noted by the National Research Council (1992), many river channel and riparian restoration projects have failed because the underlying processes were not sufficiently well understood - rather they involved physical reconstruction of desired habitats, which were not sustainable without the processes to maintain them. Here we consider some distinct characteristics of process-based riparian and channel restoration projects, and review recent and ongoing restoration efforts emphasizing preservation or restoration of natural processes. Three case studies: the Sacramento River SB1086 program, the Clear Creek restoration program, and the realignment and restoration of Best Slough, illustrate the influence of factors such as watershed land use changes, water resource development, and urbanization on opportunities and constraints on process-based restoration.

INTRODUCTION

Worldwide, streams and adjacent riparian zones have been subjected to a tremendous array of modifications. Since as early as 5200 BC, humans have altered riparian zones and stream channels (Drower 1954). Frequently, these alterations have had negative impacts on the assemblages of flora and fauna associated with stream corridors. Several legal influences, including the Clean Water Act and endangered species concerns, have forced a shift in predominant views of stream corridors. These views have shifted, especially in the United States, from a perception of stream corridors as areas of potential flood risk or transportation to a perception of stream corridors as important ecological resources with significant societal benefits. This shift in views, coupled with the substantial list of degraded stream and riparian systems in North America, makes it likely that stream restoration will continue to attract public attention and consume significant resources for the foreseeable future.

Because streams and riparian systems are longitudinally continuous and span a variety of land ownership and land use conditions, projects concerned with stream and riparian restoration necessarily involve a diverse array of participants. Restoration efforts also frequently involve multiple and complex objectives (Kondolf 1996, Brookes and Shields 1996). A common effect of this combination of complex restoration problems with diverse stakeholder groups is the tendency to simplify the situation in order to proceed with what is perceived as "the real work of stream and riparian restoration" – the implementation of restoration designs.

Perhaps the most frequently repeated simplification in the restoration of stream corridors has been to focus on the restoration of desirable (for a variety of reasons) channel and riparian forms without adequately considering the fundamental geomorphic processes operating at the site. This simplification has been fueled by actively marketed stream classification systems that promote the restoration of specific in-channel and riparian forms. Non-technical stakeholders find these classification systems and the associated restoration advice relatively easy to understand and apply. However, when adopted, such simplifications tend to limit the communication of the principles of fluvial geomorphology and the benefits that an understanding of those principles could bring to a restoration project. In stream corridor restoration projects with limited resources or aggressive schedules, as is so often the case, the form-based restoration approach is often selected because it can be easily scoped and readily leads to restoration designs that can be rapidly implemented in the field and show impressive short-term channel changes. Because few post-project evaluation results for stream restoration projects have been reported (Kondolf 1995), the form-based approach has maintained a level of perceived success and therefore sustained in popularity.

However, an expanding body of evidence from recent monitoring efforts (Frisell and Nawa 1992) suggests that form-based stream corridor restoration efforts do not achieve long-term project objectives with a reasonable level of success. A committee of the National Research Council (NRC 1992) attributed the low success rate of river and stream restoration projects to the failure of most projects to take hydrology and natural processes into account. Ironically, the NRC committee, which did not include a fluvial geomorphologist, recommended that a popular stream channel classification system be used to incorporate geomorphology in restoration projects. However, application of this system commonly results in design of projects that are form-based, are not necessarily sustainable by current processes, and which have commonly failed (though the project performance has not often been documented; see Smith 1997 and Kondolf et al. 2001 for examples).

Consideration of process in restoration appears to be on the rise, but without understanding ways in which a process-based approach differs from a form-based approach, it will continue to be difficult to effectively integrate geomorphic principles into riparian and stream restoration projects.

In this paper we suggest some concepts to help stream and riparian restoration stakeholder groups incorporate process-based considerations into riparian and stream channel restoration projects. We briefly review two examples of stream corridor restoration projects in California that have successfully integrated a process-based approach, present a more detailed case study of a third (Best Slough near Marysville), and consider opportunities and constraints to implementing a process-based approach more broadly.

