environment can be observed at high resolution. Moreover, experiments can be planned to observe the influence of: (a) gravel augmentation (large volumes of gravel have been stored on-site by the agencies in anticipation of this), (b) controlled flow releases; (c) engineered modifications of channel and floodplain form; and (d) irrigation of floodplain plants. During the first several post-project years, the channel and floodplain are expected to change slowly, so there is time to make a detailed study of physical and biological processes in their near-initial condition, and then to take advantage of later changes and manipulations to increase understanding over a wider range of conditions. It is difficult to find such a convenient and appropriate site for a multi-disciplinary investigation of how river restoration actually influences physical and biological processes and conditions.

PROJECT GOALS AND WORKPLAN

The overarching project goal is to answer the question posed at the beginning of the proposal in a quantitative manner, transferable to other sites in a form that is useful for other restoration projects. We will try to accomplish this goal through a set of parallel, interactive programs of field measurement and mathematical model construction. Specific goals, questions, and hypotheses for each component of the project are listed in the following sections, and may need to be modified after further consultation with agency personnel. Because the object of the restoration is to restore biological populations in the Merced River and elsewhere, we will synthesize most of our results in statistical and other mathematical models describing the response of channel and floodplain communities to the physical activities of channel restoration. Model construction will occur from the outset of the project, --- however simple the initial formulations. This action will require us to formalize our conceptual models, develop consistency between disparate data sets, identify critical variables, and communicate among ourselves and with collaborators and users in an exact manner. We expect those models to be refined as the study unfolds. Because the physical alterations of the site provide the template for all the biological studies and population modeling, the proposal begins with an outline of the research on the hydrodynamics and geomorphology of habitat creation and maintenance. We will then describe the proposed work on restoration of invertebrate communities, followed by the research on use of the reach by fishes and reestablishment of floodplain communities. We emphasize the nature of the research products and the ways in which they might support decision-making about restoration.

A. HYDRODYNAMICS AND GEOMORPHOLOGY [Dunne and Faulkenberry]

Description of the Topic

Most of the work in river and floodplain restoration involves manipulating flow and re-grading channels and floodplains to create more favorable conditions for certain ecological processes. However, most of the desired biological responses are predicted from fragmentary information, transferred from disparate sites, and the details of the hypothesized physical-biological interactions remain unquantified or untested. Design and assessment of river restoration projects could be facilitated if these interactions were understood well enough to improve the reliability of ecosystem-level predictions.

To characterize and explain the creation and functioning of the physical habitat we will concentrate on measuring the following features:

- the flow field of the in-channel water column
- flow within the channel bed
- the transport of suspended load (including organic particles and organisms)
- the transport of coarse and fine bed material
- the trapping of fine sediment within the coarse framework of the channel bed

- the microtopography of the bed surface
- re-shaping of the bed into pools, riffles, and bars by bed-material transport
- bank erosion and consequent channel migration
- overbank flow and deposition of fine sediment

We understand that subsurface flow within the floodplain is being monitored and modeled by other scientists.

Scientific Questions to be Addressed

- What are the patterns of flow depth and velocity throughout the restored reach at various discharges, and how are they affected by factors that can be manipulated in channel design and that evolve after project construction (such as channel geometry, bed texture, in-channel structure, bank roughness)?

- How do the temporal and spatial patterns of suspended load and bed-material load respond to the flow field and the constructed channel geometry to create biologically relevant changes of bed state and morphology?

- How do bar deposition and bank erosion combine to create patterns of in-stream habitat and drive re-surfacing of the floodplain?

Background

An investigation of how abiotic and biotic processes affect habitat components in a river system can be generally subdivided into three broad categories – (i) how processes and habitat components change when the riverbed is relatively stable; (ii) how a mobile riverbed affects processes and habitat components; and (iii) how the mobility of riverbanks affects processes and habitat components in the channel and floodplain. A conceptual model of the river channel and riverbed that provides a basis for understanding the importance of different processes affecting the river bed and the river channel during various flow conditions is described in the following two paragraphs.

Many river channels in the Central Valley of California have a channel bed consisting of a framework of coarse sediment particles (gravels and cobbles) with fine sediment particles (sands, silts) filling some of the interstices and also forming patches on the surface of the coarse framework. Channel banks cut in to these sediments may be reinforced to varying degrees by plant roots, allowing them to stand at near-vertical angles along parts of the channel margin; other parts of the channel margin are not reinforced, and slope gradually. Within a range of low flows, coarse sediment remains immobile and the water simply flows over a static riverbed, adjusting its depth and velocity gradients to the morphology. The only changes aquatic organisms experience at this stage are variations in depth and velocity. As flows increase, the patches of finer sediment are selectively mobilized and transported either in suspension or by rolling and hopping along the bottom of the bed. The river channel is still considered stable at this point because the coarser gravel framework is immobile. Fine sediments enter the reach and may settle out as new patches on the surface of riffles, settle into pools, or infiltrate into the bed. When discharge increases to near bankfull stage, but before water spills extensively onto the floodplain, the shear stresses exerted by the flow on the bed are usually high enough to begin selective mobilization of the gravel and cobble framework. As flow increases still further, shear stresses in the channel are high enough to begin reshaping the river channel boundary by eroding the banks and depositing sediment on the point bars that become assimilated into the floodplain. The interplay of these sediment transport processes results in a variety of ecologically relevant processes over the range of flows.

For example, the quality of spawning habitat in a stable riverbed will change over time as fine sediments infiltrate into the subsurface, fine sediments are deposited and remobilized from the surface, and female salmon dig up the riverbed for laying their eggs. On the other hand, flood events that can mobilize the larger gravel particles can either rejuvenate or scour away the redd. Thus, the condition of the spawning gravel is the result of a stochastic 'game' resulting from the sequence of suspended sediment concentrations and flow applied to the reach. Quantifying the rules of this game provides a method for estimating the risk of the spawning gravel being in a variety of states under specified conditions, but this concept has only recently been applied to spawning gravels [Lang, 2004]. A similar approach can be taken to the temporal variation of microtopography that shelters juvenile salmon, strongly affecting their condition and mortality [Suttle et al., 2004]. When the coarse bed material moves, not only is the gravel either 'flushed' of or impregnated with fine sediment, but the morphology of the bed is molded into bars, pools and riffles, and into more complex forms around in-channel woody debris. It is to be expected that the relatively simple geometry of the restored channel will become more complex as a result of spatial patterns of bed-material transport, but the details of this process are difficult to predict. There is a need for detailed measurements of how this happens in a restored channel reach, and for an attempt to predict the remolding of the bed over time. At even higher flows, it is known that channel banks can be undermined, but the threshold flow conditions, spatial pattern, and rates of this process are not well understood; nor is the role of vegetation either in stabilizing the bank or invading the channel. Both quantitative descriptions and predictions of these effects for restored and un-restored reaches are needed. Other interactions between flow, sediment transport, and bed characteristics affect invertebrate populations and fish as detailed later.

Flow fields

There is a considerable body of literature on cross-section-averaged flow conditions through straight channel reaches, but relatively little documentation of complex flow fields in sinuous, natural reaches. Yet it is the goal of many river restoration projects to re-establish habitat complexity to channels [Brookes and Shields, 1994]. Availability of new instruments, such as the acoustic Doppler velocimeter and acoustic Doppler current profiler, and of new two-dimensional, vertically integrated flow models for complex bed topographies [e.g. Bates and Lane, 1999; Pasternack et al., 2004; or the new quasi-2D public domain model MD-SWMS, developed by the US Geological Survey for flow, sediment transport, and channel migration] allow realistic definition of flow conditions in which fish and invertebrates swim, float, feed, shelter, and reproduce. These flow fields also affect the patterns of sediment transport that mold the channel bed into spawning, rearing, and other kinds of habitat, as well as determine the amount, depth, and extent of any overbank flow [Trush et al., 2000]. **We are not familiar with a study of habitat formation and biological responses in which the local flow environment of all measurements and calculations is specified, but we intend to create such a simulated environment, interpolating between our own detailed measurements of the flow field at a range of discharges.** Such a model could then be queried to explore how alterations of channel geometry, bed texture, meander planform, and in-channel physical structure could alter the flow field and the amount of various habitat conditions. Field tests of the predictions could then be designed.

The amount of habitat can be quantified through a technique pioneered by Lamouroux et al. [1995, 1998], who demonstrated that point values of depth and vertically averaged velocity from a range of stream sizes and discharges exhibit similar probability distributions with parameters that vary with discharge. This insight yields one efficient metric of habitat quality that can be compared across discharges, over time, and between restored, un-restored, and natural channels.

Bed material sediment: condition, transport, and morphology

Aquatic habitat, created and maintained by sediment transport processes, can be categorized as: (i) macro-scale habitat units (e.g. pools and riffles for rearing and spawning), (ii) cross-sectional shape (e.g. shallow margin habitat near point bars, pools, or bank overhangs that provides refuge for juvenile salmonids), and (iii) riverbed characteristics (e.g. a gravelly surface with varying amounts of fine sediment that creates hiding and resting spots for juvenile salmonids. In order to evaluate whether the restoration oft the Robinson reach will provide the habitats needed to support a healthy population of salmon over the long-term, the quantity and quality of all three habitat categories should be evaluated and linked to the flow and sediment transport processes that are necessary to sustain them, and that are manipulated by river restoration projects.

In the following sections we outline our specific approach for investigating (i) changes in the habitat under stable bed conditions, (ii) changes due to mobile riverbed conditions, and (iii) changes due to mobile riverbank conditions. Floodplain processes and their effects on habitat will be considered in a later section.

Methods

Flow fields

We will conduct detailed mappings of channel topography, water surface elevation, and flow depth at a range of discharges. The bed will be surveyed with a total station, and we hope to map continuous fields of flow depths using an optical remote sensing technique developed by Legleiter et al. [2004], which should allow continuous digital mapping of flow depth from a low-flying airplane, significantly increasing the ability of restoration specialists to document habitat morphology over long reaches of river. We have applied for separate funds from the National Science Foundation for this task. If the continuous optical mapping is not possible, we will have to interpolate from measurements of flow depth and vertically averaged velocity that have been measured repeatedly at the 25 cross sections by Faulkenberry's CDWR team and several detailed mappings of the bed that have been made by Legleiter and Faulkenberry's team. The texture of the bed sediment will also be defined in detail (see below). Discharge is continuously monitored at the upstream end of the reach by the CDWR. Current speed and direction will continue to be measured at many locations (number varying with discharge) within the reach at a range of discharges using the acoustic Doppler velocity meter and electromagnetic current meter.

