

LOWLAND RIVER-FLOODPLAIN SYSTEM GEOMORPHIC MONITORING AND ADAPTIVE ASSESSMENT FRAMEWORK: SEDIMENT CONTINUITY AND TRENDS, COSUMNES RIVER, CA

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INTRODUCTION

In California's Central Valley, almost 4,000 km² of floodplain riparian habitat have been converted to agriculture and other land uses over the past two centuries (TBI, 1998). Changes in sediment supply and channel-floodplain connectivity resulting from land use changes that accompanied this transformation has contributed to a significant decline in biocomplexity, culminating in the listing of multiple threatened and endangered aquatic and terrestrial species. The progressive loss of floodplain habitat has led to considerable recent efforts, such as the joint federal-state-stakeholder effort (CALFED, 2000), to restore habitat in lowland portions of the Sacramento-San Joaquin River watershed. However, to date, there has been no development of a long-term adaptive monitoring, assessment, and management framework to advance the science needed to assess the effectiveness of the floodplain restoration effort in the lowland Central Valley. In this paper, we propose a framework for monitoring and adaptive assessment of a distinctive floodplain restoration project implemented by the Cosumnes River Preserve Partners in the lowland Cosumnes River, CA (Fig. 1). This framework is applied to a geomorphic monitoring program for the lower Cosumnes River, but it can be adapted to a range of monitoring or assessment objectives in other lowland rivers.

The objectives of the restoration project evaluated in this paper included reestablishment of hydrologic and geomorphic processes necessary to sustain floodplain ecosystem attributes by intentionally breaching levees along the Cosumnes River at the Cosumnes

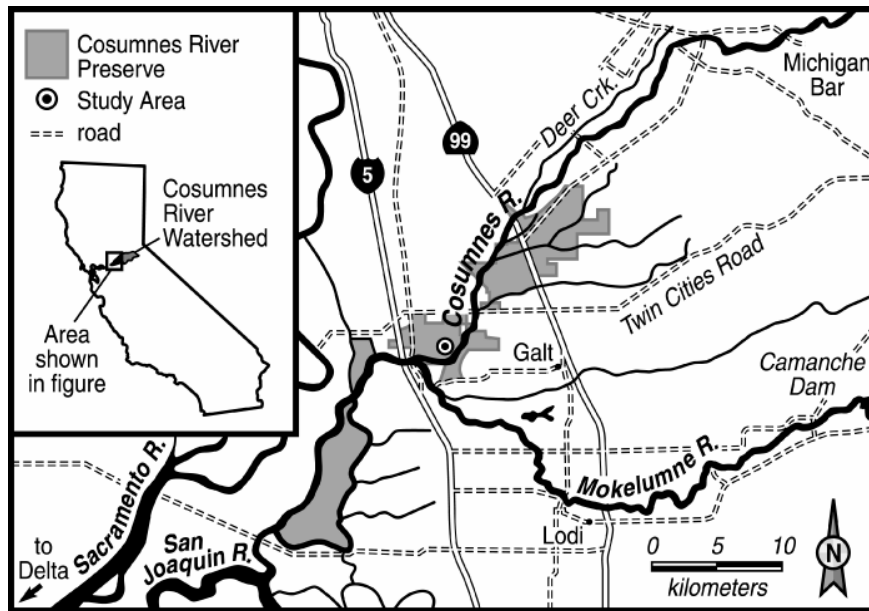


Figure 1. Cosumnes River basin showing the location of the Cosumnes River Preserve floodplain restoration area and the lower Cosumnes River upstream of and adjacent to the Preserve.

River Preserve (Fig. 1). We address this objective through evaluation of longitudinal and lateral sediment continuity in the downstream 52.7 km of the lowland Cosumnes River with particular emphasis on continuity between the main channel and floodplain at intentional levee breaches at the Cosumnes River Preserve. The scope of this monitoring paper covers the geomorphic component of an applied interdisciplinary research program underway by the UC Davis Cosumnes Research Group (<http://watershed.ucdavis.edu/crg/>). The purpose of this paper is three-fold: 1) to help answer a critical question at the intentional levee breaches at the Cosumnes River preserve, namely, what is the linkage between upstream channel alteration and downstream sand splay complex evolution in the floodplain restoration area?; 2) to provide an example of how knowledge gained from detailed assessment of historical trends and baseline geomorphic conditions following construction of the intentional levee breaches in the Cosumnes system is used to define specific geomorphic monitoring elements needed for long-term assessment; and 3) to present an overall monitoring framework relevant to habitat restoration and integrated ecological research in lowland rivers with floodplains. While this strategy includes design of geomorphic monitoring

elements specific to the unique attributes of the Cosumnes River system, the overall long-term geomorphic monitoring and adaptive assessment framework may be utilized in other river-floodplain systems in California's Central Valley or in lowland river systems in other areas.

In many lowland rivers, anabranching channel networks formed by episodic avulsion dominate floodplain geomorphology. Lateral connectivity during floods is critical in multiple channel networks as it accounts for creation and maintenance of floodplain topography, or the physical structure of habitat in a linked channel-floodplain system (Bravard et al, 1985; Amoros et al, 1987; Petts, 1990; Pinay et al., 1990; Sparks et al., 1990; and Wissmar and Swanson, 1990; Bayley, 1990; Stanford et al., 1996; Florsheim and Mount, 2002). While a hierarchical classification of stream reach morphology that reflects fluvial processes in steep channels provides a framework for monitoring processes and changes in mountain rivers (Montgomery and Buffington, 1997; Montgomery and MacDonald, 2003), a monitoring protocol addressing geomorphic processes in lowland river-floodplain interactions have received less attention. In order to address this gap, we utilize recent detailed field investigations of post-project "baseline" geomorphic conditions in the Cosumnes River and the floodplain restoration area during the first several years after the levee breaches were constructed (Constantine, 2001; Florsheim and Mount, 2002; Florsheim and Mount, 2003; Constantine et al., 2003). These studies provide the rationale for selection of geomorphic monitoring elements needed for science-based adaptive assessment. In this paper, we propose a phased monitoring and adaptive assessment framework appropriate to document geomorphic changes in lowland river systems with floodplains.

WATERSHED CONTEXT OF RESTORATION AREA

Project Setting

The floodplain restoration area at the Cosumnes River Preserve is located in the downstream-most reach of the Cosumnes River (Fig. 1). The Cosumnes River (drainage

basin area $\sim 3,000 \text{ km}^2$) drains the Sierra Nevada and flows southwest across the Central Valley to its confluence with the Mokelumne River upstream of the Sacramento-San Joaquin River Delta (Fig. 1). Today, most of the Lower Cosumnes River channel is fixed in place by levees and agricultural activity dominates the floodplain. Because there are no large dams on the Cosumnes River, longitudinal connectivity is relatively intact. In contrast, levees separate the river from its floodplain along most of the lowland reaches, inhibiting lateral connectivity except during accidental breaches such as the numerous breaches that occurred during the 1997 flood (DWR, 1997).