INCORPORATING PROCESS-BASED CONSIDERATIONS INTO STREAM AND RIPRIAN RESTORATION

The complex problems faced in the restoration of stream and riparian systems make the introduction of fluvial geomorphological principles to stakeholders a difficult endeavor. In addition to financial and time constraints placed on restoration projects, stakeholders frequently have a range of strongly held objectives for the restoration program and are not necessarily concerned with understanding the system to guide reasonable restoration, rather they are interested in seeing some specific outcome that may or may not be appropriate in the system. One of the major difficulties in pursuing a process-based restoration program is that process-based restoration solutions are less “visible” than form-based restoration solutions. It is easier for stakeholders to see a rootwad placed in the corner of a stream channel, for example, than a reduction in peak storm flows or sediment loads.

A process-based approach also has a higher degree of short-term uncertainty than a form-based approach. This occurs because natural fluvial processes are relied on to do some of the work of restoration in a process-based approach, and since geomorphic processes are variable and often unpredictable, no guarantees can be made about the early development of a restoration project. This short–term uncertainty can be difficult to favorably present to regulators and the public who may be interested in a range of short term guarantees. The key to integrating geomorphic processes into stream and riparian restoration projects then, is to introduce the benefits of a process-based approach at the inception of the program so that they are on equal footing with the perceived benefits of a formbased approach. The following three points highlight important benefits of process-based restoration.

1) “Unstable” channels formed by active geomorphic processes may have significant ecological value

Form-based restoration projects tend to focus on creating and then protecting specific channel forms and habitat types (e.g. meander bends of a specified geometry or a “low flow” channel). Frequently these forms are protected by elements such as logs, boulders, and rootwads in the bank, and rock weirs in the bed. However, even if appropriate in the channel in an undisturbed state, these forms may not be sustainable over the long term in the context of the current, altered hydrology and land-use practices in the watershed, even with the heavy stabilizing elements in place. Stakeholders should recognize from the inception of a restoration project that there is significant ecological value in the habitat gradients produced by natural geomorphic processes, and that “stable” channels are not natural in some riverine environments, such as Mediterranean climate streams. Habitat should not be viewed only as individual fixed, discrete elements in the channel, but rather as a continuous assemblage of conditions in the channel and riparian zone that change over time.

2) Investigations of geomorphic processes and historical geomorphic change can help in the development of realistic stream and riparian restoration goals

Channels change. Especially in California, where the magnitude, frequency, and duration of flow events can change drastically from year to year, and where development continues to alter watersheds. Therefore, the current condition of a stream or its watershed may not provide sufficient information about a system to guide a restoration program. Incorporating a thorough investigation of geomorphic processes during the early stages of a restoration project can help avoid some of the failures that result from restoration projects based solely on a channel classification system that captures only a snapshot of the current conditions of the stream corridor. An understanding of the past, present, and expected future geomorphic processes in the system will facilitate the development of goals and objectives that are realistic in the context of the stream being restored.

3) Geomorphic processes result in channel forms appropriate to the stream or riparian system

This point speaks to the long-term success of stream and riparian restoration projects. Whenever feasible, restoration projects should allow natural geomorphic processes to do some of the restoration work. In the short term, this is less predictable than the manual construction of desired channel forms. But over the long term it is inevitable that process will win out over form. In addition, resources can be saved by not constructing channel forms, and those resources can be beneficially applied to adaptive management and monitoring of restored geomorphic processes and the resulting channel forms.

It is likely that skepticism about a process-based approach will remain among stakeholders in many stream restoration projects, even after the benefits of the approach are identified. Without a continuous presence from the start of the project through its implementation, it is possible that the restoration efforts will revert to a form-based approach. Therefore, a strategy for integrating a process-based approach at each milestone in a restoration project is important to the overall successful integration of a process-based approach. The discussion below presents milestones shared by many stream and riparian restoration projects, and process-based considerations that should be introduced at each milestone.

