

Task 2: Geomorphology

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Executive Summary

The **Task 2: Geomorphology** research and monitoring program focused on providing the geomorphic information necessary to assess the relationship between hydrogeomorphic processes and ecosystem function within the Cosumnes and Mokelumne watersheds and critical baseline information for future long-term monitoring. The work emphasized analysis of the lower Cosumnes River, where multiple adaptive floodplain and river management experiments are being conducted by the Cosumnes River Preserve Partners and various agencies, but also included a collaborative river restoration effort on the Lower Mokelumne River. These activities provide an ideal learning laboratory for similar projects proposed throughout the CALFED region of interest.

The geomorphic research and monitoring activity resulted in the preparation of ten manuscripts that are either published or currently in review in peer-reviewed scientific journals, along with two technical reports, three MS theses and one PhD thesis. These manuscripts are assembled in this binder based on the subtasks that they address. In addition, information from this research was highlighted in more than 40 public presentations at universities and scientific meetings, principally by J. Florsheim, J. Mount, and G. Pasternack.

Subtask 1: Geomorphic Impacts of Non-Structural Floodplain Management Measures.

Throughout the Central Valley of California, land conversion, levee construction and flow regulation associated with dams has eliminated or severely degraded more than 90% of floodplain and riparian habitat. Recent studies within and outside the Central Valley have demonstrated that seasonal flooding is critical to aquatic and terrestrial ecosystem integrity. These studies routinely note that restoration of seasonal flooding can be incorporated into non-structural floodplain management methods.

The Cosumnes River Preserve Partners have been conducting an adaptive management experiment that seeks to restore hydrologic and geomorphic processes in the lower Cosumnes River. Taking advantage of the unregulated hydrograph of the Cosumnes and the limited urbanization of the area, the partners have constructed two levee breaches that have re-established hydraulic connectivity between the main channel and the floodplain. The Cosumnes Research Group has conducted detailed surveys of the geomorphic response to levee breaches. This information forms a critical baseline for assessment of the impacts of levee breaches in the future and will help guide future levee breach design.

Levee breaches on the lower Cosumnes appear to provide a viable method for creating dynamic floodplain topography necessary to restore and support floodplain and riparian ecosystems. Sand splay complexes, which form adjacent to levee breaches, generate a range of floodplain elevations that creates local variability in (i) inundation duration and frequency and depth to ground water that influence riparian vegetation establishment; and (ii) flow depth and velocity that creates refugia for fish. The two intentional levee breaches along the lower Cosumnes River were evaluated during water years 1999 and 2000 in order to document changes in morphology and relief associated with deposition of sandsplay complexes. During the study period, 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. At the two study sites, rapid vertical accretion and scour occurred within the first several years after intentional levee breaching.

Sand splay complexes are organized into a variety of landforms, including lateral levees and lobes separated by new floodplain channels.. Relief on the floodplain 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. Progradation of main and secondary splay channels takes place by down-floodplain sand transport. Large wood recruited onto the floodplain through the breach promotes local scour and deposition that enhances topographic variability. At one of the study sites, initial grading of a low setback berm prior to opening the breach forced a change in floodplain flow direction and the geometry of the splay complex. Additionally, progradation of the complex is arrested by an excavated pond that creates a sediment trap.

In Florsheim and Mount (2002) we present a conceptual model that describes the importance of floods in constructing and modifying sand-splay complexes that create floodplain topography. The potential habitat variability created as floodplain topography evolves is the linkage between physical and ecological processes that are critical for restoration.

Subtask 2: Meander Migration Modeling of Non-Structural Floodplain Management Alternatives

The experiments being conducted by The Cosumnes River Preserve Partners and agencies working in the lower Cosumnes provide an opportunity to evaluate long-term geomorphic changes associated with floodplain management and ecosystem restoration. The intent for this subtask was to model historic and potential future changes in channel patterns based on various land use practices using a meander migration model currently in development by Dr. Eric Larsen. This model, which is still under development under a separate CALFED contract, simulates potential meander rates and patterns for specific types of single-channel rivers. After initial analysis of historical and current data, it was

determined that the Larsen model would be inappropriate for the lower Cosumnes River. Unlike single-channel meandering rivers (the Sacramento, for example) the Cosumnes is an anastomosing system characterized by relatively stable, multiple channels in highly cohesive soils. Channel evolution takes place principally through avulsion, with only limited lateral migration. In order to meet the objectives of this task, we conducted a detailed analysis of historic changes of the Cosumnes floodplain as a guide for future efforts to restore natural processes as part of a floodplain management program.

