Sacramento River Ecological Flows Study
Final Report

Prepared for

CALFED Ecosystem Restoration Program

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1 Introduction

This Final Report synthesizes the results and analyses of the Sacramento River Ecological Flows Study (the “Study”), which was initiated by The Nature Conservancy (TNC) in collaboration with a team of ecologists, geomorphologists, and river management specialists from Stillwater Sciences, ESSA Technologies, the University of California (UC) Davis, and UC Berkeley. The Study was developed, in part, as an outgrowth of nearly two decades of restoration work by TNC and its partners in the riparian corridor of the Sacramento River.

Since 1989, TNC’s habitat restoration efforts on the Sacramento River have emphasized revegetation of riparian areas through active planting. Such efforts were conducted with the understanding that they neither addressed the underlying physical and ecological mechanisms controlling riparian plant recruitment and recolonization on the Sacramento River, nor the needs of native aquatic species in general. TNC and its partners thus sought to develop a complementary strategy for ecosystem restoration on the Sacramento River. In 1999, TNC initiated a pilot study on mechanisms affecting riparian vegetation recruitment along the Sacramento River. These studies suggested that a variety of altered riverine processes were limiting natural recruitment of riparian vegetation. The Sacramento River Ecological Flows Study was initiated to address such processes and to complement existing revegetation efforts. It also expanded the scope of investigations to address the needs of both terrestrial and aquatic species.

The effort began in 2001, with the submittal of a proposal by the Ecological Flows team to the CALFED Ecosystem Restoration Program (ERP). After extensive reviews by CALFED, independent technical reviewers, and individual stakeholders, the Study was funded in 2004 under CALFED Grant # ERP-02D-P61 to The Nature Conservancy.

1.1 Study justification, goals, and tasks

In addition to TNC’s pilot studies on the Sacramento River, numerous water-planning efforts were also underway that highlighted the need for the Ecological Flows Study. These included conjunctive use investigations, integrated storage investigations (such as a potential off-stream reservoir and increasing storage behind Shasta Dam), and a re-evaluation of the operating criteria for the federal water project known as OCAP (Operations Criteria and Plan). Upon reviewing these efforts, we noted a lack of synthesis of existing ecological information, scientific uncertainties limiting the decision-making process, and an absence of ability or tools to easily integrate this existing and potential new ecological information into water-planning processes. Addressing these needs would facilitate a balanced approach to future development of the water resources of the State of California for both ecosystem and human demands on those resources.

At the time of this project’s formulation, the CALFED program reflected the perspective of an emerging body of literature that emphasizes the interconnections between a river’s flow regime and the species that have adapted to live within the riverine environment. CALFED’s Ecosystem Restoration Program included restoring the variability of the flow regime and associated river processes “as an important component of restoring ecological function and supporting native habitats and species in the Bay-Delta ecosystem.” The Ecological Flows Study was therefore formulated to address these CALFED program goals and hopefully lead to restoration and conservation of species and an eventual decrease in regulation resulting from listed species concerns.

The Study was specifically *not* focused on returning to some historical, unaltered flow regime. Instead, the Study sought to identify how the river's flow regime (i.e., the magnitude, timing, duration, and frequency of flow) and management actions (such as gravel augmentation and changes in bank armoring) influence habitats, species, and hydrogeomorphic processes in the riparian corridor. Maintaining or restoring the critical elements of these ecological processes and characteristics could contribute to more informed future development of scarce resources while still providing for human needs.

We formulated goals and tasks of the project for two specific audiences that are often engaged in water planning exercises: managers and decision-makers, and technical specialists. To address the needs of technical specialists, we conducted new studies to fill in information gaps and synthesize the findings of past and ongoing studies. We developed new tools and visual output to communicate our findings to managers and decision-makers who are often not able to remain current on details of research in the areas of resource management they are tasked with managing.

The Study was designed to achieve the following specific goals:

1. synthesize existing interdisciplinary information on linkages among habitats, biota, and hydrogeomorphic processes along the river;
2. develop a decision-analysis tool to evaluate trade-offs among different ecological objectives for different management scenarios;
3. propose strategies for achieving conservation benefits for multiple species; and
4. improve the understanding of how flow corresponds to ecological needs, and thus improve decision making in projects that seek to balance human land and water use with the needs of the ecosystem.