Typical Stream and Riparian Restoration Project Components

- *Objective Setting*

Stream and riparian restoration project objectives should be framed in terms of the desired geomorphic processes as opposed to desired channel forms. For example, instead of having the objective of a low flow channel, a restoration project should have the objective of producing conditions where the existing hydrology can generate shear stresses with an adequate frequency, magnitude, and duration to sustain a defined channel at low or base flow conditions. Project objectives should also include a temporal element. This will help eliminate some of the motivation for a form-based approach that achieves immediate and visible results. Objectives should also recognize economic tradeoffs. For example, the difference between the long-term costs and benefits of purchasing riparian lands to allow natural processes to shape channel and riparian forms versus the long-term costs and benefits of major channel modifications and habitat creation efforts and the associated maintenance costs.

- *Data Collection*

The data collected in support of a form-based stream or riparian restoration project can also benefit a process-based approach. However, additional information should be collected to generate a sufficient level of understanding about the geomorphic processes at work in the system. This will include historical information on watershed and channel change in addition to a compilation of data describing existing channel geometry.

- *Conceptual Design*

Unlike designs in form-based restoration, conceptual designs for process-based restoration projects should not be developed as pre-cursors to drawings that specify final, static features of the post-project channel or riparian zone, but rather as a means to investigate how natural channel forming processes will shape the new channel as a result of the restoration interventions. For example, rather than showing “bioengineered bank stabilization” at all channel bends, process-based conceptual designs should convey information like the expected channel evolution after a reduction in peak storm flow magnitude, or the development of low-flow habitat after a constrained channel is given access to a floodplain.

- *Final Design*

This phase of stream and riparian restoration projects can be difficult under a process-based approach, especially when formal design documents must be produced to implement the project. Traditional engineering design documents can be excruciatingly specific, and there is a tendency amongst designers to strive for this level of detail in restoration projects. It should be stressed during this phase of restoration that such precision is unreasonable given the uncertainties associated with the restoration of channels by natural processes. Resources that in a traditional engineering project might be used to finalize every last detail should be reserved for post-project monitoring and adaptive management efforts.

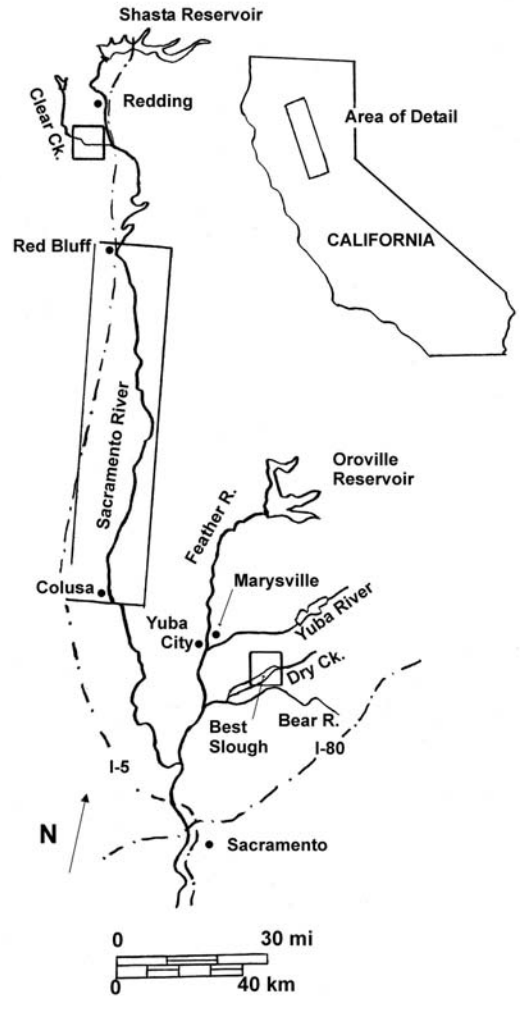
- *Implementation*

Implementation of a process-based restoration program should be viewed as an on-going process rather than a discrete construction job. Until geomorphic processes are sufficiently understood to reliably predict the development of channel forms after process alterations, no project should be considered finished when construction is done. If riparian and stream restoration is looked at as an on-going effort to restore natural channel forms through the facilitation of natural geomorphic processes, restoration expectations are likely to be met more reliably.