A schematic diagram of the watershed context of the Cosumnes River floodplain restoration area is illustrated in Fig. 2. This watershed context delineates the critical linkage between: 1) the alluvial and incised segments of the Cosumnes channel upstream of the restoration reach; 2) the floodplain within or immediately adjacent to the restoration reach; 3) the input, or supply of sediment and water from the upstream basin; and 4) the output, or yield of sediment and water to the downstream Mokelumne-North Delta system. This context promotes flexibility and adaptation of the design to utilize data from concurrent sediment monitoring programs in the forested headwaters (Coe and Macdonald, 2002), at the Michigan Bar gaging station (Meyer, USGS personal communication, 2002), and in the downstream Mokelumne River-Delta Islands (Shmutte, California Department of Water Resources, personal communication, 2002).

The Cosumnes River has a relatively natural winter rainfall and spring snowmelt hydrograph, in contrast to adjacent watersheds with multiple large dams that regulate flow. Thus, the Cosumnes basin provides a unique opportunity to attempt restoration of floodplain processes in a fluvial system that still receives annual winter and spring flood pulses. Taking advantage of the opportunity to restore seasonal flooding to portions of the floodplain at the Cosumnes River Preserve, the Cosumnes River Preserve Partners initiated the experimental floodplain restoration program by breaching levees on the right

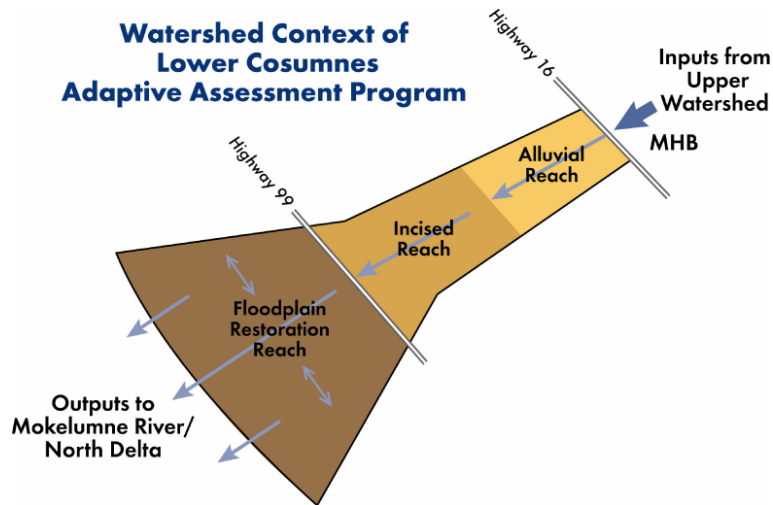


Figure 2. Watershed context of study area showing the linkage between the Cosumnes River channel and the downstream Preserve, the upstream source area, and the downstream Mokelumne system.

bank of the river (Fig. 3). The first intentional levee breach was opened in Fall 1995 at the “Accidental Forest” floodplain. Two years later, in Fall 1997, a second breach was constructed upstream at the “Corps Breach” floodplain as part of a long-range watershed plan (The Nature Conservancy, 1992). Secondary breaches at these sites either convey relatively little water and sediment into the restoration area, as at the Accidental Forest floodplain or are apparently becoming dominant, as at the Corps Breach floodplain.

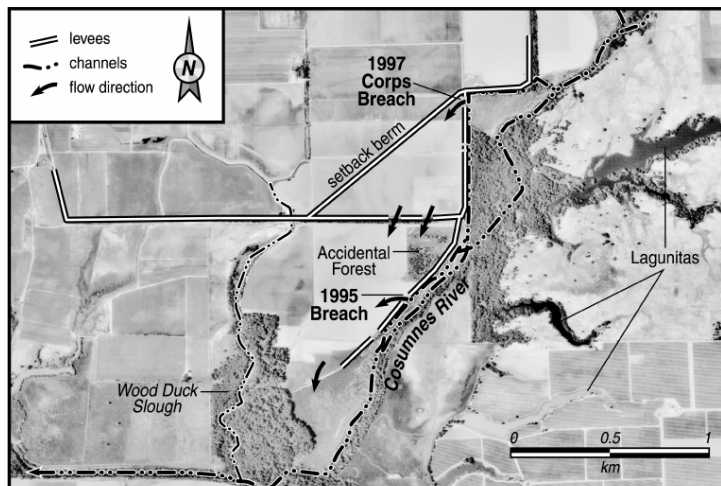


Figure 3. Locations of Corps Breach and Accidental Forest floodplain levee breaches at Cosumnes River Preserve.

Pre-Disturbance Conditions and Land use Alteration

The Cosumnes River Preserve is located upstream of the confluence with the Mokelumne River in the lowland portion of the river and floodplain system that was once a seasonal marsh. Prior to European settlement, the lower Cosumnes River floodplain ecosystem consisted of multiple channels associated with dense riparian forests. Inter-channel floodplain islands contained natural levees, splay complexes, seasonal marshes, and perennial floodplain lakes (Florsheim and Mount, in press). These landforms supported a riparian ecosystem that extended across most of the floodplain, and remnants of the once thriving valley oak forest remain along the natural levees of former channels at the Cosumnes River Preserve. Dynamic geomorphic and hydrologic processes such as avulsion, sediment erosion, deposition, and seasonal flooding created the natural disturbances that modified and sustained ecosystem attributes in this complex anastomosing river habitat (Florsheim and Mount, 2003).

Levee construction and agricultural leveling during the past century concentrated flow from the multiple channel system into a main channel isolated from its floodplain. While hydraulic mining in the Sierra Nevada and dredging for gold in the lowland riparian zones once increased sediment supply to the study area (Florsheim and Mount, 2003), current aggregate extraction reduces supply. Grazing, timber harvest, riparian forest clearing, floodplain agriculture, water diversions, woody debris removal, and urbanization upstream of the restoration project reach further influence fluvial processes and ecology. The magnitude of change in the annual sediment budget related to these land uses has not been documented at this time, but should be addressed in the long-term monitoring program proposed in this paper.