The resulting three–dimensional descriptions of the flow field will be used for (a) defining habitat for the organisms studied by other components of this investigation ; (b) for calibrating a two-dimensional, vertically integrated, mathematical model of the flow field (initially River2D) so that the flow field can be estimated at other discharges; and (c) as a means of understanding how the river channel itself is molded by flow and sediment transport (see below on sediment transport and bank erosion). We will utilize the calibrated model to predict ways of altering the flow field by adding structure to the channel, and then testing the predicted velocity perturbations and measuring their effect on habitat use by various organisms at a range of discharges. The model would also facilitate the comparison of other channel designs for the Merced River and elsewhere, in the manner illustrated by Pasternack et al. [2004]. The research on flow documentation and modeling and its ecological significance will be conducted by Legleiter and by Postdoctoral Researcher #1. The flow measurements will be made over two flood seasons, augmenting measurements that Faulkenberry and Legleiter will have accumulated by the beginning of the contract period.

The current simplicity of channel morphology, bed textural pattern, bank geometry, and floodplain topography in the Robinson reach provides an excellent opportunity for experimenting with the physical and biological effects of adding structural complexity to the system. For example, after the initial characterization of channel topography, flow field, bed sediment, and use of local environments by invertebrates and various fish species, we could collaborate with the responsible agencies to design various installations of large boulders, or anchored woody debris, or modifications of the channel-floodplain boundary. We could then model the expected influence of the structural changes on the flow field and check the predictions against measurements of depth and velocity changes at a range of discharge in order to test our ability to apply the method elsewhere. Our colleagues could then repeat their measurements of the use of the local environments by various organisms to measure directly the ecological significance of the structural modifications. We have similar ideas for experiments on the effects of locally altering the topography of the floodplain, its connection to the channel, and its elevation above the water table in order to measure their effects on plants and animals in a direct, experimental fashion. The initial simplicity of the Robinson reach would facilitate rapid accumulation of a large amount of such information for river restoration design, and the information could be transferred to other sites with the aid of the modeling effort.

Bed material condition, transport and morphology

We will conduct a high-resolution mapping of *substrate texture*. Recent studies demonstrated the utility of digital photography and image processing techniques for automated measurement of sediment grain-size distributions [Sime and Ferguson, 2003]. We will extend these techniques to a field situation to develop continuous maps of the streambed texture. A waterproofed digital camera will be used to acquire substrate images, adjusted to a common scale using a reference object and then combined into a mosaic. Image processing software can be used to estimate individual particle sizes and the fines content of the substrate. The image-derived estimates will be compared with weighed samples, and appropriate corrections applied to account for the difference between the exposed projection of a grain on a two-dimensional image and its actual three-dimensional geometry. The samples, obtained with surface scoops and with a standpipe modified for freezing cores [Barnard and McBain, 1994], will also be used to quantify the relationship between surface and subsurface texture, both for sediment transport predictions (see below) and for studying the effect of fines on spawning gravels (see below).

Microtopography of the gravel bed is another physical characteristic of ecological significance because it affects flow resistance, influences vertical velocity profiles and turbulence, and defines the habitat conditions for invertebrates and juvenile salmonids [Suttle et al., 2004]. We expect this microtopography to vary with average texture and sorting of the sediment, and therefore with position (shear stress) in the channel in a systematic way, and will be modified by surface accumulation of fine sediment. The detailed measurements needed to characterize microtopographic variability will be conducted on 1 m^2 sample hydrodynamic environments (characterized by their velocity profiles) with a surface roughness template consisting of a series of horizontal support bars and closely spaced vertical rods that reproduce a profile of the substrate by sliding up and down freely when placed on the bed. This profile can be captured by taking a digital photograph of the rods, with the horizontal support bar serving as a scale object, resulting in a form of habitat description relevant to studies such as that by Suttle et al. [2004], who measured the survival and condition of juvenile fishes living over gravel beds that had been inundated with various amounts of sand. The seasons of measurement will be coordinated with the surveys of invertebrates and juvenile fishes, in order to develop a mathematical model of how the bed surface condition varies with time during critical life stages of the organisms. The measurements of bed material condition will be conducted by Graduate Student Researcher #1 during the first year of the contract, and will be repeated by undergraduate assistants working under the supervision of Aleksandra Wydzga at intervals if there is significant change caused by high flows and sediment flux. If gravel augmentation experiments are planned by CDWR, bed material surveys will be necessary before and after the augmentation, and we will collaborate with the agency on these characterizations.

The *fine sediment content of spawning gravels,* along with their *hydraulic conductivity,* and the *dissolved oxygen content of the percolating water* are known to affect spawning success of fishes as well as populations of invertebrate organisms. Hydraulic and physical bed characteristics affect where adult salmon choose to spawn [Geist and Dauble, 1998], how many eggs survive into alevins [Chapman, 1988; Groot and Margolis, 1991], and how many fry emerge from the substrate [Chapman, 1988; Groot and Margolis, 1991]. Subgravel flow, along with adequate dissolved oxygen of the percolating water, are known to affect both where salmon choose to spawn [Geist and Dauble, 1998] and the survival of salmonid embryos [Chapman, 1988]. Fine sediment content of the bed not only affects the subgravel flow rate but can physically block the emergence of fry from the gravel bed [Chapman, 1988]. These indices of habitat quality will be measured using a modified standpipe [Barnard and McBain, 1994]. A dense survey of this kind at the beginning of the study will measure the effects of approximately five years of flows since the restoration, with some knowledge of where and how frequently the bed has been scoured, supplied by existing surveys of 24 channel cross sections (CDWR monitoring program). Sampling of fines content will then be repeated in the autumn of each year; sample numbers will depend on the variability that we encounter.

We will install batteries of radio-tagged tracer gravels and scour chains in the channel bed (3 per cross section on five cross sections) to establish the critical flows and stresses required for mobilizing various parts of the bed, and with these data we will test our ability to predict the threshold of bed-material motion from theory [Buffington and Montgomery, 1997]. We will also deploy geophones buried along the channel margin to record the acoustic signal of this mobilization and of vibrations that may lead up to the mobilization. At the scour chain sites, we will also bury cans in the bed and retrieve them before each spawning season to measure the infiltration of fine sediment [Lisle, 1989]. We intend to construct a hydraulic model of fines accumulation in the bed between flow-driven scour events, and to relate the fines content to reductions in measured hydraulic conductivity. Graduate Student Researcher #1 will also conduct local experiments releasing slugs of fine sediment upstream of some of the measurement sites to extend our data beyond the local range.

At each site where we study the accumulation of fines, we will make regular measurements of near-surface fines transport with a Helley-Smith bedload sampler on a frequent enough basis to capture selective transport of fine bed material and test our ability to predict it with a conventional bedload equation [Wilcock and Kenworthy, 2002]. We will also monitor the transport of suspended load into the reach with a USDH-48 suspended load sampler to keep track of changes in supply. We will measure vertical velocity profiles over the scour and fine-sediment accumulation sites at a range of low to medium flows and use them to check the value of the vertically averaged two-dimensional flow model referred to above for predicting the localities of fine sediment accumulation and scour. In this way, we intend to relate the accumulation and flushing of fine sediment in the bed to the larger scale environment of the restored reach and to the history of flows to understand how fine sediment accumulation responds to these design factors. Later studies, or comparative studies by colleagues involved with other CALFED restoration projects, could test our predictions by means of rapid surveys of fine sediment in spawning gravels with a modified stand pipe. The study of fine sediment accumulation and release, and its effect on habitat conditions will form the Ph.D. thesis of Aleksandra Wydzga, who will have completed all degree requirements except for the thesis, and be able to work full-time on the project. She is also an unpaid collaborator in the Stillwater Sciences/UC Berkeley flume study of sediment transport, funded by CALFED, and she will be able to form a link with that project by which some measurements made in the flume might be repeated at natural scale in the Merced River.

Larger-scale remolding of the coarse bed material into bars, pools, and riffles as the restored reach becomes more complex will be studied through regular topographic surveys after each flood season, extending and increasing the density of the cross sections regularly monitored by the CDWR since the original construction. We intend to survey a sufficient density of points to develop high-resolution digital elevation models from which to make morphologic estimates of bed material transport rates [Lane et al., 1995; Ham and Church, 2000]. Geostatistical techniques [Goovaerts, 1997] will be employed to interpolate elevation points and differences explicitly quantify the uncertainty in the measurement of morphological change and thus morphology-based estimates of bed material transport. This approach is particularly advantageous when morphological techniques are applied over short time scales at low transport rates, which will often be the case in river restoration projects. Both travel distance and sediment budget-based methods (Gaeuman et al., 2003) of obtaining transport rates from morphologic data will be evaluated using tracer gravels and direct bedload measurements at the upper end of the reach, respectively. The morphological estimates of transport rates will be compared to traditional measurements that we will make with a Helley-Smith bedload sampler at local scales, but the former have several advantages, including their spatial extent over the entire reach and their incorporation of the effects of channel-bed morphology on local, effective shear stresses and transport rates.

We will attempt to calibrate a bed material transport equation specific to the Robinson reach by using a sediment transport rating curved based on Helley-Smith sampling at the upper end of the reach to invert the morphology-based estimates. For this inversion, we will initially use both the flume-based equation developed by Wilcock [2001] for sand-gravel mixtures and the Engelund-Hansen equation that Singer and Dunne [2004] re-calibrated with field measurements on several Western gravel-bed rivers. We will also attempt to route the bed material through the reach and model the resulting changes in bed topography using a cellular model of flow and sediment transport [Thomas and Nicholas, 2002]. The RIVER2D model and the empirical mapping of flow fields described above will be used for verification. A simple channel such as the Robinson reach presents an attractive first target for examining whether the morphology-based method will allow us to explain the small amount of change that has already occurred and to make high-resolution predictions of the effects of gravel augmentation that could then be tested by a designed experiment.