- *Monitoring*

Monitoring is critical to the refinement of the process-based restoration approach and should in fact be considered part of project implementation. For how can we truly know if a restoration project has been successful without understanding the changes that occur over time after restoration has been implemented? Monitoring should capture the changes in channel forming processes appropriate to each project and the changes in channel form in the context of the restored channel forming processes.

FIGURE 1. Location map of the northern Sacramento Valley, showing locations of the three case studies, on Clear Creek, the Sacramento River, and Dry Creek (Best Slough) (in boxes).



PROCESS-BASED RESTORATION PROJECT EXAMPLES

The Sacramento River SB1086 Program

The flow regime of the Sacramento River has been profoundly modified by reservoirs, diversions, levees, flood control channels, and land-use change in the watershed. Most notably, Shasta Reservoir has reduced flood magnitudes and cut off the upstream sediment supply, as has been especially evident in the reach near Redding (Parfitt and Buer 1980). The Sacramento River was once flanked by extensive forests of riparian vegetation, but only about 2 percent of the original forests remain as a result of clearing, land conversion, and flood control (Bay Institute 1998). Despite these humaninduced changes, the Sacramento River from Red Bluff to Colusa (Figure 1) still exhibits limited processes and characteristics of a dynamically migrating, meandering alluvial river, including the establishment and successional change of riparian cottonwood forests.

Along with the San Joaquin River, the Sacramento River and its tributaries formerly supported runs of chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*O. mykiss*) that probably totaled 2-3 million annually (Yoshiyama et al. 1996). Native runs of these salmon and steelhead are extinct in many drainages, and several runs are listed under the state and federal endangered species acts (U.S. Fish and Wildlife Service 1997). With the recognition of the value of riparian forests in providing habitat for a range of species, including salmon, there is an increasing consensus on the need to preserve and restore these forests. The health and ecological value of these forests depends, in turn, upon the flow regime of the river and the ability of the channel to migrate across its floodplain.

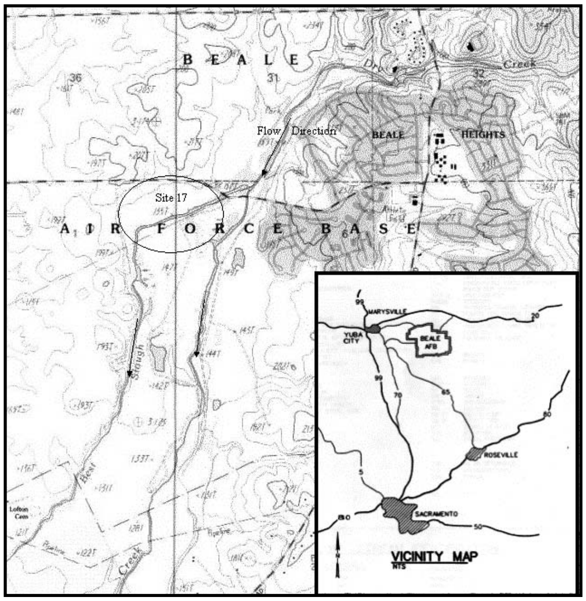
SB1086 is a major program actively engaged in the restoration of the Sacramento River. SB 1086 was passed by the State Legislature in 1986 and called for a management plan for the Sacramento River that would protect, restore, and enhance fish and riparian habitat. The management plan, entitled Upper Sacramento River Fisheries and Riparian Management Plan, was prepared by an Advisory Council and action team. The plan includes both a specific action-oriented fisheries plan, and a more conceptual riparian habitat plan.