Baseline Conditions

Cosumnes River Upstream of Floodplain Restoration Area

Comparison of early topographic data and recent surveys shows that the Cosumnes River between Hwy 16 and Twin Cities Road (Fig. 1) has undergone two to three meters of

incision since the early 1900's. Recent surveys between the upstream Hwy 16 to Meiss Road reach suggest that channel adjustment has shifted to aggradation, while in the downstream reach between Meiss and Twin Cities Roads the trend of channel-bed lowering persists (Constantine et al., 2003). In both reaches, connectivity between the main Cosumnes River channel and the adjacent floodplain is inhibited. In the upstream aggrading reach, where erosion of unconsolidated coarse sand to cobble-sized alluvial banks contributes sediment to the river, the wide channel and relatively high banks increase channel capacity and minimize floodplain inundation. In the incised reach downstream, the enlarged channel and agricultural levees contains moderate floods within the channel without overflowing onto the floodplain. Where present, agricultural levees are lateral barriers, and floodplain inundation only occurs during accidental breaches. The loss of channel-floodplain connectivity upstream of the restoration project reach is presumed to have an impact on hydrologic, water quality, geomorphic, and ecologic conditions within the restoration area. To date, however, these impacts have not been quantified and represent an important information gap that should be addressed in the long-term monitoring program.

Another significant effect of incision upstream of the restoration area is the alteration of the self-formed alluvial river morphology into a river that behaves as a rock-controlled channel due to exhumation of indurated duripan layers. A knickzone formed by incision into bedrock and duripan separates the aggrading channel bed upstream of Meiss Road from the incised reach downstream (Fig. 4). Resistant duripan outcrops, as well as numerous engineered diversion weirs, affect channel gradient, channel geometry, patterns of sedimentation, and pool spacing. In the incised reach (between 18 km upstream of Wilton and 32 km ~Hwy. 99), where duripan or erosion control structures increase bank stability, cross section geometry is characterized by low width to depth ratios. The narrow and deep incised geometry augments the ability of the channel to transfer material downstream and sediment transport achieves equal mobility at or below bankfull discharge, defined as the flow with recurrence interval ~1.5 to 2.0 years. In this reach, all material supplied is transported downstream regardless of size, with only minimal

transient sediment storage in bedforms such as riffles. Moreover, where present, the indurated or artificially hardened banks limit sediment supplied from bank erosion in the reach downstream of Meiss Road.

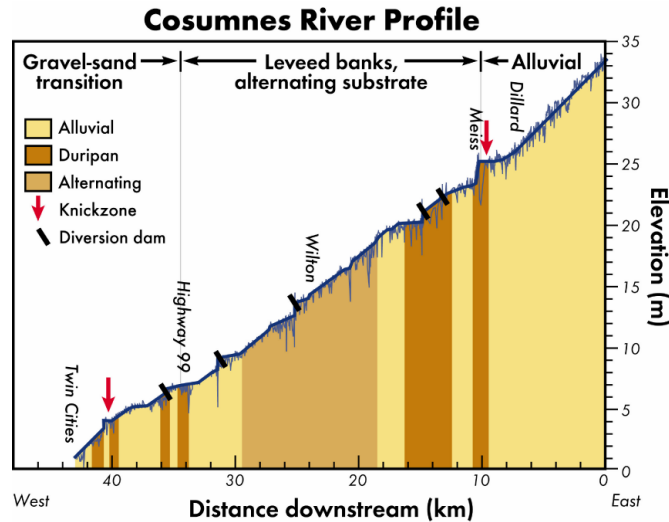


Figure 4. Cosumnes channel longitudinal profile and downstream variation in substrate showing location of knickzone formed by incision into bedrock and duripan that separates the alluvial channel bed upstream of Meiss Road from the incised reach downstream.

Channel incision and exposure of duripan layers has a significant impact on grain size and sediment transport upstream of the project reach. Longitudinally, the median grain size of bed sediment follows an exponential fining pattern with a diminution coefficient of 0.074 per kilometer in a 42.8 km reach downstream of Hwy. 16 (Constantine, 2001), with local variation due to deposition upstream of weirs or duripan knickpoints. The gravel sand transition is evident in the lower Cosumnes River over a 9 km long reach between ~30 and 39.2 km. Based on the work of Constantine (2001) this represents a 10-15 km downstream shift in the gravel-sand transition over the past century. While some gravel is present downstream of Twin Cities Road, the bed of the channel primarily consists of sand. Further downstream shifts in the gravel-sand transition may influence sediment supplied to the Cosumnes River Preserve floodplain restoration site.

Floodplain Restoration Area at the Cosumnes River Preserve

Documentation of floodplain processes at the intentional levee breaches at the Cosumnes River Preserve restoration areas suggest that sand splay complex development re-established floodplain topography over the previously leveled agricultural fields during the first several years after the breaches were opened (Florsheim and Mount, 2002). Two intentional levee breaches along the lowland Cosumnes River, Central Valley, CA, were assessed through detailed field work during water years 1999 and 2000 in order to document changes in morphology and relief, or topography associated with deposition of sand splay and channel complexes on the floodplain. Rapid vertical accretion and scour occurred within the first several years after intentionally breaching the levees. The new topography creates habitat variability and is the physical structure of habitat critical for restoration in the previously level agricultural field.

The morphology of the splay complexes is organized as landforms including lateral levees, lobes and main and secondary channels (Fig. 5 and Fig. 6). Results of the baseline study documented that the maximum short-term deposition rate measured on the splay surface is 0.36 m/yr while maximum scour rate in channels is 0.27 m/yr (Florsheim and Mount, 2002). A breach scour zone immediately inside the breaches lowers floodplain elevation at the heads of new floodplain channels. Relief becomes more pronounced over time as higher magnitude floods scour channels in the old floodplain sediment and deposit new sand and silt onto the surface of the splay. Juxtaposition of floodplain splay deposition and adjacent channel scour created initial relief ranging from ~1.6 to 0.25 m with the greatest relief closest to the breach. Progradation of main and secondary splay channels takes place by sand transport in the down-floodplain direction, extending topographic variation over the previously level agricultural fields. Additionally, large wood transported onto the floodplain through the breaches promotes local scour and deposition that enhances topographic variability. Initial grading of a low setback berm and excavated pond at the Corps Breach floodplain prior to opening the breach influenced floodplain flow direction and the geometry of the splay complex, while the excavated pond acts as a sediment trap that stops progradation of the splay complex.