As a check on the bed material transport computations, we will track a large sample of gravel particles tagged with magnetic tracers, which can be installed and monitored continuously during each spring's high flow or during higher discharges that cannot be predicted at the present time. We will use the tagged particles to develop an empirical relationship between travel distances and shear stresses along paths computed from the flow model, and the resulting relationships will be used in an alternative method for obtaining a transport equation through inversion of the bed morphology surveys. Our various attempts to produce a sediment transport model should yield results that are directly useful for the design of gravel augmentation projects in the Robinson reach, and our larger goal will be to produce a model that can be applied to similar sand-gravel bed rivers in the region. The research on the re-molding of the channel bed by sediment transport will constitute the Ph.D. thesis of Carl Legleiter, who will work full-time on the project, supported by a research fellowship from external funds. Postdoctoral Researcher #1 will be responsible for overseeing the tagging experiments through two years of high flows, assisted by undergraduates.

Bank erosion and channel shifting will be measured after each high-flow season, extending the 24 post-restoration cross-section surveys by CDWR. We will also make a higher-resolution visual mapping of undercut banks each year to define the evolution of near-bank habitat. We expect the pattern of small-scale bank erosion features to foreshadow larger-scale bank erosion and channel shifting. We will then attempt to predict this pattern of bank erosion and bar formation on the opposite side of the channel by a number of strategies. We will implement the FLUVIAL-12 quasi-two-dimensional model of flow and sediment transport [Chang, 1988] or the new US Geological Survey model MD-SWMS referred to above to compute bank mobility as a result of the flow and sediment budget for the channel. Such a procedure would later allow the modeling of gravel augmentation strategies on channel morphology as well as bed texture. These predictions could then be tested with an experimental release of sediment at a time appropriate for project management. If successful, the research would produce a useful tool for extending results to the design of channel form and gravel augmentation projects elsewhere. If the sediment-budget-based modeling of bank erosion, bar formation, and channel migration is not successful, we will calibrate the Ikeda et al. [1981] bend theory to the reach, based on the small observed changes, and use it to forecast a testable pattern of channel migration, bar formation, and floodplain resurfacing affecting the development of the floodplain vegetation. This work will be conducted by Postdoctoral Researcher #1.

Overbank sedimentation, which is likely to be rare and small for the first few years, will be monitored by means of clay pads, and modeled as an overbank transport process, based on computations of overbank flow (see earlier on flow modeling) and the computed vertical profile of suspended sediment concentration [Dunne et al., 1998; Malmon et al., 2004]. However, we will pay particular attention to detailed sampling of deposition within the riparian vegetation where it may have an ecologically significant soil-building role even in the short term. The research will require a small amount of occasional fieldwork. The work will be overseen by Postdoctoral researcher #1, assisted by undergraduates, if overbank deposition takes place..

Products

We intend to produce detailed quantitative descriptions of the physical habitat and the processes that create and sustain it, so that measurements of various biological processes, described in other sections of the proposal can be related to the spatial extent and timing of physical conditions. The physical characteristics to be studied were chosen for their direct relevance to biological processes. We also intend to construct mathematical models of: the flow field; morphology and sedimentological characteristics of the channel bed; and channel mobility, as they are affected by flow, sediment supply, bank conditions, the initial restored condition of the reach and various manipulations such as flow and gravel supply to which the channel may be subjected in future management actions. With these tools, we will consider management strategies and how they might affect the production and maintenance of habitat in the Robinson reach and elsewhere.

As the channel evolves, we expect the diversity of physical habitat to increase, and we should be able to predict, track, and explain such changes, or continue to refine our understanding. Our results should also facilitate the design of future management actions, including gravel augmentation, flow regime management, or new restoration projects by helping to predict not only the physical habitat changes, but also the interactions between physical change and the biological processes studied by the collaborating team. We expect to develop biologically relevant metrics of how much habitat of various quality is evolving inside the Robinson reach, and how this progression relates to the controlling variables (both natural and those subject to design and management).

B. RESTORATION OF INVERTEBRATE COMMUNITIES [Lenihan]

Description of the Topic

This portion of our collaborative proposal explores specifically how the modification of physical characteristics, including the re-scaling of channel dimensions to available flows, altering of channel bed material and geomorphology, encouragement of channel migration, and the re-establishment of floodplain plant communities, affects macroinvertebrate communities and other components of the Merced River food web that supports juvenile Chinook salmon, and other salmonids and native fishes.

Invertebrate species provide a critical energy source for salmonids and other native fishes in river food webs. Juvenile salmon and steelhead trout (*Oncorhynchus spp.)*, California roach (*Hesperoleucas symmetricus*) and three-spined sticklebacks *Gasterosteus aclectus*), among other fish species, prey on benthic, water column, and surface-dwelling macroinvertebrates, including various species of insects, gastropods, crustaceans, and their larvae [Allan 1995]. Fish and invertebrates are embedded in food webs that consist generally of benthic algae (e.g. chlorophtyes, diatoms, and cyanobacteria), primary consumers or herbivores (e.g. haptageniid mayflies, chironomid and Dixid midges, and caddis flies), secondary consumers or carnivores (Odonates-dragonflies, Plecopterans-stoneflies, and Meglopterans-dobsonflies), and fishes that are tertiary consumers [Power 1990, Power et al. 1995]. Adult salmonids and other fishes also prey on juvenile and small fishes that, in turn, prey on invertebrates [Power, 1992]. Benthic invertebrates, especially those living in redd sediments, may prey upon salmon eggs. Finally, juvenile and small adult fishes also prey on river zooplankton, which consists mainly of Copepoda, Cladocera, Diptera, Amphiopoda, Oligochaeta, Coleoptra, Collembola, Decapoda, and larva or nymphs of Epemeroptera, Hemiptera, Lepidoptera, Mollussa, Odonata, Podocopida, and Trichoptera. River geomorphology and hydrodynamics influence the abundance, distribution, and population dynamics of macroinvertebrates directly through effects on dispersal, recruitment, habitat use, and resource availability; and indirectly by modifying species interactions such as competition, predation, and facilitation [Allan, 1995; Palmer and Poff, 1997; Hart and Finelli, 1999]. **Understanding how physical processes influence invertebrate populations, and examining trophic links between invertebrates and fishes, provides a means of coupling river restoration with the population dynamics of salmonids and other native fishes.**

Large–scale habitat restoration, like that in the Merced River, provides an unprecedented opportunity to examine experimentally how physical mechanisms influence the composition, trophic structure, and dynamics of food webs that influence fish populations. Ecological processes in any ecosystem are influenced by multiple environmental drivers, which can interact in complex ways [Powell, 1989; Lenihan and Peterson 1998]. Identifying cause-and-effect relationships between physical drivers and population and community responses requires one to examine processes at different spatial and temporal scales, utilize hierarchically designed field studies, and synthesize information using various modeling techniques. Accordingly, large-scale experimental studies of physical-biological coupling are rarely attempted [Powell, 1989]. Rarer still are studies designed in an adaptive management framework to evaluate the processes modified in restoration programs [Palmer et al., 1997; but see Lenihan, 1999].

The few studies that have successfully examined physical-biological coupling in river or estuarine food webs [e.g. Power et al., 1995; Lenihan et al., 2001] have integrated large-scale experimental manipulations of physical variables (e.g. substrate type and flow regime) with large-scale sampling and small-scale experimental manipulations of demographic responses of target populations. Missing are integrated multidisciplinary studies of how modification of river geomorphology, flow, and their interaction influence demographic responses of invertebrates and the habitat they require; how demographic responses control invertebrate population dynamics; and how variation in invertebrate populations influence food webs that sustain salmonids and other native fishes [Allan, 1995; Hart and Finelli, 1999]. We propose to employ this integrated research framework in a sampling, experimental, and modeling program designed to identify mechanisms by which rehabilitation efforts influence ecological function in the Merced River. The work would be conducted by H. Lenihan and a Graduate Student Researcher and undergraduate assistants in Ecology.

Scientific Questions to be Addressed

We propose to address the following questions in an interdisciplinary research program that will take advantage of the unprecedented definition of hydrodynamic and geomorphological conditions and processes in a restored river:

Over-arching question: *How do restored hydrodynamics and channel bed dynamics influence macroinvertebrate populations, predator-prey interactions between macroinvertebrates, juvenile Chinook salmon and other native fishes, and the structure of food webs in the Merced River?*

Specific questions for analytical design:

1. *How do the species composition, population abundance and demographics, and trophic structure of macroinvertebrate communities in the restored portion of the Merced River vary with small-scale (1-10 m) physical features (flow velocity, bed sediment, benthic plant community composition), large-scale (10-100 m) physical features (channel cross section, water depth), and time (seasons, floods, and temporal changes in bed texture, plant communities, debris, and flow conditions)?*

2. *How do species interactions among macroinvertebrate, juvenile Chinook and other salmonids and native fishes vary with small- and large-scale physical features of the river, and with temporal changes in physical features?*

3. *How do temporal changes in physical features of a river influence the structure of food webs that support salmonids and other native fishes?*

Methods

To address these questions we will conduct:

1. a sampling program to identify relationships between physical characteristics (measured and related to watershed-level controls and restoration design by our collaborators) and food web components, including macroinvertebrates;
2. manipulative experiments to quantify physical-biological interactions
3. description and modeling of food webs to integrate the physical and biological information for use in predicting long-term consequences of different geomorphological conditions and alternative river management strategies

The study will aim specifically to provide quantitative guidance on ways of promoting favorable populations of prey for salmonids and other native fishes in future restoration projects in the Merced and similar rivers.

1. *Community patterns: sampling and statistical analysis*

Identifying correlations among community composition, trophic structure, and the local physical characteristics of a river is a first step in understanding physical-biological coupling. The sampling program would be designed to (a) measure variation in common community parameters (abundance, species richness, and trophic structure) of benthic and zooplankton macroinvertebrates and (b) estimate how much of that variation is explained by geomorphology (channel cross section, reach, microhabitat, and substrate type), flow (velocity and turbulence), and temperature. We will also measure how invertebrate communities co-vary with organic matter (periphyton, macrophytes, and organic debris) and local fish abundance.