The stated purpose of the Upper Sacramento River Fisheries and Riparian Habitat Management Plan (SB 1086 Advisory Council and Action Team 1989) is “to preserve remaining riparian habitat and reestablish a continuous riparian ecosystem along the Sacramento River between the mouth of the Feather River and Keswick Dam.” The management plan introduces the idea of a meander belt along the Sacramento River (in which natural channel migration can occur) in the reach between Red Bluff and Chico Landing, “the most significant area of remaining habitat, as well as the most feasible location for reestablishing a functional Sacramento River riparian ecosystem.” The primary focus of the SB 1086 program has been to work with landowners, the public, and local government to set aside and protect land within the proposed meander corridor. To date, this effort has met with significant success. The SB1086 program is an example of a project that requires no physical modifications to the existing, degraded channel, but rather seeks to create conditions (through the acquisition of riparian lands) where the existing natural processes will be allowed to modify channel and riparian forms.

The Clear Creek Restoration Program

Clear Creek drains 590 km^2 in the Klamath Mountains and northern Coast Range, on the southern edge of Redding, at the northern end of the Sacramento Valley (Figure 1). Its headwaters are impounded by Whiskeytown Reservoir, a large reservoir of the Central Valley project, and part of the system that diverts water from the Trinity River to the Sacramento River. The flows in Clear Creek have been substantially reduced by reservoir regulation, and sand and gravel supply from upstream has been cut off by the dam. In the lower, alluvial reach of Clear Creek, gravel mining in the 1950s through 1980s completely disrupted channel form, leaving large pits, in which the stream channel confinement is lost and fish migration interrupted. A 100-year old dam about 7 mi (10 km) upstream of the Sacramento River confluence was only 20 ft (6 m) high, but blocked upstream migration of salmon to the best spawning and rearing habitats. Most of the Clear Creek floodplain is in public ownership, offering a potential opportunity to restore dynamic fluvial processes.

FIGURE 2. Location map for Best Slough case study. Best Slough is a distributary channel of Dry Creek, carrying overflow from Dry Creek during floods. The rest of the year it drains about 1 km^2 of Dry Creek bottomland



Ecosystem restoration on Clear Creek is being funded by the US Bureau of Reclamation, US Fish and Wildlife Service, and the Calfed Bay-Delta program, and implemented by a local team and their geomorphological consultants. Their approach has been to restore ecosystem processes by removing the dam to permit salmon to access upstream habitats, by seeking to increase the controlled release capacity of Whiskeytown Dam, by adding large quantities of gravel to the stream to compensate for upstream trapping by the dam and losses to mining downstream, by purchasing private land or easements along the creek, and by rebuilding a floodplain in the reach severely affected by gravel mining. Rebuilding the floodplain requires importing large quantities of gravel from piles left by gold dredgers nearby, to provide confinement to the channel. However, the precise dimensions of the channel are not to be designed, but rather to be sculpted by high flows (when they occur). Channel migration is expected to occur, and indeed is desired. The Clear Creek restoration effort is an example of a restoration program that seeks to partially restore channel forming processes of flow and sediment supply, and which includes direct alteration of channel and floodplain form to facilitate the process-based restoration.