To meet these goals, the Study was organized into four tasks:

Task 1. Synthesize existing information and produce the “Linkages Report.”

Task 2. Develop plans for five studies that address remaining uncertainties, conduct the studies, and summarize the findings in technical reports.

Task 3. Develop a new decision-analysis tool (the Sacramento River Ecological Flows Tool or “SacEFT”) and a new sediment transport model to evaluate flow-related management strategies.

Task 4. Conduct outreach, complete reporting, hold a final stakeholder review workshop, and release a Final Report.

These tasks are described in greater detail below.

1.1.1 Task 1. Synthesize existing information

The Sacramento River empties into the largest estuary on the west coast of the United States and drains roughly 27,000 mi^2 (70,000 km^2), making it the largest watershed in California (Figure 1-1). Its diverse ecosystem has been the focus of many reports and data sets on Sacramento River species, habitats, and the physical and biological processes that affect them. In the Linkages Report (Appendix A), the Ecological Flows team used a focal species approach to synthesize existing information and provide stimuli for developing new hypotheses about how habitats and species are affected by changes in the flow regime. An important secondary function of the Linkages Report was to inform development of study plans for the targeted studies of Task 2. It was also used to inform the development of models that were used to construct the SacEFT of Task 3.

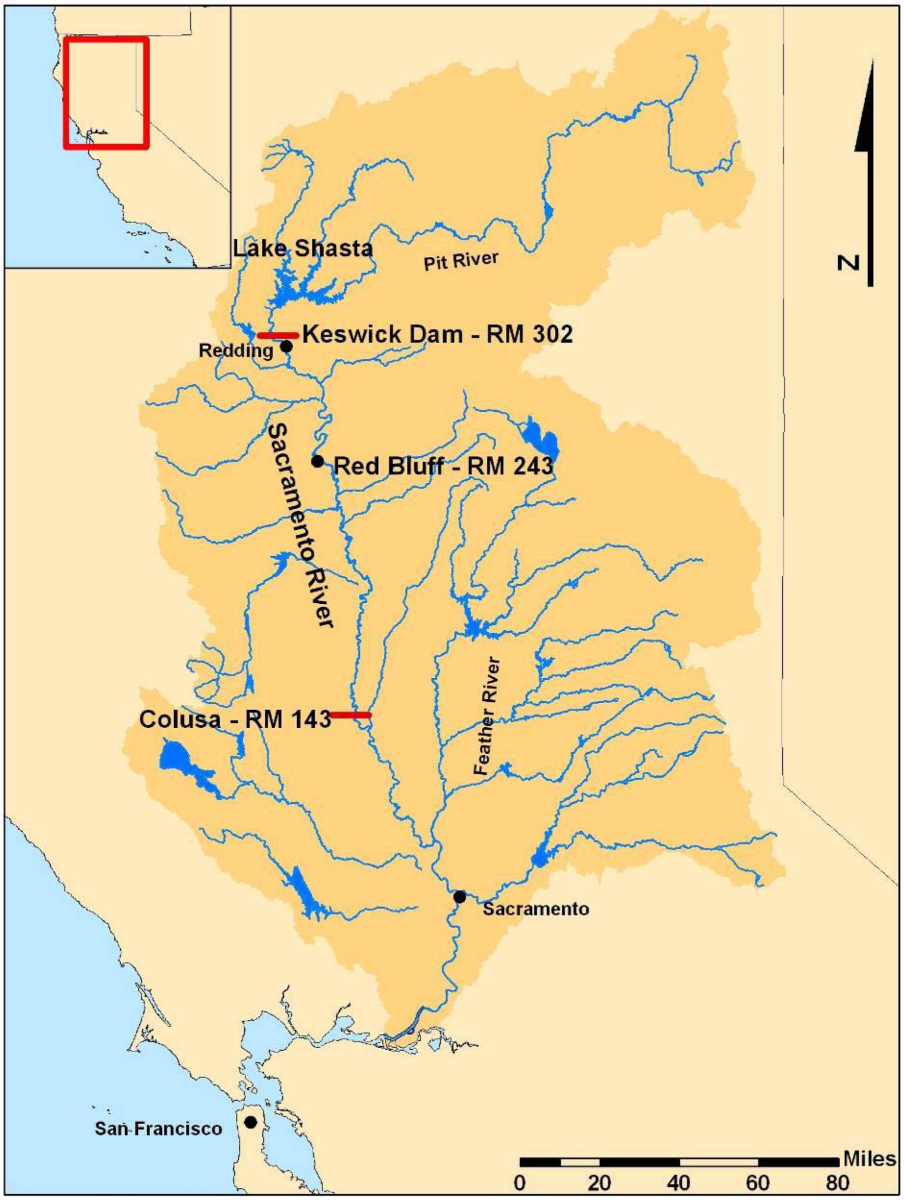

Figure 1-1. Sacramento River watershed.

1.1.2 Task 2. Conduct targeted studies to address uncertainties

The Ecological Flows team worked together to prioritize key uncertainties and develop study plans for the targeted studies, which included:

Task 2.1: Quantify and refine the relationship between flow and sediment transport (Appendix B: Gravel Study Final Report).

Task 2.2: Quantify fluvial geomorphic processes that create and maintain off-channel habitats and characterize ecological attributes of these habitats (Appendix C: Off-channel Habitats Final Report).

Task 2.3: Characterize channel substrate composition and permeability (Appendix B: Gravel Study Final Report).

Task 2.4: Assess and compare the effects of bank protection on in-channel habitat conditions.

Task 2.5: Refine a meander migration model (Appendix D: Meander Migration Final Report).

Most of the targeted studies were designed to address needs that were originally identified in the CALFED Integrated Storage Investigation report (Kondolf et al. 2000). Study findings and their relevance to resource management were summarized in technical reports for all but one of the targeted studies. The findings of each of the targeted studies are discussed in Section 2.2 and have been integrated into the overall synthesis of this Final Report (Section 3). Although a substantial amount of field data was collected for Task 2.4 (Section 2.2.5), the results did not satisfy the requirements of the study plan and so the work was abandoned prior to completion.