River invertebrates are usually divided into feeding groups representing, for example, shredders, gougers, suspension-feeders, deposit-feeders, grazers, and predators. Species within each trophic group inhabit the benthos, water column, and water surface. We plan to sample invertebrates from each habitat type in four replicate pools and riffles along five reaches of the Merced River: immediately upstream of the restored Robinson Reach; the first 250 m of the Robinson Reach where the channel gradient is 0.0029; a middle section of the Robinson reach where the gradient is 0.0023; a lower section with a gradient of 0.0017; and a 250-m reach located just downstream of the restored section. We also plan to sample salmon redds identified by agency biologists and by Healey in another section of the proposal, and locations down river that have experienced anthropogenic inputs of sediment, which can have profound influence on invertebrate and salmonid population biology. We expect that the differing gradients (and sediment inputs) will affect sediment transport and the evolution of the bed state (texture and packing) and morphology (bar accumulation), as identified and explained in the physical habitat study. In each pool/riffle combination within a reach, we will employ stratified random sampling to collect invertebrate community samples using a variety of sampling methods, including plankton nets, sweep nets, drift nets, kick nets, core sampling, and diver counts within quadrats or along transects placed on the river bottom. We will quantify species composition, abundance, size frequencies, and biomass. To quantify algal abundance and biomass on the river bottom at locations where invertebrates are sampled, we will record the percent cover and take algal scrape samples from 6 replicate 49 cm^2 areas, primarily on rocks and cobbles at locations where algae usually grow. All invertebrates collected in the field will be procured in 10% buffered formalin, returned to the lab, and sorted by trophic group, taxi, sex, and size categories. Plant samples will be procured and later analyzed for dry weight and total Chl a concentration.

The percent cover of each substrate type (sand, pebble, cobbles, organic debris) will be recorded for each benthic invertebrate sample. Percent cover will be estimated from direct counts or from digital underwater photographs of each substrate type. Flow speed will be recorded during high and low flow seasons across each substrate type, in mid-water, and near the surface over 10-minute periods at each site that is sampled for invertebrates. Flow samples will be taken with an Acoustic Doppler Profiler (ADP), which will also be used for the high-resolution flow field studies. The ADP will also measure water depth and temperature. Measures of turbulence at each sampling station will made based on multidimensional velocity profiles recorded by the ADP [Allan, 1995; Lenihan, 1999]. The ADP will also be used to monitor flow in our manipulative experiments. Sediment grain size will also be measured as described in Hydrodynamics and Geomorphology section of this proposal. All invertebrate and plant sampling will be conducted in different flow conditions, seasons, and after significant disturbing flows.

To test whether community responses (total abundance of each taxon, feeding groups, species richness, size frequencies, and biomass) within each habitat type (benthos, mid-water, and surface) vary with location (i.e. pool vs. riffle) and site (i.e., reach) in the Merced River, a three-way hierarchically-nested ANCOVA with habitat type nested within location, location nested within reach, and flow characteristics as a covariate. Multiple regression and Principal Components Analysis will quantify relationships between physical variables, including flow speed, temperature, algal biomass/Chl a concentration, and organic matter content. The emphasis of these studies will be on developing predictive relationships that can be applied to, and tested at other sites, and used to guide manipulative experiments.

The interpretation of habitat use by macroinvertebrates (and fish, see later) could be enriched the geostatistical work on flow fields and bed texture and morphology, described in Section A of this proposal to establish a quantitative link between hydraulic complexity at a range of scales and the habitat utilization by invertebrates or fish. For example, we hypothesize that a reach with greater small-scale variability in depth and velocity (which can be summarized with a variogram) will tend to have a greater diversity of insects. Fish diversity and numbers might respond to habitat complexity over another spatial scale. The same idea could be extended to the assembly of the floodplain plants communities, and would be easy to implement because of our tightly organized team approach to the field work.

2a. *Experiments on invertebrate population demographic responses*

Cause-and-effect relationships between physical drivers and community structure and composition are best revealed by identifying how specific factors, or combinations of factors influence demographic rates of individual organisms. Key demographic rates that underlie changes in population abundance, and therefore variation in community composition, are births, recruitment, growth, reproductive output, dispersal (emigration-immigration), and mortality. Quantifying demographic rates allows for the creation of population dynamic models in order to explore relationships between river characteristics and responses in invertebrate communities.

We propose to explore how key habitat features influence population responses of invertebrates using a suite of manipulative field experiments, consisting of mesocosm-flumes that are designed to control water depth, flow speed (using in-situ flumes pioneered by [Cooper and Baramuta, 1993]), bed type, organic debris content, and algal growth. The structures would provide the means to test relationships interpreted in our sampling program. The flumes (4-m long x 1.5-m wide; rebar supports, plexiglass sides that extend above surface water and control light penetration, and mesh entrance and exit ports) are designed to modify relative flow speed [Cooper and Barmuta, 1993]. One set of flumes increases ambient flow by forcing a larger volume of water to flow within their borders via a funnel-shaped up-stream opening. A second set of flumes retards ambient flow by baffling water before it enters the enclosure. A third set of flumes acts as a control by not influencing flow speed. The goal of these experiments is to identify how specific hydrodynamic and geomorphological features interact to influence demographic rates of a circumscribed set of invertebrate species representing different feeding groups. For example, if the abundance of gammarid amphipod grazers (i.e. important prey for juvenile Chinook salmon) on the benthos in deep pools is found to vary in response to substrate type (e.g. coarse gravel vs. mixed pebble-sand) in the restored Robinson's Reach; to organic debris in the un-restored downstream reach; and to flow speed in both pool-reach combinations, we will design and conduct an experiment that entails an orthogonal manipulation of these three factors to test management options to maximize gammarid abundance. Such an experiment would entail the measurement of recruitment, growth, and survivorship of individual gammarids that colonize replicate rocks of similar dimensions that support different levels of algal growth (e.g., zero, 10%, 50%, and 100% cover) outplanted on to different substrate types (e.g., coarse sand vs. gravels of various size), that, in turn, are situated within the mesocosm flumes. Twelve mesocosm-flumes would be required (one for each treatment combination) and the experiment would be repeated (i.e. blocked) through time to provide replication. Multifactor MANOVAs or MANCOVAs would be used to detect differences in various demographic responses among treatments (including the effects of predator-prey interactions among invertebrate species). The specific questions to be addressed in the experiments will be driven by the patterns observed in the community sampling.

2b. Experiments on predator-prey interactions among invertebrates and salmonid fishes

Top-down control through predation by fishes, and bottom-up control through primary production control invertebrate population dynamics in river food webs [Power, 1990]. Habitat heterogeneity and flow can influence both top-down and bottom-up processes [Power et al. 1995; Hart and Finelli, 1999]. Work in Northern California rivers indicates that while fish forage for invertebrates in two major habitat types, on (1) rocks and boulders and (2) on gravel and sediment bottoms, predation by fishes significantly affects invertebrate populations only on rocks and boulders [Power, 1992]. However, effects of fish foraging in gravel and sediments have not been adequately examined as a function of flow conditions, channel configuration, sediment type, and organic debris content. In addition, we know little about the effects of invertebrate predators on salmon eggs in redds. We propose to use a series of experiments using fish predator enclosure and exclosure mesocosms-flumes to examine how changes in physical habitat structure at different spatial scales, flow, and the structure of food webs (e.g., three-level vs. four-level food chains) influences predator-prey interactions among invertebrates and fishes. We will also test with experiments whether invertebrate predators influence salmon egg hatching success in varying flow and substrate conditions. These experiments are designed to identify what factors or interaction of factors affects the distribution and abundance of macroinvertebrate prey species, and predation rates of salmonids, especially juvenile Chinook. In addition, rates of predation among different trophic levels recorded in these experiments will be used in food web modeling.

To test whether substrate type, flow, and fish predation interact to influence macroinvertebrate species in the Robinson Reach, we will install replicate large pens, pen controls, and open pens on replicate bottom areas in different locations of the river (pools vs. riffles vs. banks), with different substrate features (boulders vs. rocks; gravel vs. fine sediment), water depths; and flow speeds. Pens will be similar to those used by Power [1992]: 6 m^2: 3-m long x 2-m wide x 1.5 m tall; 3-mm mesh; and constructed of plastic screen lined with black plastic shade cloth. Juvenile salmon, and adult roaches or three-spined will be placed into pens (enclosures). Pen controls will be used to exclude fish predators (exclosures). Open cages will used to examine the effect of cage structure (controls). The species composition of algal and invertebrate communities and demographic responses of invertebrates will be examined in the different cage treatments. Flow speeds will be measured with the ADP.

In one set of experiments, we will allow natural invertebrate communities to be established on rocks and in surrounding sediment, and record changes in the populations of species known to be important fish prey or functional members of the food web (algae, primary consumers, and secondary consumers) over periods of days to weeks. In a second set of experiments, we will add known numbers of marked invertebrate individuals from each trophic level within the cages and measure their survival over short-time intervals (3-12 hours). Benthic algal (cyanobacteria, chlorphytes, and diatoms) percent cover and biomass will be sampled non-destructively in each replicate cage treatment. We will also sample zooplankton communities in the different cage treatments. This experiment will be conducted under high- and low-flow conditions and through time as river geomorphology changes, for example, after major flooding events. In a third experiment, conducted in a set of fish exclosures placed on salmon redds identified in Healey's portion of our study, we will test the effect of invertebrate predation on salmon egg hatching success. Salmon eggs will be placed in redd sediments of different grain size and organic content, and with different flow speeds, that contain natural populations of infaunal invertebrates and matching sediments from which invertebrates have been removed. Data from these experiment will be used (1) to describe the structure of food webs as it changes temporally with the larger scale physical characteristics of the river; (2) to quantify the relative effects of within-river location, substrate type, flow, algal cover, fish predation, and number of trophic levels (three vs. four) on invertebrate populations in Robinson's Reach; and (3) to produce feeding rates that can be used in food web modeling (see below).

3a. Isotopic Analysis of Food Web Structure

Stable isotope analysis will be used to examine the structure of the river food web in the initial stage of our research, and periodically throughout time as physical characteristics change. Our objective is to use stable carbon and nitrogen isotope ratio analysis of consumers of varying trophic status to evaluate the relative contribution of different algal species, detritus, macroinvertebrates, and small/juvenile fishes to the food web that supports salmonids in the portions of Robinson's Reach. To identify carbon and nitrogen sources used by various consumers, we will measure the isotopic composition of natural populations of various species in the food web in the different portions of Robinson's Reach that will be sampled for invertebrate communities. The use of stable isotope ratios in food web studies is well established and the merits and limitations of the technique are reviewed in Fry and Sherr [1984], Simenstad and Wissmar [1985], Currin et al. [1995], and Peterson et al. [1985]. The carbon isotope ratio (expressed as ^{13}C in $^{0}/_{00}$) of a consumer closely reflects the ratio of dietary carbon [Fry and Sherr, 1984] whereas the stable nitrogen isotope ratio is typically enriched in ^{15}N from 2 to 4 $^{0}/_{00}$ relative to dietary nitrogen [DeNiro and Epstein, 1981; Peterson and Fry, 1987].