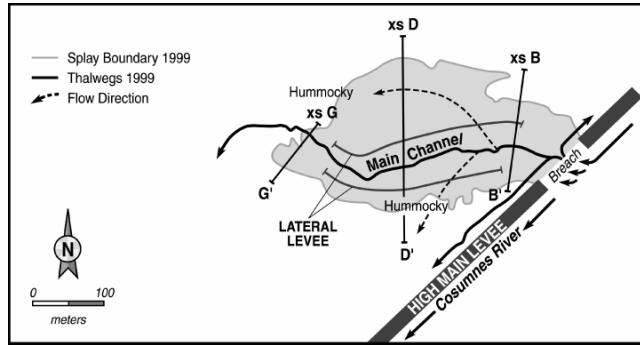


Figure 5. Morphology of the floodplain restoration area splay complexes is organized as natural lateral levees, lobes, and main and secondary channels.

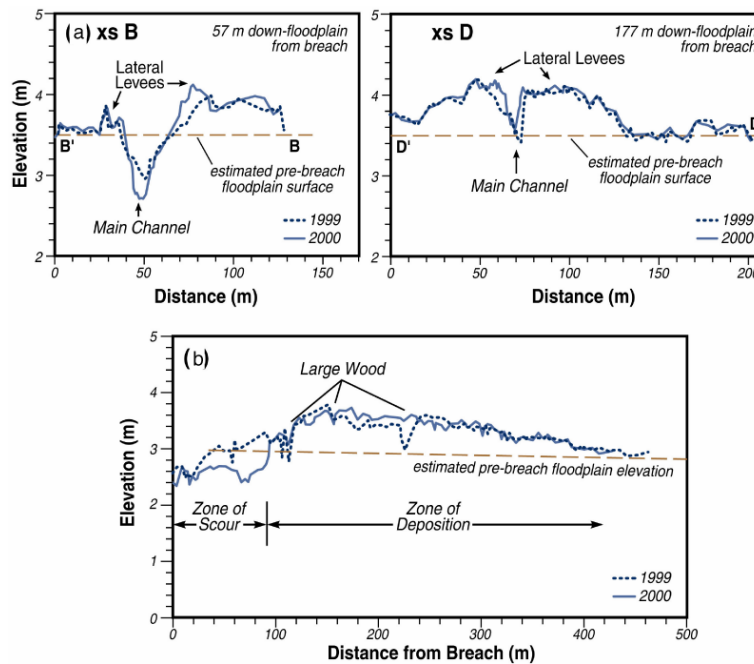


Figure 6. (a) Transects showing sediment deposited and channels incised in the splay complexes (b) Profiles shows near breach scour and deposition decreasing in the down-floodplain direction.

Main Channel Adjacent to Intentional Levee Breaches

Incision in the reach of the Cosumnes River adjacent to the floodplain restoration area at the Cosumnes River Preserve is substantially less than in the reach upstream, and may be related in part to local aggregate extraction (Constantine, 2001). In this downstream

reach of the river in the vicinity of the Cosumnes River Preserve, floodplain inundation occurs frequently in areas where levees are absent. Documentation of channel geometry in the main Cosumnes River and secondary channels adjacent to the floodplain restoration area suggest that sediment transport onto the floodplain through the intentional breaches affects main channel morphology. Cross sections surveyed upstream and downstream of the breaches in the main and secondary channels illustrate minor changes during water years 1999 and 2000, however, the geometry suggests that sediment is eroded from the bed of the main channel upstream and deposited downstream of the two main intentional levee breaches.

LONG-TERM GEOMORPHIC MONITORING AND ADAPTIVE ASSESSMENT AND MANAGEMENT FRAMEWORK

A Lowland River Monitoring and Adaptive Assessment Framework

In this paper, we utilize our understanding of the watershed context of the restoration area, to develop a three-phase framework for organizing historical and baseline data and analyses within the context of the physical characteristics unique to the Cosumnes basin, its legacy of land use disturbances, and most importantly, the goals of the levee breach restoration project at the Cosumnes River Preserve (Fig 7). The framework is intended to provide a mechanism to facilitate data analysis, interpretation, and communication through integration of the physical and biological aspects of ecosystem function, processes, and habitat. The framework indicates that development of the restoration project design should follow documentation of pre-disturbance conditions and baseline studies. However, as in many other restoration projects, the Cosumnes River floodplain restoration project design and implementation preceded the other elements. The following sections define the original goal of the Cosumnes River Preserve floodplain restoration project and the applicability of the reference condition concept towards the Cosumnes project monitoring design prior to discussion of the watershed context of the

monitoring area, research hypotheses and monitoring goals, and development of the monitoring design.

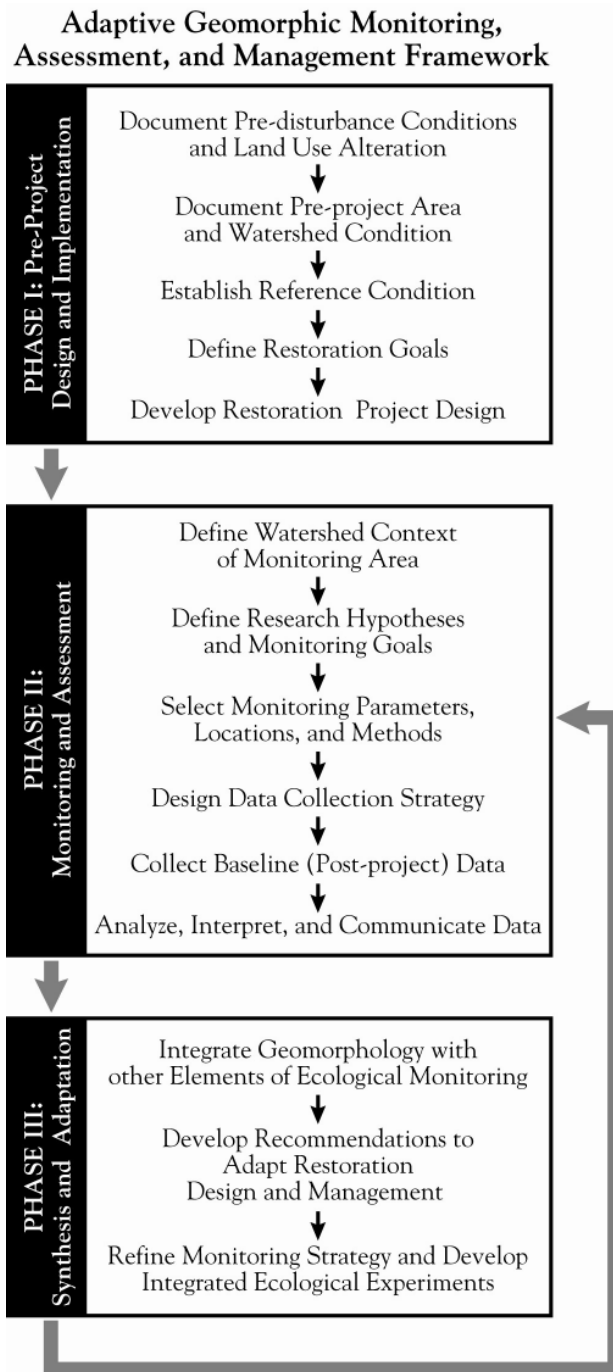


Figure 7. Adaptive monitoring, assessment, and management framework for lowland Rivers.