Best Slough Realignment and Restoration, Beale Air Force Base

Best Slough is a distributary of Dry Creek (drainage area = 260 km^2), a tributary to the Bear River east of Marysville, California (Figures 1 and 2). At base flow, Best Slough drains approximately 1 km^2 of valley bottom land along Dry Creek, flowing south to join Algodon Slough, and then the Bear River. During floods, Best Slough also carries overflow from Dry Creek, and these overflows are the channel forming discharges in Best Slough. Dry Creek and Best Slough flow through Beale Air Force Base, and historical landuse practices and waste disposal on the base have altered the biological, physical, and chemical characteristics of Best Slough. Cleaning solvents were disposed in trenches in an area designated as “Site 17”, less than 500 feet from Best Slough. These trenches released chlorinated volatile organic compounds, including trichloroethylene (TCE), into the groundwater and soil adjacent to

FIGURE 3. Best Slough in degraded reach, showing simple channel and lack of riparian vegetation. View upstream from right bank. Photo by Tompkins Winter 1998.

FIGURE 4. Oblique aerial view of Best Slough pre-project, showing initial restoration proposal (for a meandering channel) superimposed on photo. Flow is right to left. Photo by Beale Air Force Base Summer 2000.

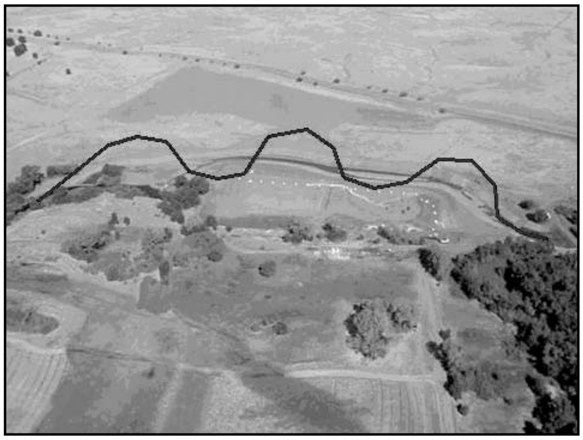
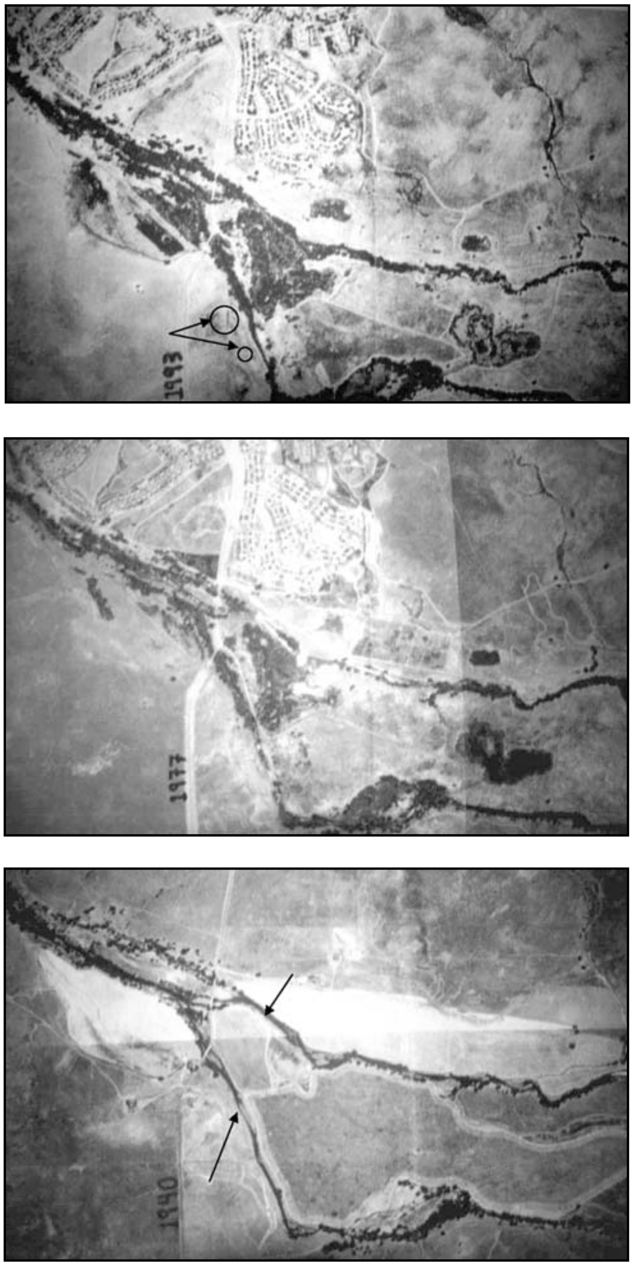


FIGURE 5. Sequential historical aerial photographs of the project site from 1940, 1977, and 1993.