3b. Food web modeling

Results of community sampling, demographic measurements, predator-prey experiments, including the biomass of each trophic level and biomass transfer through grazing and herbivory, and isotope studies will be used to erect food web models designed to predict, among other things, the total biomass of salmonids that can be sustained under different river configurations. Food web models will be generated using the EcoSim food web model developed by Walters et al. [2000]. This model and its variations (e.g. EcoSpace) provide a powerful tool to examine variation in biomass and production within different trophic levels as they respond to variation in resource levels, species interactions, disturbances, and habitat structure. Our objective is to model the food web of the restored portion of the Merced River, and then to observe how the food web responds to fluctuations in flow regimes, habitat characteristics, species composition, and trophic structure of invertebrates and fishes. EcoSim modeling will allow us to estimate the long-term effects of changes in the abundance of fish and prey populations.

Products

The research program is designed to help us understand and predict the population and community responses of macroinvertebrate communities to variation in restored habitat characteristics, and to changes in fish populations, as they evolve and become more complex over time. This is critical for understanding population dynamics of salmonid and other native fishes. Our sampling program will establish a baseline for monitoring invertebrate communities on the restored reach, quantify environmental controls on invertebrate populations, and measure the relative influence of geomorphology, flow and predator-prey dynamics on food web structure in the Merced River. Our experimental studies will elucidate mechanisms that explain relationships identified in our sampling program, including how the engineered geomorphology and hydrodynamics influence invertebrate population dynamics and species interactions. Modeling will simulate the response of invertebrate species to larger-scale and long-term changes in environmental drivers, and to explore how management strategies (further physical modifications of the river, removal of nonnative species, stocking of fishes) might influence food web dynamics. Findings from this research component will relevant to river restoration design in the CALFED region and in other Mediterranean-climate systems in California and elsewhere.

C. EFFECTS OF RESTORED PHYSICAL PROCESSES ON FISH ECOLOGY AND BEHAVIOR [Healey and Kendall]

Description of the Topic

The larger objective of this research is to understand and develop models of the relationships among: (i) physical forcing of habitat attributes in stream reaches; (ii) associated biotic processes (plant and benthic invertebrate production and distribution); (iii) the use of the habitat by the local fish community, and (iv) the consequent impacts on fish population dynamics. Understanding these relationships has been a long-standing objective of river ecologists. However, as Armstrong et al. [2003] point out: "By drawing on published data it is possible to divine broad ranges of acceptable conditions for the life stages of each species. However, it is not possible to partition this variation into between-population differences, within-population preferences, within-population tolerances, and effects of interactions between habitat variables." In a thoughtful examination of the state of habitat modeling, Hardy [1998] acknowledged that: "... integration of all the pieces has yet to be accomplished, field validation remains unproven, availability of an integrated analysis framework (i.e. computer software system) is not yet available, and a clear framework for selection and application of specific tools has not been developed." Hardy [1998] concluded with a plea for a broader collaborative effort between biologists, engineers and resource managers. **A fundamental premise of our research is that, as a team of physical and biological scientists, engineers and resource managers we can make significant progress in the integration that Hardy was looking for.**

The Robinson Reach provides a unique platform on which to investigate the processes connecting physics to fish. Because Chinook salmon is a focal species for the restoration, the majority of questions posed address aspects of the life history of salmon. However, the reaches also provide habitat for other native species about which very little is known. Our research on these species will be of a more exploratory nature [Brown and Ford, 2002].

Scientific Question to be Addressed

Overarching Question: *How do Chinook salmon and other native fish species make use of habitat characteristics and functions in river channels and floodplains, and how do their behavior, energetics, and population dynamics respond to changing environmental conditions, especially after channel restructuring?*

Specific questions for analytical design:

1. *What is the relationship between selection of spawning sites by female Chinook salmon and substrate characteristics and flow field and water quality at tributary, reach and local scales?*
2. *How is survival of eggs related to physical, chemical and biological characteristics in the vicinity of the redd?*
3. *What is the relationship between juvenile salmon habitat use and substrate and flow field characteristics at the reach and local scales and how are these modified by food availability?*

4. *How do the characteristics and extent of various habitats contribute to the net production of Chinook salmon smolts within the Robinson reach?*
5. *How do habitat quality and the patterns of habitat use affect the growth of juvenile salmonids?*
6. *What is the relationship between the distribution and abundance of non-salmonid native fishes within the Robinson reach and substrate, flow field, cover, and food availability? How do the spatial patterns of these variables and resulting fish movement interact to influence population dynamics of these species?*

1. *What is the relationship between selection of spawning sites by female Chinook salmon and substrate characteristics and flow field and water quality at tributary, reach and local scales?*

This question has been studied mainly at the reach or local scale [Healey, 1991]. At the tributary scale, observations suggest that fish tend to move to upstream spawning areas first and move downstream again as the upstream areas become filled with spawners. However, this is not an absolute rule and different segments of a run may do different things. At the tributary scale, our research will depend heavily on collaboration with CDFG personnel, who have conducted tributary-scale monitoring of spawning Chinook for many years. At the reach scale, emphasis has been on depth, velocity and substrate characteristics as factors determining suitability of habitats for spawning [Bjornn and Reiser, 1991]. Habitat suitability assessment based on these parameters has, however, had mixed success [Shirvell, 1989; Gibbins et al., 2002]. Selection at the local scale has also been related to flow, depth, substrate, and subgravel flow [Tautz and Groot, 1975; Bernier-Bourgault and Magnan, 2002]. Each of these variables will be measured.

2. *How is survival of eggs related to physical, chemical and biological characteristics in the vicinity of the redd?*

Siltation of redds resulting in slow percolation of water through the gravel is a frequent cause of poor survival of salmon spawn [Bjornn and Reiser, 1991]. The well-sorted gravels of the restored reach and the low amount of fines entering the reach suggest that egg survival should be high in Robinson Reach. However, other factors are known or suspected to play a role in egg survival, such as predation and disease, and these have not been well studied. Recent evidence also suggests that even small amounts of silt, if it is deposited at the bottom of the egg pocket, may cause high mortality [Meyer 2003]. Fine sediment accumulation and its effect on subgravel flow will be studied and related to hydrodynamics and channel morphology in conjunction with the physical component (A) of this study. Flow-related mortality of embryos in the redd is often identified as an important factor in population viability [e.g. Jager et al., 1997] but the mechanism remains uncertain. We plan to study embryo survival and associated physical and chemical conditions directly. Temperature, DO, and TDS will be monitored continuously during the incubation period in a sample of redds.

3. *What is the relationship between juvenile salmon habitat use and substrate and flow field characteristics at the reach and local scales and how are these modified by food availability?*

Detailed work has been done on the daytime use of habitats by some salmon species but not juvenile Chinook. Distributions in relation to flow and substrate are size-dependent but also related to food availability and social relationships within the group of fish. Fausch [1984] hypothesized that stream dwelling salmonids occupy locations where they can obtain maximum net energy gain from foraging. The choice of specific habitats is influenced by physical attributes, food availability and predation risk, and the response of fish to these factors is modified by size and age [Giannico and Healey, 1999; Reinhardt and Healey 1997, 1999]. Social status is also important, however, and individuals adopt different tactics for getting food depending on social status [Neilsen, 1992].

Day and night distributions of juvenile salmon and other fishes are known to be very different [Helfman, 1993; Heggenes and Dokk, 2001]. However, the relationship between day and night distributions and whether individual fish typically move between the same locations on consecutive days has not been determined. Chinook also undertake seasonally concentrated redistributions to different habitats [Healey, 1991]. In larger rivers these redistributions can take fish into and out of tributaries and downstream.

4. *How do habitat quality and the patterns of habitat use affect the growth of juvenile salmon?*

A juvenile fish uses assimilated food to provide energy and resources for basal metabolism and respiration, active behavior such as swimming, and growth. Since food uptake is not continuous, some energy also is stored in reserves, which are drawn upon later. Dynamic energy budget (DEB) models provide a framework for integrating the feeding, behavior, and physiology of the fish to understand how fast it can grow under various (and variable) environmental conditions [Kooijman, 2000, Nisbet et al., 2000, Fujiwara et al., 2004]. The energetic structure of juvenile salmon has been well studied [e.g., Rombough 1994, Azvedo et al., 2004], and statistical techniques have recently been developed to estimate parameters of DEB models from longitudinal data on growth [Fujiwara et al., 2005].

5. *How do the characteristics and extent of various habitats contribute to the net production of Chinook salmon smolts within Robinson Reach?*

A detailed simulation model that links Chinook adult spawning, egg and alevin survival, and fry growth and maturation to environmental features was developed by Jager et al. (1997). This model has been used to explore effects of management strategies and climate change on Chinook productivity [e.g., Jager et al. 1999, Jager and Rose 2003]. This model has only been tested against relatively sparse data [Jager et al. 1997]; we should be able to collect a particularly rich data set for testing through the detailed, interdisciplinary investigation of the Robinson reach.

5. *What is the relationship between the distribution and abundance of non-salmonid native fishes in the Robinson reach and substrate, flow field, cover and food availability? How do the spatial patterns of these habitat variables and resulting fish movement interact to influence population dynamics of these species?*

The ecology of native fishes in California rivers is poorly known, and understanding their distribution and habitat use is complicated by the presence of large numbers of non-native invasive species [Brown and Ford, 2002]. Native species appear to be most successful in rivers subject to the least flow regulation or other human alteration. Most conservation and restoration emphasis in the Central Valley has been on salmonids with relatively little attention paid to native species upstream of the Delta. An integrated research study on the Robinson reach and elsewhere on the Merced provides a unique opportunity to study the behavior and response of non-salmonid native species to habitat variables.

Methods

We propose a number of observational and manipulative studies related to the questions posed above. We are aware that any research that interferes with salmon in the Merced will be subject to regulatory oversight. In designing the studies every effort has been made to limit the invasiveness of the proposed methodology, and we will plan our proposed studies in consultation with the responsible permitting agencies.