1.1.3 Task 3. Develop numerical models and a decision analysis tool.

The Study supported the development of two additional computer models, a new sediment-transport model (Task 3.1; Appendix E: TUGS Final Report) and a decision-analysis tool, dubbed the "Sacramento River Ecological Flows Tool" (Appendix F: SacEFT Analysis). The SacEFT was developed to evaluate the ecological consequences of management-related changes in flow regime. Other management-related changes to the ecosystem were also modeled with the SacEFT. For example, changes to bank armoring and gravel augmentation were evaluated with the help of the TUGS and meander migration models. The new sediment transport model is unique in that it explicitly accounts for inputs of fine sediment and can therefore predict how flow is likely to influence the deposition of riverine sediment in both the surface and subsurface layers of the channel bed. The meander migration model is unique in that it can now account for the effects of variable flow, whereas the predictive capability of previous meander migration models was limited a single non-variable flow.

1.1.4 Task 4. Outreach, reporting, and workshop

This Final Report integrates the findings of Tasks 1, 2, and 3, and explains how new data were used to assess the effects of several management scenarios. The information synthesized in this Final Report will be presented at a stakeholder workshop.

1.2 Study rationale

Prior to Indo-European colonization, approximately 500,000 ac (200,000 ha) of riparian and upland forest flanked the Sacramento River in swaths as wide as 5 mi (8 km). Over the past 150 years this habitat has been reduced by nearly 95%. TNC's Sacramento River Project team and its partners have worked for nearly two decades to restore natural ecosystem function to extensive tracts of the riparian corridor of the

Sacramento River, one of California's most important rivers. Restoration strategies to date have focused on active revegetation of the floodplain to provide immediate ecological benefits and ameliorate habitat fragmentation and loss. Results of several studies confirm that it is possible to rapidly improve ecological conditions using this strategy, because channel and floodplain habitats in restored reaches are utilized by a wide array of wildlife including threatened and endangered species (Golet et al. *in press*).

Organizations and agencies involved in the conservation and restoration of the Sacramento River have concentrated their efforts in the "middle river," between Red Bluff and Colusa (Figure 1-2), where natural ecological processes, such as lateral channel migration, continue to operate to some degree. The choice of this reach reflects the belief of project cooperators that long-term conservation of key Sacramento River habitats will need to focus on restoring or replicating the natural processes that create and maintain dynamic riverine ecosystems. The natural dynamics of this reach suggest that it may respond favorably to such efforts.