Restoration Goals

The Restoration goal defined prior to construction of the intentional breaches at the Cosumnes River Preserve was straightforward: restore hydrologic connectivity between the main Cosumnes River channel and adjacent floodplain in order to promote riparian habitat (TNC, 1992). This goal was based on observations following a levee breach along the lower Cosumnes River in 1985 that resulted in establishment of an “Accidental Forest,” a patch of cottonwood (*Populus fremontii*) and several species of willow (*Salix*) coincident with $\sim 0.06 \text{ km}^2$ sand deposited inside the breach (Rich Reiner, TNC, personal communication, 2001). This previously farmed area that included the Accidental Forest was later added to the Cosumnes River Preserve and in effect provided a physical model for habitat creation at the intentional levee breaches. Later work showed that connectivity promoted by the breaches are crucial for supporting native fish use of the floodplain (Crain et al., in press), and the restoration goals have evolved in response to acquisition of this new knowledge.

Reference Condition

Monitoring schemes often define a reference condition, or an unchanged site to use as a comparison to help assess and interpret the magnitude and causes of change documented by the monitoring data. Approaches utilized in other studies include: 1) an upstream-downstream comparison; 2) comparison to an adjacent watershed or to regional reference sites (Conquest and Ralph, 2001); or 3) comparison to pre-disturbance conditions. The concept of a reference site is useful because it may be used as a measure of the potential of an area to recover (Frissell and Ralph, 2001) and as a guide to what type of ecosystem attributes may be restored.

An upstream-downstream reference condition is not feasible in the lowland Cosumnes River, because of the disparate nature of the floodplain and adjacent channel at the Cosumnes River Preserve vs. the nature of the floodplain and channel in the upstream incised reach. Moreover, a paired watershed or regional reference site selection is not possible because of the Cosumnes River’s unique status as the largest unregulated river

draining the west side of the Sierra Nevada. For example, while the current flow regime of the Cosumnes basin is sufficient to inundate the lowland floodplain for habitat rehabilitation, in contrast, neighboring watersheds, such as the Mokelumne and American cannot be used as a references because dam releases are regulated to prevent inundation of downstream floodplain areas. Thus, for the Cosumnes geomorphic monitoring program, we select the pre-disturbance condition as a reference to understand the dominant processes active in the system prior to changes associated with land use activities. This selection does not imply that the Cosumnes River floodplain will be restored to its pre-disturbance condition. Rather, understanding the dominant processes prior to anthropogenic changes is valuable because it aids in our understanding of potential changes at the Cosumnes River Preserve as constraints such as levees are removed. Analysis of the pre-disturbance and baseline data helps define the dominant geomorphic processes needed for sustainable floodplain restoration, namely: floodplain inundation, erosion, sedimentation and avulsion.

Watershed Context of Monitoring Area

In order to design, construct, and evaluate ecosystem restoration programs it is essential that the hydrogeomorphic and ecologic setting of the project be fully documented. Identification of hydrologic, geomorphic, and ecologic processes that are likely to impact the project in the future helps constrain what habitat conditions can and cannot be reasonably expected. The key elements to document within the watershed context include: an overview of the watershed scale project setting, pre-disturbance conditions of the project site, and documentation of “as-built” or baseline conditions following project completion. The watershed context for monitoring the Cosumnes River Preserve levee breach restoration project includes the sand splay complexes at the Cosumnes River Preserve as well as the 52.7 km of river upstream and adjacent to the project area.

Research Hypotheses and Monitoring Goals

The goal of the long-term geomorphic monitoring program is to test the hypothesis that intentional levee breaches, sometimes called ‘non-structural management measures,’

restore or rehabilitate geomorphic processes in the lowland Cosumnes River channel and floodplain system at the Cosumnes River Preserve. Testing this hypothesis has bearing on restoration of floodplain ecotone habitat for aquatic-terrestrial species. The geomorphic monitoring program stems from the premise that longitudinal sediment continuity between upstream and downstream reaches and lateral connectivity between the channel and floodplain at the Cosumnes River Preserve, link upstream morphologic alteration to sediment supply delivered to the sand splay complexes at the restoration area. Because the sand splay complexes form the physical structure of new habitat, quantifying upstream channel changes that affect sediment supply to the floodplain restoration area is of critical importance.

Monitoring Parameters, Locations, and Methods

Watershed Overview

We utilize our understanding of historical trends and analyses of baseline conditions to define monitoring parameters to test the hypothesis that intentional levee breaches rehabilitate or restore geomorphic processes on the Cosumnes River Preserve floodplain. The approach for selecting parameters requires identification of the appropriate spatial scale over which the dominant processes operate, both within the restoration area and in the upstream channel. However, the watershed context—or the entire area—affecting parameters within the monitoring area must be considered. Therefore, prior to initiating each cycle of the field-monitoring program in the downstream 52.7 km of the lowland Cosumnes River and floodplain, a reconnaissance level watershed overview should be conducted. This overview is intended to identify upper watershed processes such as wildfire or land uses such as timber harvest activities, that alter sediment supply to the monitoring area, local levee construction, breaching, or removal, the addition or removal of bank protection structures, channel or floodplain gravel extraction, changes in agricultural activity, changes in riparian vegetation, or conservation measures. Moreover, changes downstream of the monitoring area such as Delta Island rehabilitation through levee breaches could influence upstream hydrology through modification of the

backwater effect, and should also be considered. This watershed scale reconnaissance may be accomplished using aerial photographs and field observations.

The monitoring design for the upstream and downstream reaches of the Cosumnes River channel and floodplain will sample sensitive indicators of geomorphic processes that affect restoration. Monitoring of these elements will illustrate the effect of a levee breach on floodplain sedimentation and erosion patterns. Results of the geomorphic monitoring would be integrated with the results from other ecological monitoring.