Observational Research

1. Redd Site Selection

- Monitor movement of Chinook into and out of Robinson Reach using videographic fish-counting equipment and note timing and location of each redd as it is constructed. Monitoring of fish movement through the reach will allow us to assess which segment of the run contributes most to the local spawning population. This work will be coordinated with the tributary-wide monitoring of spawning salmon distribution by CDFG.
- Radio-tag individual adult salmon entering the reach and monitor their behavior in the reach and as they take up residence or move upstream. Tagging fish from different segments of the run will define more precisely behavior within the reach and upstream, and will determine stream life in relation to migration timing and physical variables such as temperature. Tagged individuals moving through the reach will be located where they settle upstream and will be subjected to a lower level of monitoring.
- Map precise location of redds within Robinson Reach and upstream. These maps will be compared with maps of physical and chemical characteristics to assess habitat preferences and to compare measured values for Robinson Reach with published habitat preference curves.
- Observe spawning behavior and nest construction on selected redds by underwater video. These observations will allow analysis of behavior in relation to physical characteristics of redd locations within and outside of Robinson Reach. Of particular interest will be the behavior of females nesting on or off the humps engineered into the riffles within the reach.

This work will be conducted and overseen by Healey and Postgraduate #2 in collaboration with Graduate Student Researcher #1 and undergraduate assistants during two years of the contract period, with the exact timing depending on flow conditions and salmonid behavior.

2. Egg and Embryo Survival

- Monitor egg development in selected redds in and outside of Robinson Reach to assess development rate in relation to physical and chemical characteristics of interstitial water (flow, salinity, DO, TDS). Freeze-core samples will be removed twice from a selected number of redds at 200 and 400 degree days to compare development and survival within and without Robinson Reach. Samples will provide data on egg burial depth, substrate composition, development stage, embryo weight, and survival index. Additional sampling will be required to measure subgravel flow using either the dye injection or electronic technique.
- Assess the possibility of invertebrate or vertebrate predation on developing eggs by sampling benthic organisms within spawning riffles. Freeze-core samples will be used to search for predators of eggs and embryos at sites where Lenihan will study the invertebrates and Dunne and Graduate Student Researcher Wydzga are studying the infiltration of fine sediment into the bed as it is controlled by the hydrodynamics and sediment supply of the restored reach.

3. Juvenile Habitat Use

- Monitor fry emergence and dispersal by means of upstream and downstream traps. Measure length, weight and degree of yolk absorption in migrating fry. The measurements will characterize the downstream dispersing fry in comparison with those residing within the reach.

- Monitor fry size and distribution within habitats of Robinson Reach and upstream by seining, minnow trapping, snorkeling, and underwater video. Particular emphasis will be on determining habitat choice in relation to depth, flow field, substrate, food, and cover. These data will be integrated with substrate and flow modeling and invertebrate sampling to model habitat preferences in relation to physics and food. By collaborating with CDFG we hope to be able to define juvenile distribution among reaches and the relative contribution of restored and unrestored reaches to juvenile production.

- Capture and tag individual fry within selected habitats to assess site fidelity and behavior in relation to conspecifics. Available tagging techniques include cold branding, vital dyes, latex injection, and tattooing. Fry behavior observations will be conducted by snorkeling and underwater video. Collaboration with vital dye and PIT tagging programs of CDFG will increase our ability to interpret and extrapolate from these studies.

- Identify nighttime habitats of fry and evaluate the relationship between day and night habitats. The technique for doing this remains to be worked out, so initially the study will involve exploration of technique. Elsewhere we have found that juveniles come into very shallow, low velocity water near shore at night but there may also be other refuges and behavior may vary with age and size, and these may increase with in-channel structure..

- Monitor feeding rates of selected fry by snorkeling and/or underwater video at different times of day and in different habitats to assess foraging efficiency during two years. Determine feeding habits and daily ration by analyzing stomach contents removed by gastric lavage. The measurements will be conducted by Healey, Postgraduate Researcher #2, and undergraduate assistants during two years of the contract period.

4. Juvenile growth

- Select tagged individuals whose behavioral and movement histories are well resolved to analyze for growth patterns. The daily growth of individual fish can be reconstructed from microscopic analysis of the otoliths (ear bones), which lay down daily rings [Hobbs et al., 2004]. We hope to have these measurements of otoliths made by an unfounded collaborated who already works with Kendall, but the measurements are not yet guaranteed.

5. Integrated productivity

- Ensure that all parameters in the salmon model are being measured.

4. Non-salmonid species

- Monitor abundance, distribution and size of non-salmonid fishes by trapping, seining, snorkeling, and snorkeling. Habitat use by non-salmonids can be compared with physical and biological attributes to determine habitat preference curves. These can be compared with published data for other systems.

- Radio and/or floy tag selected individuals among the non-salmonids to obtain detailed information on movement patterns and daily routine.

- Determine diets and feeding rates of non-salmonids by gastric lavage. Particular attention will be paid to the behavior and distribution of benthic feeding fishes during spawning and egg incubation as they may be egg and embryo predators.

All of these measurements will be incorporated into the monitoring listed above for salmonids.

Experiments

1. Redd Site Selection

- Modify depth, substrate composition, and/or subgravel flow in selected locations to assess their effect on redd site selection. An experiment of this nature is already underway as riffle topography was designed with humps to provide preferred redd sites for Chinook, and the results are being monitored by Dr. Randy Mager of CDWR. Our own experiments will be informed by the observational data on redd site selection, and will test whether we can enhance or detract from the desirability of sites by specific kinds of manipulations.

2. Egg and Embryo Survival

- Plant egg baskets in areas of the reach having specific physical characteristics to determine development and survival of embryos under specific conditions. The nature and development of the physical characteristics will be studied simultaneously by A. Wydzga (see section A). Sites outside Robinson Reach may be used to increase the contrast in conditions.

- Raise eggs under different temperature and DO regimes to determine if development patterns of the Merced population are consistent with published information on the effects of temperature and oxygen concentration on development.

The results of these experiments will allow better tuning of population models that incorporate egg-to-fry survival as a discrete component. A goal is to elaborate and tune models such as that published by Jager et al. [1997] to more accurately represent the dynamics of Chinook ecology in the Merced River and Robinson Reach.

3. Juvenile Habitat Use

- Alter local depth, flow, and substrate characteristics and food delivery to determine if juvenile use of a habitat can be enhanced or discouraged. The intent here is to test assumptions and preliminary predictions of models that derive habitat value from physical and biological attributes. These experiments will be informed by the observational data on habitat preferences and results of other studies that relate food and physical attributes to habitat choice in salmonids.

4. Non-salmonid species

- No experiments planned at this time

Model Development

The overarching objective of the entire study is to integrate information from measurement and modeling of the physical habitat, invertebrate abundance, and production of fish (particularly salmonids) to develop a model of habitat use and habitat value within the Merced and the Robinson

Reach in particular. The models developed will eventually be transferable to other rivers. Several modeling approaches will be employed over the duration of the research:

- Using existing habitat models to assess and predict habitat value in advance of making biological measurements to generate predictions and help direct sampling design. We would use PHABSIM and various statistical models of habitat suitability and habitat value.

- Re-tuning existing models based on measurements made within the study (For example, improving PHABSIM predictions using locally derived habitat preference curves, and re-parameterizing statistical models with Merced-specific data).

- Developing new statistical models of various aspects of habitat use based on the data collected on the Merced.

- Developing dynamic energy budget models that reflect salmon biology, and using data from the experiments and the measurements of individual growth rates to estimate parameters of the models. These fitted models will allow us to relate patterns of growth among individuals to the measurements of both abiotic factors and the availability of invertebrate food that have been made in the locations where the fish were sampled. This will allow us to understand what factors influence the growth of fish and how these are related to the various habitats in the reach.

- Parameterizing (and modifying if needed) the Jager et al. [1997] model. Comparing the predictions of this model with the observed number of adults entering the reach and subsequent juveniles leaving the reach will allow us to determine whether our understanding of the conditions influencing salmon spawning and juvenile survival is complete. This model will also allow us to estimate the relative contributions of the various habitat types in the reach to salmon recruitment, which will inform future restoration projects.

- Developing a spatially explicit population model for the resident non-salmonid species, using data on movement of marked individuals as well as spatial data on biotic and abiotic factors along the reach. This model will be similar to that of Anderson et al. [2005], in which space is treated as one-dimensional and the fish movement and the population dynamics of both the fish and their invertebrate prey are modeled at each location. This will allow us to understand the role of the various habitat types, as well as their spatial configuration, in maintaining the health of the fish populations. This model will also allow us to predict the spatial extent of the response of a disturbance (such as an input of bed-material sediment) at a particular location [Anderson et al., 2005].

The modeling will be conducted by Kendall and Graduate Student Researcher #3 in collaboration with Healey and Postdoctoral Researcher #2, in the first two years of the project. Since a unique feature of the modeling of fish utilization of the reach will be use of a detailed flow model to characterize the habitat, we also plan a close involvement between this group of ecologists and the flow characterizations by Postdoctoral Researcher #1, Dunne and Legleiter

Products

We hope to produce three kinds of results from this research. The first is a more detailed assessment of how completely restructuring and re-scaling a river, such as the Robinson Reach restoration project, and other CALFED restoration projects, affects biological resources. These projects are extremely expensive and deserve a thorough evaluation of how they affect the mechanisms of fish production. The second is a better understanding of habitat use within the tributary by Chinook and other fish species. Improved understanding of habitat values for spawning, incubation and juvenile rearing will provide a firmer basis for future conservation and restoration projects throughout the Central Valley. Our research concentrated on the Robinson Reach will be augmented by lower intensity measurements outside the reach and by collaboration with CDFG in tributary-level assessment. The third kind of result will be a new generation of integrated "Physics-to-Fish" models that will improve the process of habitat evaluation and provide a better understanding of the dynamic relationships that tie fish ecology and behavior to managed physical habitat. We intend to take advantage of the special characteristics (simplicity, newness, gradually evolving complexity, and opportunity for experimentation) in the Robinson and neighboring reaches of the Merced to further this goal. The biggest advantage of the Merced project is the potential to integrate physical studies with biological responses in ways that have not been reported in the scientific literature.

D. RESTORATION OF FLOODPLAIN VEGETATION UNDER ALTERED FLOW REGIMES [Davis]

Description of the Topic

Understanding the relationship between floodplain revegetation, planting strategies, partially restored flow regime, and long-term vegetation dynamics is critical to successful restoration planning and design. It can suggest strategies for planting, controlling flow regimes and water table heights, and designing floodplain topography, as well as provide a risk-based expectation for the time scales for revegetation. This part of the research plan will be conducted by Davis and Graduate Student Researcher #4, supported by the Computer Technologist and under-graduate field assistants for surveying vegetation.