The results of our study (Florsheim and Mount, 2003) demonstrated that during the late Holocene, sediment deposition and morphology of the lowland Cosumnes River, has depended on factors that varied temporally and spatially, such as basin subsidence, sea level rise, flow, and sediment supply from both the Sacramento River system and from the Cosumnes River system itself, along with anthropogenic changes principally associated with farming. Through field investigations and analyses of historical maps, bridge core logs, and sediment size distributions, we link hydrogeomorphic processes to three stages of floodplain sedimentation on the lowland Cosumnes River.

- Stage I (1000–200 YBP). Combined late Holocene pre-disturbance flood basin overflow and anastomosing river processes deposited spatially variable sediment consisting of gray-blue clay (87% clay) interlayered with relatively thin coarser sediment. Pre-disturbance Holocene deposition rates of up to 3.0 mm/year kept pace with sea level rise and tectonic basin subsidence.

- Stage II (200 to 10 YBP). Anthropogenic disturbances caused a rapid increase in floodplain sedimentation rates up to 25 mm/year between 1849 and 1920, and deposited a relatively coarser reddish-brown sandy clay (40% clay) layer that overlies the basin deposits. Between 1920 and 1990 AD, sedimentation was greatly limited on the lower Cosumnes floodplain because levees inhibited connectivity between both the Sacramento and Cosumnes River systems and the Cosumnes floodplain. During this stage, the density of channel segments in the anastomosing river floodplain decreased by 30% as agricultural activities filled secondary channels and leveled floodplain topography.

- Stage III (10 YBP to the present). Post-rehabilitation floodplain sand splay complex sediment deposited after 1998 AD resulted from intentionally breaching levees to promote habitat at the Cosumnes River Preserve. The splay complex is dominated by medium to very coarse sand with finer intervening layers. The post-rehabilitation splay complex overlies the older basin deposits in a generally upward coarsening sequence that reflects depositional processes and land use changes that continue to affect the lowland Cosumnes River floodplain today.

Subtask 3: Levee Setback and Breach Design Parameters for Optimization of Restoration and Flood Damage Reduction

In order to guide future efforts at levee modification and flood management within the Cosumnes River, the geomorphologic studies focused on the interaction and feedbacks between biotic and abiotic processes on the floodplain. This information will specifically inform which flood management methods are likely to be most effective in achieving ecosystem restoration goals. The focus of this work was on the geomorphic and related hydrologic controls on the establishment and growth of native and non-native vegetation on the floodplain. One manuscript (Mount et al., 2002) and a dissertation (Trowbridge, 2002) contain the results of this work. Related reports on the impacts of levee breaches on aquatic communities are compiled in a separate binder (see Task 4 – Aquatic Resources).

The impact of seasonal flood inundation on riparian tree establishment has been extensively investigated in the southeastern United States, but similar research has not been undertaken in the West where the timing of flooding is different. The impacts of inundation duration and timing on germination of a major late successional dominant in Californian riparian forests, *Quercus lobata*, was investigated in order to address this issue. Mature oak forests can withstand long periods of winter flooding while they are dormant, but it is not clear what impact such flooding has on acorns, which do not experience winter dormancy. Preliminary observations on the restored floodplain on the Cosumnes River, where levee breaches have established hydraulic connectivity and dynamic floodplain topography, suggest that prolonged flooding limits oak establishment. This observation was tested using greenhouse experiments that measured the impact of inundation patterns, soil texture, and maternal family on acorn germination. Flooding tolerance of *Quercus lobata* appears to be similar to southeastern riparian oaks. Sustained flooding substantially reduces acorn germination rates, but short flooding periods and flooding that ends early in the spring does not have a significant impact on subsequent germination. Maternal groups exhibit significant differences in emergence time, weight and overall survival, but the pattern of response is broadly similar. Soil texture also affects seedling emergence. Acorns planted in sandy soils are more likely to germinate after flooding than those in clay. These results have important implications for restoration of floodplain forests. The presence of healthy adult trees does not necessarily predict the success of natural regeneration, since the trees may have been established under a historic flooding regime. Rather, timing and duration of seasonal inundation is likely to be a more important indicator of potential restoration success.