Cosumnes River Upstream of Floodplain Restoration Area

Selection of monitoring parameters in the Cosumnes River upstream of the restoration area (Table 1) is intended to provide data that may be used to understand the effect of upstream channel alteration on the floodplain restoration area over time. Through geomorphic and topographic mapping, analysis of repetitive profile and cross section surveys, and the distribution of grain sizes, the monitoring program will address changes in channel morphology, transport capacity, and local sediment supply and storage. Baseline data suggest that significant incision altered the profile and particle size distribution of sediment in the Cosumnes River effectively changing the alluvial channel to a non-alluvial channel in some segments. Monitoring future changes in the longitudinal profile, cross sections, and topography in incised and non-incised reaches upstream of the preserve will afford quantification of the magnitude and rates of change and help our understanding on the role of longitudinal connectivity between the upstream channel and downstream restoration area.

Table 1. Parameters to Consider Upstream of Floodplain Restoration Area

Parameter	Method	Analysis
Morphology	Low altitude aerial photo and geomorphic map Surveys: Longitudinal profile Channel topography	Magnitude and frequency of channel planform change Changes in geomorphic attributes: pool to pool spacing, patterns of sedimentation or scour, riffles, pools, bars, steps, woody debris
Gradient	Surveys: Longitudinal profile	Changes in: gradient, profile shape (e.g. convexity)
Bed elevation	Surveys: Longitudinal profile Cross sections Sub-reach topography	Changes in location and rates of deposition, incision
Exposure of duripan	Surveys: Longitudinal profile	Location and extent of non-alluvial channel structure
Channel geometry	Surveys: Cross sections	Changes in width to depth ratio
Bank erosion and local sediment supply	Surveys: Cross sections, erosion pins Aerial photographs Field reconnaissance	Changes in sediment erosion rate, production volume
Grain size distribution	Surface and subsurface sediment samples	Downstream fining, diminution coefficient, gravel sand transition, sorting, pavement ratio
Hydrology	Analysis of USGS gaging station records (at Michigan Bar)	Discharge (Q), flow duration, flood frequency, changes in timing of flow, rates of change
Transport capacity and shear stress	Surveys: Longitudinal profile Cross sections Grain size sampling	Dimensionless shear stress (τ^*) Stream power per unit width ($\omega = \gamma QS/w$)
Large woody material	Mapping, EDM surveys of topography	Changes in distribution, extent of log jams, wood volume

Floodplain Restoration Area

Selection of monitoring parameters in the floodplain restoration area is identified in order to document long-term changes (Table 2). Through analysis of repetitive maps, photographs, longitudinal profile and cross section surveys, grain size distribution, and flow and sediment transport measurements data will document sand splay and channel complex change over time. Our baseline data suggest that future floods that transfer water and sediment onto the floodplain restoration area through the breaches will continue to incise new channels, aggrade lobes and lateral levees, prograde down-floodplain, and in general contribute to the physical variability needed to restore floodplain habitat. However, considerable uncertainty related to sediment storage and supply from the upstream channel, the influence of newly established vegetation, and local morphologic changes could cause the breaches to plug or become ineffective in transporting water and sediment onto the floodplain. Topographic surveys, maps,

profiles, and transects will quantify rates of change in sediment deposition, incision, and progradation of the sand splay and channel complexes and to related these changes to adjustments in the upstream channel.

Table 2. Parameters to Consider in Floodplain Restoration Area Sand Splay Complex

Parameter	Method	Analysis
Topography (morphology and relief)	Low altitude aerial photo and geomorphic map EDM surveys: Topography of sand splay complexes Lidar, Avaris or similar high resolution spectral image	Extent of splay complex, changes in topographic complexity, changes in elevation and distribution of new surfaces Morphology: pattern of sediment deposition and erosion: scour zone, new floodplain channels, lobes, lateral levees Relief: height from thalweg of new floodplain channels to adjacent splay surface Floodplain elevation relative to main Cosumnes River channel thalweg elevation (I)
Breach geometry	EDM surveys: Breach cross section, scour zone topography	Evolution of breach geometry, incision, plugging
Floodplain channel bed elevation	EDM surveys: Longitudinal profiles Transects	Deposition, erosion, bedforms
Floodplain gradient	EDM surveys: Longitudinal profiles	Gradient, profile shape
Lobe and lateral levee depositional rate	EDM surveys: Transects Topography	Deposition, erosion
Progradation rate	EDM surveys: Transects Topography	Change in extent
Grain size distribution	Surface and sub-surface bulk samples	Spatial variability on surface of splay complex, layering of strata
Effect of initial grading	EDM surveys: Transects Topography	Effect of setback berm, excavated pond
Flow and sediment transport onto floodplain	Flow velocity and stage recorders ISCO sampler; ADCP	Flow magnitude (Q), depth (d), duration (Q_{dur}); timing, rate of filling and draining, compare to upstream gaging station hydrology Sediment concentration or bedload transport flux(Q_s)

Main Channel Adjacent to Intentional Levee Breaches

The main parameter to consider in the main Cosumnes River channel adjacent to the floodplain restoration area is bed elevation. The question to answer through analysis of repetitive EDM surveys (Table 3) is how do the levee breaches affect main channel morphology? Our baseline data suggest that incision occurs upstream and aggradation occurs downstream of the breaches. Thalweg longitudinal profiles, cross sections, and topography will provide data to quantify local changes in channel gradient, aggradation

and incision, width to depth ratio, and bedform alteration. An additional factor to consider is large woody debris, as debris jams may lead to levee breaches and avulsion.

Table 3. Parameters to Consider in Main Channel Adjacent to Intentional Levee Breaches

Parameter	Method	Analysis
Bed elevation	EDM surveys: Longitudinal profile Cross section Topography	Changes in gradient Changes in w/d; rates of deposition, erosion bedforms
Large woody material	Mapping, EDM surveys of topography	Changes in distribution, extent of log jams, wood volume

Data Collection Design: Frequency and Timing-When to Monitor

A continuous long-term monitoring program would identify critical periods or events responsible for changes in morphology of the Cosumnes River and floodplain. However, continuous monitoring would likely be cost-prohibitive. Alternatively, geomorphic monitoring designs often suggest periodic data collection annually, biannually, or every three to five years. However, in the episodic Mediterranean climate of California's Central Valley, such prescriptions could result in either missing important responses if significant events occur between sample dates, or alternatively, needlessly sampling during drought periods when the recurrence interval of significant events is longer than the period between selected sample years. Additionally, geomorphic thresholds can confound attempts to predict when and to what extent erosion and sedimentation processes will occur and effect sediment supply. While predicting future climate and system responses at the initiation of a monitoring program is not possible, some direction toward when measurements should be taken is necessary to initiate the adaptive monitoring, assessment, and management program.