The floodplain of the Robinson Reach of the Merced River has undergone extensive rehabilitation at the scales of the site and river reach but the river still experiences reduced flows, flow variability, and sediment loads. Restoration of the floodplain has involved grading, planting, mycorrhizal inoculation, and irrigation in 6 management areas and an adaptive management program involving some experimentation and a monitoring program is underway [California Department of Water Resources 2003]. We propose a 3-year research program designed to complement these ongoing management experiments with additional observations, manipulative experiments and modeling of the processes of plant community assembly. Our interdisciplinary research will focus on elucidating the coupling of hydrologic and geomorphic processes to the development of floodplain vegetation under regulated flow. The program will be implemented in close consultation with agency staff and consultants to ensure that our experiments are compatible with site restoration goals and management activities.

Based on scientific research to date, we expect novel plant communities to develop in the different management areas of the study reach that retain some characteristics of the original riparian species assemblages and successional relations but exhibit very different species abundances, structure, spatial pattern and dynamics. Because of the strong coupling and feedbacks between abiotic and biotic components of the system, we also predict that plant community development from simple starting conditions to more complex biological communities will vary considerably depending on initial floodplain restoration and re-vegetation practices at both the site and river reach scales as they interact with the flow regime and sediment and channel that will be documented in component A of the integrated study.

Scientific Questions to be Addressed

Overarching question:

What degree of restoration of riparian plant communities is achievable under partial restoration of historic flow regimes, which may affect moisture conditions in the riparian root zone, sedimentation, and channel mobility?

Specific questions for analytical design:

1) *What is the relationship between flow regime, water-table elevations, and floodplain vegetation pattern and succession on restored river reaches experiencing reduced flow levels and variability?*
2) *How do initial plant community pattern, structure and composition influence restoration outcomes for floodplain plant communities? In particular, do restoration strategies initiate ecological patterns and processes that promote the assembly of resilient communities and long-term persistence of desired species?*
3) *How are species-specific patterns of tree establishment and growth affected by management actions to control exotic plant species?*

To address these questions we will conduct observational and manipulative experimental studies at the local scale. These studies will be coupled to the development of dynamic models of site, reach-, and catchment-scale processes to examine long-term consequences of alternative vegetation restoration and water management strategies. The research will be conducted in close consultation with California Department of Water Resources and the California Department of Fish and Game, the agencies responsible for the initial restoration design and post-project monitoring, to ensure that the research is compatible with restoration goals and constraints and takes maximum advantage of the existing restoration design, management and monitoring.

Background

The mature floodplain vegetation of the site is classified as Valley Foothill Riparian (VRI) habitat. Mature VRI forest has a canopy layer of some combination of white alder, cottonwood, California sycamore, valley oak, and one or more willow species, a subcanopy tree layer, an understorey shrub and liana layer, and an herbaceous layer consisting of sedges, rushes, grasses, and some forbs [Warner and Hendrix, 1984; Moyle et al., 1996; Harris, 1999].

We have fair understanding of the basic autecology of dominant floodplain tree species in relation to streamflow regime and fluvial geomorphology [e.g., Naiman and Decamps, 1997; Mahoney and Rood, 1998; Stromberg, 2001; Nilsson and Svedmark, 2002; Shafroth et al., 2002]. Patterns of tree establishment and growth reflect species-specific responses to the timing and magnitude of flood stage and the rate of water-table recession [Alpert et al., 1999; Amlin and Rood, 2001; Amlin and Rood, 2002]. Flood disturbances and interactions between the floodplain topography and the water table maintain a mosaic of seral communities that vary with geomorphic position, which in the case of the initial study site has been simplified, but which is expected to become more complex topographically, sedimentologically, and hydrogeologically over time. Disturbance history, seed supply, local soil conditions and inter-specific competition cause actual community structure and composition to vary considerably from site to site. Observations of rivers where historical flow regimes have been partially restored (e.g., the Truckee River) indicate potentially rapid response of local riparian vegetation patterns to catchment-scale processes and highlight that floodplain community dynamics are governed by multiple scales of control [Wissmar and Beschta, 1998; Stromberg, 2001; Rood et al., 2003]

Research to guide restoration of floodplain vegetation has generally focused on the site scale and on practices to accelerate establishment and growth of desired tree species. These practices include grading, soil replenishment and site preparation, planting (seeds, seedlings and/or cuttings), soil amendments (mulch, fertilizer), and maintenance activities (e.g., weed control, pest control, irrigation). Such practices are expensive, labor-intensive and risky Rood et al. 2003) but they can achieve rapid re-vegetation Alpert et al. 1999). **A key question is whether such restoration practices initiate ecological patterns and processes that will promote the assembly of resilient communities and long-term persistence of desired species.** Because little long-term monitoring has been conducted on restored floodplains, we have poor understanding of the relationship between initial vegetation composition and structure and associated management actions undertaken early in the restoration process (such as weed control or irrigation), and the growth and development of more complex vegetation structure (with associated biotic and abiotic feedbacks) and long-term floodplain vegetation dynamics.

Methods

The proposed research will combine (a) observational research on historical and current vegetation and environmental conditions, (b) experimental manipulation of tree composition and density, and (c) mathematical modeling of floodplain tree populations and vegetation dynamics.

Observational Research

The goal of the observational research is to describe spatial and temporal patterns of floodplain vegetation dynamics in relation to hydrology, soil, and biotic factors. Eventually we will construct formal demographic models for the dominant tree species en route to predictive modeling of floodplain vegetation dynamics. To do this we must monitor species-, age- and size-specific rates of establishment, growth and mortality. This can be accomplished using a mixture of air photos and plot measurements.

We will make intensive measurements of vegetation colonization of the immediate riparian zone because it directly affects geomorphic processes of bank erosion, bar stabilization, and near-bank flow velocities in the channel. In turn, these factors are expected to alter the near-bank channel-bed morphology and thus the availability of shallow-water rearing habitat for juvenile fishes [Trush et al., 2000]. Aggressive invasion of the channel margins by strongly rooted woody plants is facilitated by reduced frequency of high flow velocities [Ligon et al., 1995], and may reinforce the bank and force the development of a rectangular cross section instead of an asymmetrical cross section that would provide a greater diversity of aquatic habitat conditions. We will monitor colonization and uprooting of woody plants along the channel margins.

Historical and modern air photos will be used to develop detailed maps of floodplain vegetation on the restored reach and along upstream and downstream reaches (ca. 1 km in each direction). We will also evaluate the use of imaging LIDAR to map and monitor 3-dimensional vegetation structure. The technique promises major efficiencies for vegetation monitoring. We will use a minimum mapping unit of ca. 0.05 ha. Modern vegetation attributes will include: general vegetation type (Sawyer/Keeler-Wolf System); tree canopy closure; canopy composition (cover values for individual tree species); shrub canopy closure; herbaceous canopy cover; and percent exposed ground. This level of information will require extensive ground survey. Using historical photos we will map tree, shrub and herb cover and, if possible, tree species composition and dominant weedy species. These maps will be used to examine spatial (landscape-level) ecological controls on vegetation development at the site.

Community composition and dynamics will be monitored on belt transects orthogonal to the channel reach. Vegetation monitoring is ongoing along 30m belt transects [CDWR, 2003]. We will augment this monitoring effort with added transects and additional vegetation attributes. The final size and spacing of these transects will be determined during initial field surveys and in consultation with other team members investigating hydrology and geomorphology of the study reach. The existing monitoring plan calls for vegetation sampling in April and June on an annual basis for at least ten years. Our design will expand the monitoring effort for the first three years to obtain more detailed descriptions of vegetation structure and composition, tree species density, recruitment, mortality and growth rates at the site. Soil texture, soil moisture in the vadose zone, and depth to water table at an existing set of wells will also be described and monitored.

Three years will only allow us to look at seedling and sapling stages on the study reach during this first phase of the study, so we will also have to rely on the published literature, archival photography, and age structure (tree ring) analysis of mature forests in adjacent reaches to reconstruct the expected demography of adult trees on the restored site over time. For dominant tree species we will monitor age-specific density and canopy height. Plant community data will be analyzed in relation to biotic and abiotic factors using canonical correspondence analysis (CCA) and species-specific direct gradient analysis. Tree demographic data will be synthesized in the form of species-specific, age-structured Leslie matrices and in more generalized stage-structured, community-specific Markov matrices. In combination with hydrological and geomorphic studies and repeat mapping of the floodplain, these analyses will allow us to describe space-time pathways that lead to patterns of tree survival and growth on different geomorphic surfaces of the floodplain. They will form the basis for predicting patterns of plant community structure that might be expected on other restored floodplains in the region, and this hypothesis can be tested in neighboring restored and relatively undisturbed river valleys.

Experimental Research

Restoration of floodplain vegetation at Robinson Reach has already been implemented with a novel experimental framework that includes experimental irrigation regimes, planting schemes and weed control in 6 management areas. Our experiments will nest inside these experiments in existing management areas. We will supplement ongoing monitoring efforts with more detailed biophysical measurements (e.g., vadose zone soil moisture profiles, soil macronutrients) and demographic data, and will manipulate local vegetation to gain a mechanistic understanding of the controls on floodplain vegetation development. Experimental results will be synthesized via ecological models that will ultimately assist in developing expectations for adaptive ecosystem management here and at similar sites through the CALFED solution area.

The details of our experimental design will be worked out in collaboration with CDWR scientists and collaborators responsible for the initial re-vegetation and subsequent monitoring of the study reach along with other members of our own research team. Here we propose two specific directions to enhance the existing experiment:

1. deliberate manipulation of plant densities within management units to examine the coupling between early successional vegetation structure and composition and longer term restoration outcomes, and
2. studies of soil moisture and plant water status across the range of environments and experimental zones to improve mechanistic understanding of the relationship between site hydrology and riparian community succession.

We hypothesize that the seasonal and stochastic patterns of moisture availability at sites within the floodplain will depend on: the generalized pattern of water-table elevations (driven by seasonal recharge outside of the floodplain, including irrigation on neighboring land), floodplain topography, textural variability of the aquifer, and local recharge (rainfall and overbank flooding). We will test the hypothesis that vegetation growth responds mainly to the first-order spatial pattern of moisture (dominated by distance from the channel) against the hypothesis that local variability dominates the revegetation pattern.