This study also looks at the influence of inundation timing and duration on performance of valley oak (*Quercus lobata*). Growth was measured over the course of three years at four different sites on the Cosumnes floodplain. The sites were chosen to represent the range of successional stages and surface age. Growth was significantly higher on younger, unforested sites. There was no difference in growth rate in the two, forested sites (early successional cottonwood willow forest and late successional mature

oak forest). Herbivory was highest in the cottonwood willow forest, where density of young oaks was also highest. The impact of flooding was measured on the youngest floodplain surface, an open floodplain restoration site where acorns were planted the year our study began. There was a significant negative impact of flooding on sapling growth in all but the first year of growth. Taken together these results suggest that existing forest trees and flooding both inhibit the growth of valley oaks on the floodplain, and that restoration in open sites may be more successful than restoration under an existing canopy. Additionally, these studies indicate the importance of dynamic floodplain topography. The generation of new topography controls the formation of new, bare ground, essential for establishment and growth of riparian vegetation. Also, by controlling local elevations, new deposition and scour control the timing and duration of inundation.

Subtask 4: Flood Flow Management, Coarse Sediment Flux and Restoration

The Lower Cosumnes and Mokelumne Rivers have significantly different flow and sediment regimes due to the different roles of levees, land use, and dams in the two river corridors. The geomorphology of the Lower Cosumnes River is primarily influenced by land use and levees, so restoration research focused on sediment and channel incision impacts caused by these external forcings. In contrast, the geomorphology of the Lower Mokelumne River is dominated by the effects of Pardee and Camanche dams. In this case, restoration research focused on developing a framework for mitigating dam impacts on geomorphic processes and salmon habitat.

Although the Cosumnes River retains a largely unregulated hydrograph, there has been considerable change in the geomorphology of the channel due to land use and flood management activity. In the segment between Highway 99 and Highway 16, levee construction and bank stabilization activity since the mid-1900's has induced a long-term cycle of channel incision. This incision has had local impacts--including increased bank instability and loss of geomorphic attributes considered critical for aquatic and riparian habitat—and downstream impacts associated with changes in sediment flux rates. The geomorphology research and monitoring program conducted a comprehensive survey of baseline geomorphic conditions of the river within the incised reaches. These surveys formed the basis for an analysis of the dynamics of incision and the geologic and hydrologic controls on magnitude and rates of channel change. The results of this work are summarized in two manuscripts (Constantine, et al., 2003, in review) and one MS Thesis (Constantine, 2002).

Incision of the alluvial segment of the Cosumnes River, between Highway 16 and Highway 99, caused exhumation and erosion of resistant duripan layers in some reaches. Changes in morphology and channel-forming processes resulted from the introduction of substrate more resistant to erosion. In contrast to the usual cross-sectional perspective of channel incision, longitudinal as well as cross-sectional morphologic responses to incision are

documented. Transformation of process is also addressed, leading to a comprehensive model of incised-channel evolution for streams with relatively resistant beds and banks. Following exposure of resistant bed and bank material, deeper cross sections develop, and the mechanism of bank erosion shifts from erosion through fluvial entrainment to erosion through mass failure. On the bed, erosional bedforms replace depositional bedforms, and variability of maximum residual pool depth and of pool-to-pool spacing increase. Average pool-to-pool spacing lengthens, and gradient evolves to reflect characteristics of the resistant material. The net result of incision into the duripan layers has been a reduction in high quality spawning and rearing habitat.

The changes in bedforms and channel shape due to incision are accompanied by significant shifts in downstream-fining patterns of alluvial material. Downstream fining is attributed to processes of selective sorting and abrasion, and is typically modeled as an exponential decrease in median grain size over the length of the river profile in response to downstream declines in bed shear stress. On the Cosumnes, channel incision and the exhumation of buried duripan layers disrupted historic downstream fining patterns. Today, high bed shear stress within the incised reach has shifted the gravel-sand transition approximately 30 km downstream from its historic position. This shift is important to monitor since it will directly impact any channel and floodplain restoration efforts that are conducted downstream of Highway 99.

Spawning habitat downstream of dams is critical to salmon survival, but it has been severely degraded by managed flow and sediment regimes. Resource managers seek improved habitat, but there existed no strategy to provide for immediate biological functioning while working toward long term geomorphic sustainability. During 1999-2001, UCD and EBMUD participated in a joint project to develop, test, and apply a 2D predictive model of spawning gravel habitat quality and sediment transport risk at river rehabilitation sites on the Mokelumne River downstream of Camanche Reservoir (Wang and Pasternack, 2000; Wang, 2002; Pasternack et al., In Press). This work was partially supported by grants from EBMUD and the David and Lucille Packard Foundation, along with CALFED funding.

In the first phase of the spawning habitat restoration modeling, the 2D model was tested on a rehabilitated site. The model successfully simulated velocity and depth patterns. When used in a predictive mode, the model yielded better habitat and sediment stability outcomes in alternative gravel placement designs than achieved in the implemented ad hoc design.