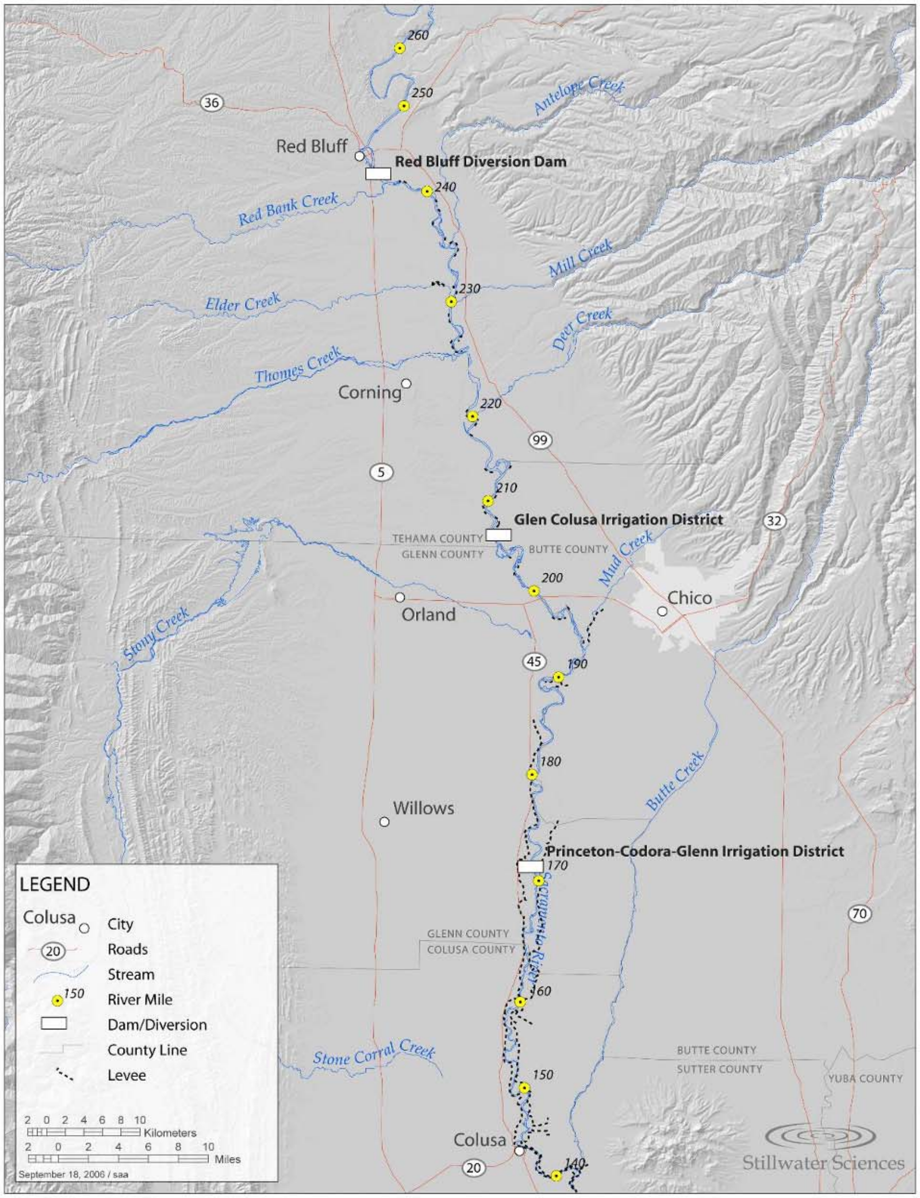

Figure 1-2. Major dams and tributaries of the middle Sacramento River.

The Sacramento River Ecological Flows Study was initiated to evaluate restoration strategies, particularly related to river discharge, that are likely to complement ongoing revegetation activities in the middle river. It also focuses extensively on the upper river, from Keswick Dam (RM 302) to Red Bluff (Figure 1-3), a reach that provides crucial habitat for many of the river's fish species, including the endangered winter-run Chinook salmon.