Species-specific survivorship and growth rates of the experimental tree populations will be monitored annually (June-July), along with vegetation structure and composition in the experimental plots. Soil texture and chemistry will be measured and soil moisture will be monitored to supplement water-table heights that are already measured. These data will be used to better understand community development and for comparing alternative restoration strategies. The data will also inform design and parameterization of a model of floodplain vegetation development, as described below.

To examine the relationship between initial conditions and vegetation development we suggest manipulating tree seed and seedling and cutting density in experimental 0.05 ha plots on different geomorphic surfaces. This will entail modifying the existing re-vegetation plantings (which are now comprised of regularly spaced willow cuttings, selective planting of oak seedlings, etc.) to create a factorial experiment that varies starting densities of the target species on different geomorphic surfaces. The potential for such manipulations will have to be negotiated with the local responsible agencies and landowner. Thus, we may alter our plans for these studies, but we have some specific ideas to propose.

Model Development

Our ultimate goal is to create a model of floodplain tree population dynamics that can ultimately be coupled to models of river hydrology (water stage regime and inundation frequency), geomorphology (sediment accumulation), and ecological interactions. However, this part of the research plan will be postponed due to curtailment of funds, and will be conducted in the future by Davis and a postdoctoral researcher. We mention the plan here only to emphasize that in the longer our aims are not only empirical, and the results will be generalized to other sites and applications. We aim to simulate tree population dynamics in space and time using stand development models linked to spatially explicit models of floodplain disturbance and seed dispersal. This is an ambitious goal, however, and we will begin by using relatively simple state-transition models that simulate the spatial and temporal dynamics of discrete patch types (seral stages of a small number of major community types) on the floodplain landscape as a function of disturbance history, vegetation patch age, and geomorphic location. This approach is reviewed by [Urban et al., 1999] and has been successfully applied in a variety of vegetation types to investigate long-term vegetation dynamics under different disturbance regimes e.g., [Davis and Burrows, 1993; Urban et al., 1999]. The model will provide the means of coupling floodplain vegetation dynamics to flow regime (and associated floodplain disturbance regime) as well as restoration and management practices. Thus it will integrate findings from the observational and experimental components of the research.

Products

The research program is designed to help us understand and predict floodplain vegetation recovery and dynamics along restored river reaches under partially restored flow regimes. Our observational studies will establish a baseline for monitoring vegetation dynamics on the restored reach, quantify environmental controls on floodplain vegetation, and characterize both short- and mid-term vegetation dynamics in relation to the hydrological and geomorphological processes and conditions that are being restored. Our experimental studies will elucidate how biological complexity develops on restored floodplains and the relationship between initial ecological conditions and longer-term vegetation succession. We will also examine the interactions between the flow, sedimentation, and morphological conditions of the floodplain, revegetation, and the effects of the evolving riparian plant community on in-channel aquatic habitat. Modeling will be used to organize and integrate our findings, link floodplain vegetation to other components of the system, and explore long-term implications of hydrologic regimes and re-vegetation strategies.

The research is designed as one component of the larger multi-disciplinary effort to understand the coupling of abiotic and biotic processes in rivers and their floodplains. In addition to providing an understanding of how hydrology and geomorphic processes affect plant communities, our detailed studies of how the dynamic riparian zone plant communities develop will directly aid in geomorphic studies of the evolution of the channel boundary, bank erosion, and the near-bank channel morphology that is expected to provide shallow-water rearing habitat for juvenile fishes (Trush et al., 2000). As the floodplain vegetation densifies, we expect that it will alter overbank flow velocities and induced fine sediment accumulation, which will be mapped if and when it occurs. Findings from this research component will improve estimation of trends to be expected in managed floodplain vegetation communities in the CALFED region and in other Mediterranean-climate systems in California and elsewhere.

FEASIBILITY, TIMING, AND MANAGEMENT OF THE STUDY

Sites within the Merced River Salmon Habitat Enhancement Project offer an excellent opportunity for studying the physical and biotic processes that are altered by river restoration. The site involves a river of significant size, with a managed flow regime and simple geometry where detailed physical and biological measurements can be made under planned conditions. The site is easily accessible with instruments and machinery. The initial state was designed after thorough interdisciplinary study, using modern conceptual models of river restoration, it has been thoroughly documented from the outset, and a regular monitoring program continues. Change is currently slow, so that the modest changes in the first four post-construction years can be documented in detail, and the designed flow processes, bed state, and related biological processes can be thoroughly documented in surveys of associations and by experimental manipulation. Measurements can be made under comfortable conditions and at times that are convenient and reliably anticipated. Thus, we expect to gather large amounts of data in two years and continue a less intensive field program with undergraduate assistants during the third year of the contract. However, there is some uncertainty about what opportunities and constraints will arise because flows are unpredictable (the past two years of exceptionally high spring and summer flows and channel change have already enhanced our research opportunities before the funding period), and because the agencies may make plans for channel management to which we will have to adjust. However, Faulkenberry's role in the management of the reach should facilitate close cooperation between the agencies' activities and our research planning.

It is also possible to envision conducting a wide range of experiments at the site to increase the state of learning about how river restoration affects biological resources. Although we do not yet know which experiments would be acceptable to the agencies responsible for river management, we have many ideas to propose. For example, sediment could be supplied to the reach from convenient stockpiles, after we have made a thorough empirical and model study of the response to be expected from such an intervention. Managed flow releases from New Exchequer Dam could also be planned in a similar manner and used for a variety of studies. Smaller experiments could be designed by locally altering the bed condition, the bank geometry, and in-channel physical structure. In each case, our own team and other scientists could mount intensive measurement campaigns, obtaining unprecedented data sets. Each experiment could be carefully planned with a modeling study based on field measurements. These convenient experiments could increase the rate of learning about responses to river restoration, and indicate approaches that could be replicated in other rivers.

The team is closely integrated, with only one member (Healey) living at considerable distance from the site, but able to travel to the Merced for lengthy sampling campaigns. Of the others, four are colleagues in the same building, and they already collaborate in teaching and supervision of graduate students. Faulkenberry designed and built the Merced restoration projects, and two of the graduate students on this project have worked part-time for him under Dunne's supervision. All of the co-PIs are experienced at running or analyzing data from quantitative field projects on rivers, floodplains, or estuaries, among their other projects. They participate in the collection of the data they analyze. However, most of the work will be done by postdoctoral researchers and three graduate students, some of whom would live near the river, and all of whom need to collect significant data sets and publish outstanding results in the scientific literature, which insures that data will be analyzed promptly. All personnel will share an interest in conducting research that is directly relevant to river restoration based on fundamental environmental science. **The focus of the project, in other words, will be on river restoration**. In order to accomplish this goal there is a profound realization of the need for fully integrated studies of physics and biology at several scales and levels of resolution.

We have also given some thought to disseminating our results effectively to people involved in the profession of river restoration. In addition to publications in the scientific literature, and presentations at the CALFED Science Conference, we have been told by agency personnel that small workshops would be an effective means of communication and we are eager to participate in such events. We would also participate in smaller group field meetings and planning sessions with agency personnel conducting joint field studies or data analyses.

PROJECT JUSTIFICATION

The long-term prospects for river restoration hinge upon the ability to design and implement projects that achieve their ecological objectives in a sustainable, economically feasible manner. We will develop information on how physical and biological processes adjust over time to river restoration. The results will be directly relevant to the design and maintenance of restored rivers in the region with its particular constraints on design and operation. The questions addressed were chosen after lengthy and wide-ranging consultations between the PIs and specialists in river restoration and ecosystem management, as well as our reading of the literature and our experience during reviewing and consulting activities as well as active engagement in experimental field research for ecosystem conservation. Each of the PIs has experience with applied conservation, and has interacted with professionals in various fields to design ways of learning adaptively from the accumulation of experience during management actions. We also intend to take advantage of the opportunity for experimental, interdisciplinary studies at this site to generate fundamental ecological knowledge that will be useful for a wide range of conservation actions. The opportunity for experiments at this initially simple site and for comparisons with more complex neighboring sites that have received other treatments or that remain un-restored will be pursued in cooperation with agencies as knowledge accumulates from this project.

SCIENTIFIC RESULTS FROM PREVIOUS CALFED FUNDING TO DUNNE

T. Dunne and M.B.Singer received a grant from the CALFED Science Program entitled "Large-scale Spatial and Temporal Patterns of Flow and Sediment Transport in the Sacramento River Basin and Their Influence on Channel and Floodplain Morphology" The grant extends from 2002 to 2005, and is funded at $390,252.

To date we have produced the following publications

1.Singer, M.B. and T. Dunne; Identifying eroding and depositional reaches of valley by analysis of suspended sediment transport in the Sacramento River, California. Water Resources Research, 37(12):3371-3382. 2001

2.Singer, M.B. and T. Dunne; Modeling decadal bed-material sediment flux based on stochastic hydrology. Water Resources Research, 40, W03302, doi: 10.1029/2003WR002723. 2004

3.Singer, M.B. and T. Dunne; An empirical-stochastic, event-based program for simulating inflow from a tributary network: Framework and application to the Sacramento River basin, California. Water Resources Research, 40, W07506, doi:10.1029/2003WR002725. 2004

4. Singer, M.B. and R.A. Aalto; Event-based sedimentation and scour in flood bypasses: A case study from the 1964 flood in the Sacramento Valley, California. Submitted to journal.

5. Singer, M.B.; Influence of major dams on hydrographs through a river network. Submitted to journal

6. Constantine, C.R., T. Dunne, M.B. Singer. Submitted to journal.

7 .Singer, M.B. and T. Dunne; Modeling the decadal influence of river rehabilitation scenarios on flow and sediment transport in large, lowland river basins. In Preparation

8. Dunne, T. *River Restoration as a Challenge to Hydrological Science,* Invited Langbein Lecture at Nice, France and San Francisco Meetings, Amer. Geophysical Union Powerpoint presentation posted on AGU website.(www.agu.org).

We have also presented talks with published abstracts at 9 conferences in California (two at CALFED Science Conference), nationally and internationally. Other papers are in preparation. We have also participated in many workshops and informal meetings with agency and university scientists working on CALFED projects.

The project continues with coring of the floodplains, flood basins, and flood bypasses of the Sacramento River. Many cores have been collected and are undergoing Lead-210 analysis to measure sediment accumulation rates over the past century. We plan at least five more papers in the international literature and a summary document describing the management implications of flow alteration, sediment augmentation, and setting back levees on the transport and accumulation of bed material and overbank sediment.