Next, the 2D model was incorporated into a rehabilitation framework called the Spawning Habitat Integrated Rehabilitation Approach (SHIRA). What sets SHIRA apart is that it integrates widely accepted concepts from hydrology, civil engineering, aquatic biology, riparian ecology, and geomorphology to design alternative river configurations for a degraded section of river and then it uses predictive computer models resolving processes at the same scale that fish

actually experience them to evaluate the relative performance of the different configurations in their specific details (Wheaton and Pasternack, 2002; Wheaton, 2003; Wheaton et al., In Press a). SHIRA includes a comprehensive monitoring program including biological, hydrological, and geomorphic datasets.

SHIRA was used twice on the Lower Mokelumne River and has undergone adaptive management (Wheaton, 2003; Wheaton et al., In Review A,B). In 2001 SHIRA was used to rehabilitate a reach using 650 m³ of gravel. In addition to assessing the degraded condition, 10 alternative channel configurations were assessed. The one that yielded the most usable habitat while promoting self-sustaining pools and riffles was selected for implementation. In summer 2002 a second SHIRA project was done involving design at 3 spatial scales and using 3 times more gravel than in 2001. At the reach scale, 2400 m³ of gravel was used to elevate the bed and increase slopes over constructed riffles. At the sub-reach scale, flow was routed through a complex assemblage of geomorphic units including 3 broad riffles (to encourage divergent flow and gravel deposition at high discharge), 3 small pools (whose widths were constricted by bars to encourage convergent flow and scour at high discharge) and 3 boulder complexes. Boulder complexes were used to encourage localized scour and create shear-zones, channel constrictions, hydraulic jumps, and standing waves. Pool exit slopes at pool-riffle transitions were shaped to promote intragravel flow and encourage flow to diverge across riffles. After the project was complete, an extensive array of biological, hydrological, and geomorphic monitoring was performed, and this is on-going (Wheaton et al, In Press b; Merz et al, Submitted). The 2002 site post-project appraisal showed that the as-built flow field matched model predictions. Furthermore, there was a 47% increase in numbers of redds, and 95% of post-project redds occurred at sub-meter resolved points predicted by the habitat model. Long-term biological and geomorphic monitoring and adaptive management continue. This is the first time that an objective approach involving 1) a transparent procedure that was documented in the open literature, 2) the hypothesis-driven scientific method, 3) specific, testable predictions at spatial and temporal scales relevant to natural processes, and 4) long-term monitoring and adaptive management has been used to design a gravel rehabilitation project.

Subtask 5: New Methods for Monitoring Sediment and Channel Impacts of Land Use Change

Although there are numerous restoration projects completed or planned for the Cosumnes and Mokelumne Rivers, there is at present no comprehensive plan for adaptive assessment. As part of the geomorphology research and monitoring program, we propose a three-phase adaptive geomorphic monitoring, assessment and management framework that can be applied broadly

to lowland river systems. Although specific to geomorphic monitoring, this framework can be adapted to all facets of project monitoring. This work is summarized in the manuscript by Florsheim et al. (in review).

Phase 1: Pre-project design and assessment. In order to implement an effective post-project assessment program for lowland river restoration projects, four elements must be completed prior to project implementation. These include: documentation of pre-disturbance site conditions, documentation of pre-project area and watershed conditions, establishment of a reference condition, and clear definition of restoration goals and objectives. These elements should be explicitly incorporated into and acknowledged in project design.

Phase II: Project monitoring and assessment. Following project completion, six elements must be incorporated into a project monitoring and assessment program. These include: definition of watershed context of monitoring area, development of research hypotheses and monitoring goals, selection of monitoring parameters, locations and methods, design of data collection strategy, collection of baseline (post-project) information, and development of a structured program for analysis, interpretation and communication of monitoring data. The latter element is most critical, and involves presenting data and interpretation to a broad range of stakeholders and agencies.

Phase III: Synthesis and Adaptation. Although many restoration projects have monitoring programs, few spell out how they will adapt to new information and incorporate existing information with other monitoring programs. Synthesis involves integrating the geomorphic monitoring program with other ecologic monitoring programs. Adaptation involves the development of recommendations for new approaches for management of the restoration program, including the possible reassessment of goals and objectives and the design of new restoration experiments. Once completed, implementation of these new designs requires initiation of a new cycle of project monitoring and assessment (Phase II). In this way, all adaptive geomorphic assessment projects are inherently iterative and experimental, involving regular adjustment and “tuning” in order to achieve the optimal results.