Best Slough. Intensive agriculture modified the riparian corridor at Site 17 through channelization, levee construction, and conversion of riparian and wetland habitats into predominantly non-native, annual grasslands (Figure 3). These alterations created a discontinuity in the high quality riparian habitat upstream and downstream of the site. Site conditions were further complicated by the fact that Best Slough passes through the contaminated source-zone. An Interim Remedial Action was implemented by the U.S. Air Force (USAF) in the Best Slough riparian corridor to contain the TCE plume with an impervious, in-ground slurry wall. The remediation work entailed disturbing and relocating the adjacent reach of Best Slough, so a project to realign and restore Best Slough was funded by the remediation.

However, initial conceptual designs for the realignment and restoration of Best Slough, developed before data collection and analysis, called for creation of a highly meandering channel to improve aquatic and riparian habitat, as illustrated on an oblique aerial photograph of the project site (Figure 4). This concept was supported early in the project because of the perceived aesthetic and habitat benefits such a realignment would have offered.

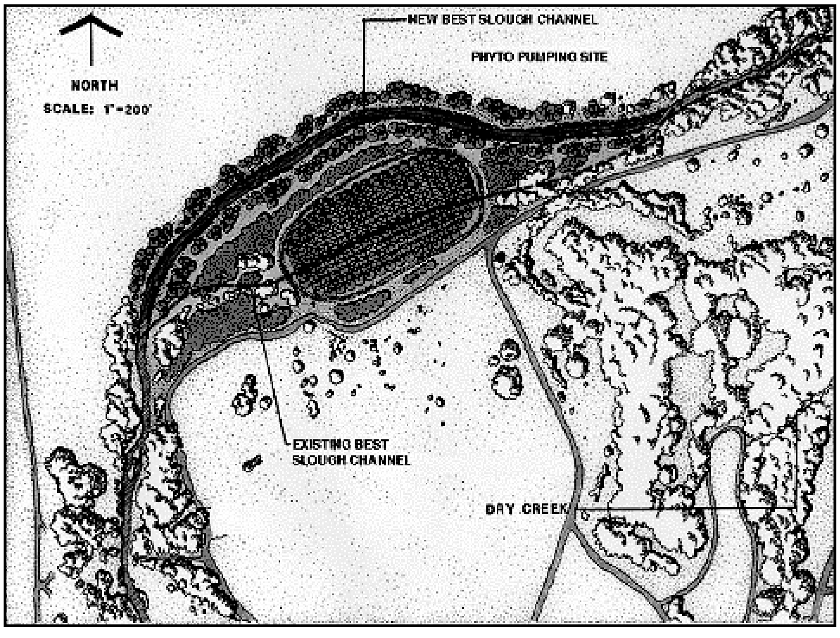
However, an investigation of a set of aerial photos of the project site dating back to 1940 and the hydrology of Best Slough indicated that a meandering channel had never been present at the project site and yielded no evidence to suggest that such a pattern would necessarily be appropriate here. In fact, as shown in Figure 5, Best Slough historically exhibited a relatively straight pattern that was extremely stable over time, not what one would expect to see in a tortuously meandering channel. This relatively simple consideration of the geomorphic processes operating at the project site led to a significantly altered design approach (Figure 6).