In order to optimize the monitoring design for future data collection in the lowland Cosumnes system, we propose a process-based monitoring trigger based on the range of flood event magnitudes and duration that construct and modify the sand splay complexes inside the intentional levee breaches. This approach focuses attention on the transfer of water and sediment from the upstream main Cosumnes River channel onto the floodplain at the Cosumnes River Preserve. During the years since the initial levee breach at the

Cosumnes River Preserve, a range of flow magnitudes occurred, from the highest during WY 1997, to one of the lowest during WY 2001 (Figure 8). During the period of baseline data collection, annual peak flow recurrence intervals ranged from ~1 to 3 years, and water flowed through the breaches for a minimum of 55 days during water year 1999 and 53 days during water year 2000. These field observations suggest that the threshold of connectivity occurs when flow magnitude exceeds ~23 to 25.5 m³/s and that the threshold of sediment transport from the main Cosumnes River channel through the breach onto the floodplain occurs when flow magnitude exceeds ~100 m³/s. While seasonal connectivity during small floods maintains new habitat established in the floodplain restoration area (Mount et al, 2002; Moyle et al., 2003; Grosholz, 2003; Trowbridge, 2003), flow through the breach must exceed the sediment transport threshold in order to create and maintain floodplain topography formed by the dynamic sand splay complexes. The duration of these moderate to large sediment transporting floods is likely to be a critical factor contributing to morphologic adjustment by deposition of sediment

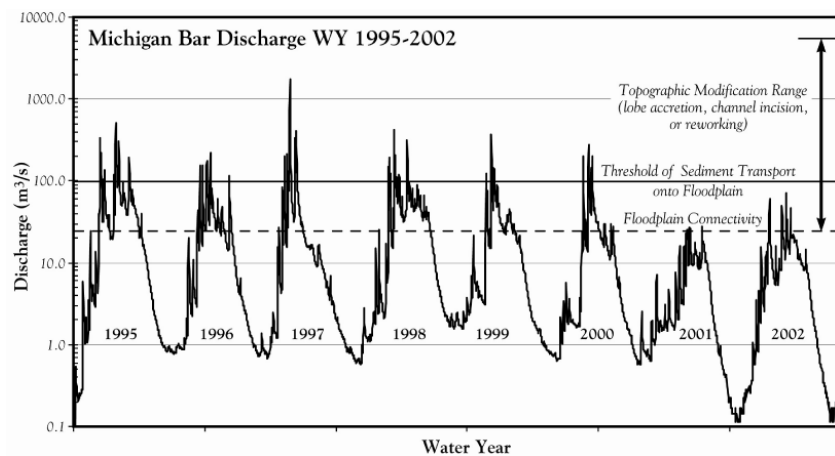


Figure 8. Hydrograph showing flow magnitude during the period from water year 1995 to 2002.

and incision of new floodplain channels in the splay complex (Fig. 9; Table 4). While WY 1997 had a significantly higher peak discharge than other years, both 1995 and 1998 had a longer or similar duration of flows that exceeded the threshold of sediment transport onto the floodplain (Fig. 10). Thus, a combination of both magnitude and

duration must be included in the definition of a monitoring trigger in order to determine when the monitoring effort is warranted.

Table 4. Percent of time threshold flow is equaled or exceeded: range from 1995-2002.

Threshold	Maximum % of time	Minimum % of time	Average % of time
Floodplain connectivity	44	2	23
Threshold of sediment transport onto floodplain	7	0	3

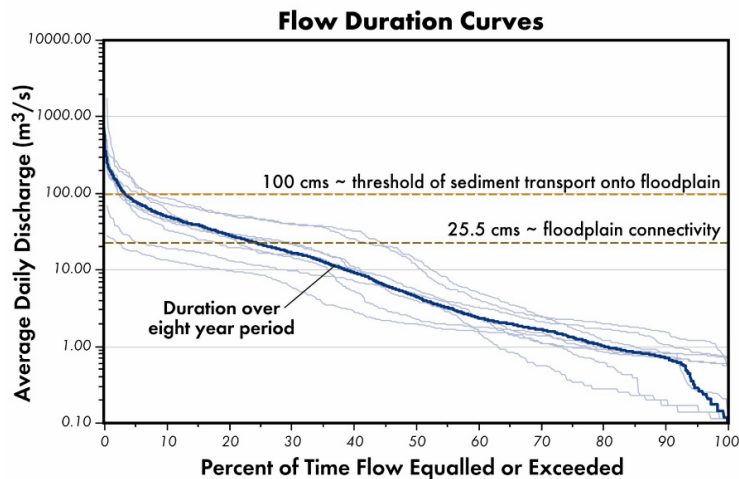


Figure 9. Flow duration curves for the period from water year 1995 to 2002.

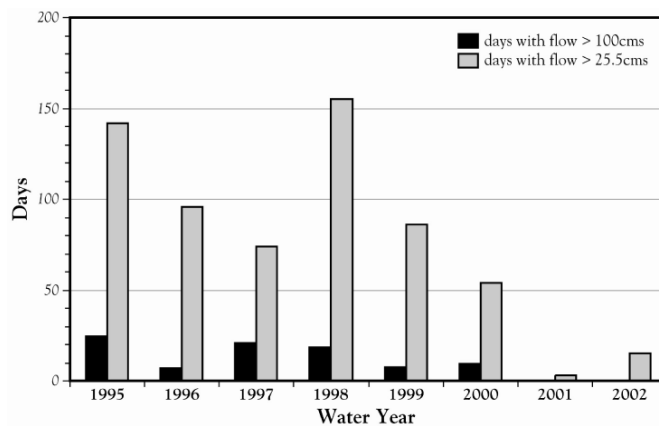


Figure 10. Bar chart showing duration of flows exceeding connectivity threshold and sediment transport onto floodplain threshold. Note that the longest duration of flows

exceeding these thresholds do not correspond linearly to the highest magnitude peak flow shown on Figure 11.

In order to identify a monitoring trigger that includes importance of both magnitude and frequency, we use a conceptual model based on stream power (Costa and O'Connor, 1995). This model illustrates the importance of both magnitude and duration of geomorphically effective floods using stream power per unit area (ω):

$$\omega = \gamma QS/w$$

where γ is the specific weight of water, Q is discharge, S is the energy slope, w is water surface width, and ω is in units of (W/m^2). Application of this model to the problem of sediment continuity and geomorphic changes in the Cosumnes channel and floodplain defines geomorphically effective floods as those exceeding the connectivity and sediment transport onto the floodplain thresholds (Fig. 11). We utilize this model to define a process-based monitoring trigger based on the range of flood magnitude and duration that construct and modify the sand splay complexes in the floodplain restoration area. The methods employed to address the monitoring hypothesis will include surveying channel longitudinal profiles to estimate water surface slope, surveying cross sections to measure width, in combination with analysis of gaging station discharge records. Development of a flood stage-discharge relationship adjacent to the floodplain restoration area through future monitoring will provide a direct link between upstream channel adjustment, and downstream floodplain restoration area channel and floodplain responses. Using our data of flow magnitude and duration for the period from 1995 to 2002 as an example, monitoring would be recommended following the wet season during each year from 1995 through 2000, but not following 2001-2002. Future monitoring data collection and analyses will refine this estimate.

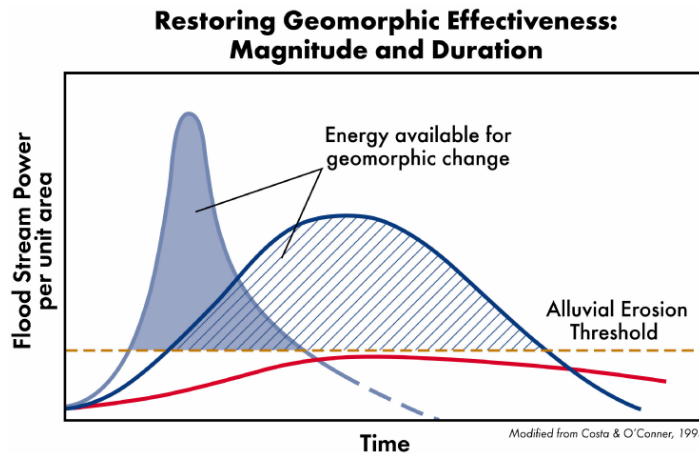


Figure 11. Conceptual model showing magnitude and duration of floods with 1) a high peak but low duration stream power per unit area; 2) a moderate peak but long stream power per unit area; and 3) a flood that does not exceed the threshold.

Channel-floodplain connectivity and lateral sediment transport onto the floodplain appears to be initiated by dissimilar magnitudes of flow at Accidental Forest Breach and Corps Breach, despite their proximity. At the Accidental Forest Breach, the elevation of the floodplain is about 1.5 m above the thalweg in the main Cosumnes River channel, while at the Corps Breach, the floodplain is about three to five meters higher than the thalweg of the main channel. Thus, sediment must be suspended higher in the water column in order to be transported through the Corps Breach, while sediment may move as bedload through the breach at the Accidental Forest breach (Florsheim and Mount, 2002). Future monitoring data collection and analyses will discern the relative thresholds for connectivity and sediment transport onto the floodplain at these two areas.

ADAPTIVE ASSESSMENT AND MANAGEMENT

Adaptive management, first defined by Holling (1978) is an approach that includes continual and systematic acquisition of knowledge of a system in order to improve management over time. Adaptive management approaches acknowledge the uncertainty inherent in our understanding of natural systems, designs management actions as experiments in order to reduce this uncertainty, and integrates information in to an

iterative process (Walters and Holling, 1990; Irwin and Wigley, 1993; Parma et al., 1998; and Wilhere, 2002). Evaluation, interpretation and communication of monitoring data are essential in adaptive management and are typically (or should be) developed concurrently with management plans. The terms “adaptive assessment” and “adaptive management” are often used interchangeably. Adaptive assessment usually refers to the project-specific assessments and adjustments in management in order to learn from and improve upon project performance (CALFED, 2002). Adaptive assessment is not necessarily hypothesis-based and does not view all management efforts as experiments. Effective adaptive management and assessment depends on data analysis, interpretation, and communication.

Data Analysis, Interpretation, and Communication

Assessment of the monitoring data includes analysis, interpretation, and communication of results. The goal of the assessment process is to document changes over time, to test hypotheses, and to determine if any change in management at the floodplain restoration area is warranted. Consistent data collection formats and analysis methods are critical in order to compare monitoring results over the long term (Statzner, et al., 1994). At the same time, flexibility in applying new technology as it is developed is essential. Thus, it is imperative that the monitoring design itself be scrutinized in order to generate recommendations for updated methods during future monitoring cycles. Further, we propose that monitoring data collection designs and the type of assessment conducted also be adapted as new questions arise, and as warranted to improve data interpretation. This will require a long-term institutional commitment to monitoring, data analysis, interpretation and communication. One aspect of communication should include written updates reporting status and trends following each monitoring cycle.

Adaptive assessment and management is a process for continuously improving the likelihood that a restoration effort will be effective. It requires iterative refinement of both the restoration and the monitoring sampling design in order to address uncertainty inherent in natural systems and in the state of restoration science. Downs and Kondolf

(2002) promote detailed post-project data collection to evaluate project effectiveness in order to improve future channel restoration designs.

While the restoration goals defined prior to implementation of the project were straightforward: restore hydrologic connectivity between the main Cosumnes River channel and adjacent floodplain in order to promote riparian habitat (TNC, 1992); the monitoring goals defined in this paper are likely to evolve as new data are collected, analyzed, interpreted, and new questions arise. Testing the monitoring hypothesis that intentional levee breaches restore or rehabilitate geomorphic processes in the lowland Cosumnes River channel and floodplain system at the Cosumnes River Preserve will require refinement over time as scientists learn more about sediment continuity and the link between upstream morphologic alteration to sediment supply delivered to the sand splay complexes at the restoration area. Because the sand splay complexes at the floodplain restoration areas form the physical structure of new habitat, results of the geomorphic monitoring assessment are needed to address the physical aspects of ecosystem function, processes, and habitat. This nested monitoring framework is expected to integrate other aspects of ecological monitoring through focussed experiments and iterative adaptive science, assessment, and management.

CONCLUSIONS

Detailed field investigations in the Cosumnes River provides the basis for a phased long-term adaptive monitoring, assessment, and management framework for lowland rivers. The geomorphic monitoring design presented in this paper stems from the premise that longitudinal sediment continuity between upstream and downstream reaches and lateral connectivity between the channel and floodplain at the Cosumnes River Preserve, link upstream morphologic alteration to sediment supply delivered to the sand splay complexes at the restoration area. Because the sand splay complexes forming on the floodplain at the intentional levee breaches create the physical structure of new habitat,

quantifying upstream channel changes that affect sediment supply to the floodplain restoration area is of critical importance.

The goal of the long-term geomorphic monitoring program for the Cosumnes River and floodplain restoration areas is to test the hypothesis that intentional levee breaches restore or rehabilitate geomorphic processes in the lowland Cosumnes River channel and floodplain system at the Cosumnes River Preserve. Testing this hypothesis has bearing on restoration of floodplain ecotone habitat for aquatic-terrestrial species. Results of the adaptive assessment will aid floodplain managers in efforts to guide floodplain restoration programs and long term monitoring programs throughout California's Central Valley.

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