The realignment of Best Slough was at its core a stream reconstruction and enhancement project, not a channel stabilization or erosion control project. Thus, based on the geomorphic analysis of former conditions, and given that the catchment runoff and sediment load had probably not changed significantly, a “carbon copy” approach (Brookes and Shield 1996) was adopted in the design of the realigned channel, and the design allowed for natural fluvial processes, including erosion and deposition, to occur to the greatest extent possible in the realigned channel, so long as those processes did not threaten the integrity of the slurry wall.

Some form-based stream restoration elements were included in the final design to “jump start” aquatic and riparian habitat, but the overall guiding principle of the design was the maintenance of the existing natural channel forming processes. It is important to point out that the habitat forms created in the realigned channel were viewed as “raw materials” and were expected to be relocated by the natural processes at work in the system. Critical areas of the realigned channel (i.e. areas adjacent to the slurry wall) were designed so that the magnitude of the impacts of natural processes would be limited. A bioengineered system incorporating biodegradable erosion control fabric, native vegetation, and stone toe protection was designed to protect selected areas without completely eliminating channel evolution. Large wood collected from the project site was also installed in portions of the new channel to provide cover during the establishment period of the new vegetation. Again, the natural materials installed in the new channel were placed with the understanding that they would not be permanent, and that in fact some distribution of the materials throughout the channel would be a positive. The realignment and restoration was completed in June 2000, and already the discontinuity in the riparian corridor is disappearing. Figure 7 shows the successful blending of the realigned channel with the high quality riparian and aquatic habitat downstream of the project site. The Best Slough realignment and restoration project was an example of the efficiency of natural processes in the development of habitat in reconstructed channels.

Discussion

The idea that natural processes must be accounted for in the restoration of stream and riparian systems should not come as a surprise. However, because fluvial processes are not always apparent, many designers of stream and riparian restoration projects continue to focus on form over process. This drawback of form-based restoration has received increased attention in the literature and amongst the professionals in the field. To the extent that the attraction of cookbook, form-based restoration approaching is a question of education and awareness, it may become less pervasive over time. To the extent it reflects a paradigm shift in riparian restoration from form-based design to natural process-based design will reveal a new set of restoration constraints, such as drastically altered flow regimes to heavily constrained stream corridors. Grappling with these constraints may force restoration designers to come to better understand the magnitude of restoration actually



.Figure 6. Final conceptual design for realignment of Best Slough.

FIGURE 7. Best Slough, looking downstream along realigned channel to original Best Slough.
Photo by Tompkins Fall 2000.

possible in a given stream. For example, the natural fluvial processes at work in a heavily constrained and urbanized watershed may not be able to produce desirable channel forms over the long term, despite actions taken to facilitate those natural processes. Recognizing these constraints may require a shift in traditional views of "healthy" streams and riparian zones, as some channel forms may simply be impossible to maintain in constrained, urban-channels without resort to heavy stabilization. To the extent that resources are directed to restoring fluvial processes and rather than construction of channel forms, the constraints may diminish with time.

In the meantime, restoration designers should strive to rely on existing or enhanced natural processes to do restoration work and then begin to gauge the magnitude of the response of channel forms to constrained processes. Research is needed to better understand the effectiveness of facilitating natural processes in highly constrained urban stream corridors. Research and pilot projects are needed to assess the potential of rescaling channels to function under a changed flow regime, such as smaller channels below large dams, or larger channels below urbanized watersheds. The Calfed Bay-Delta Ecosystem Restoration Program, which provided funding for the Clear Creek and Sacramento River projects reported here, has adopted a strategy calling for restoration of ecosystem processes where possible, and implementation of pilot projects to test restoration approaches under an adaptive management framework (Calfed 2000).

The rate at which process-based restoration becomes the standard approach in the restoration of stream corridors will depend on the extent to which form-based and process-based stream and riparian restoration projects are monitored and reported. Without quantitative evidence of the successes and failures of each approach, it will be difficult to convince project stakeholders of the benefits associated with a process-based approach.

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