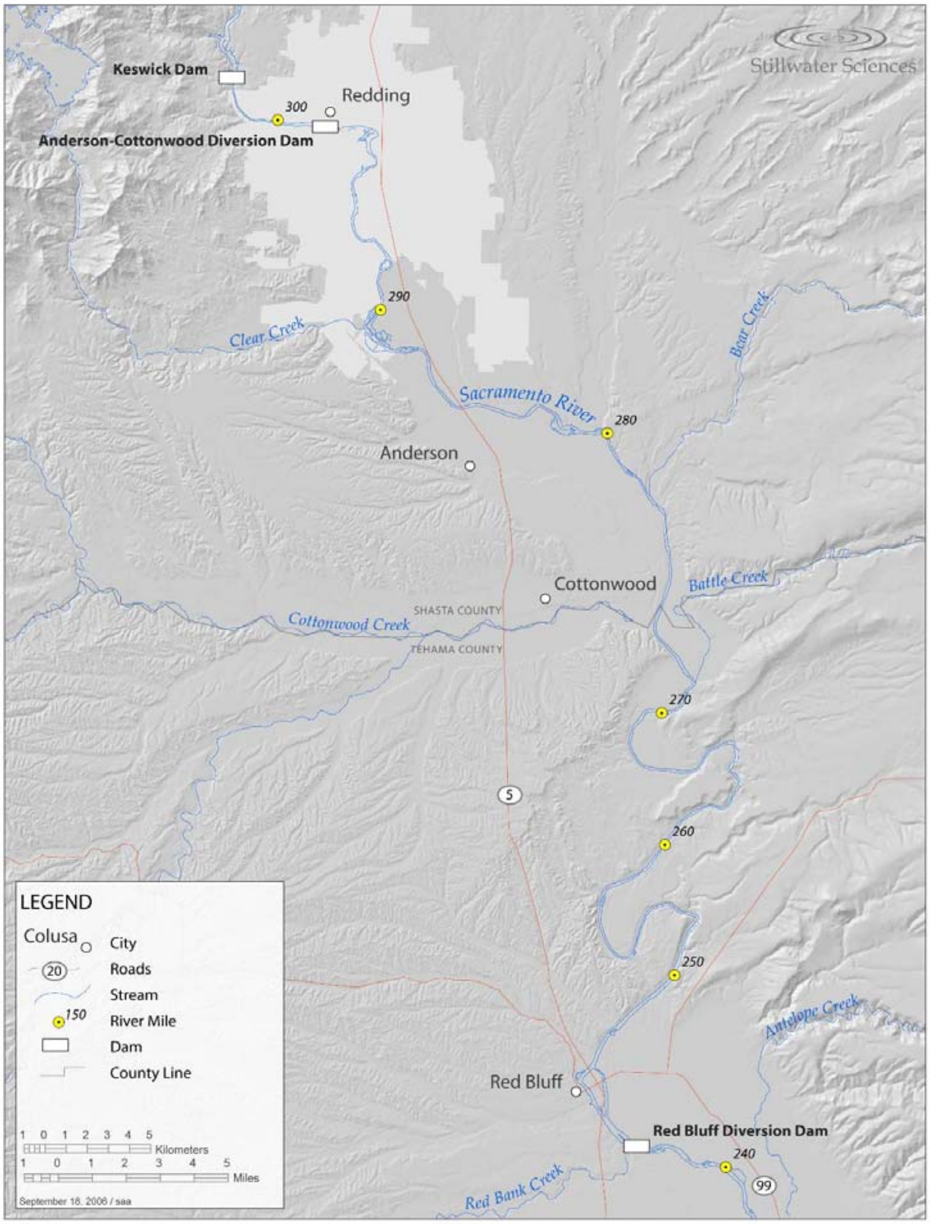

Figure 1-3. Major dams and tributaries of the upper Sacramento River.

The Ecological Flows Study treats flow as the “master” variable regulating the form and function of riverine habitats. This view is shared by a growing body of international researchers who seek to understand how riverine ecosystems are affected by changes in parameters such as the frequency, magnitude, timing, duration, and rate of change of flow. Dam-related alterations of river flow regimes have been identified as one of three leading causes of declines in imperiled aquatic ecosystems (the others being nonpoint source pollution and invasive species; Richter et al. 1997, Pringle et al. 2000). Many river-dependent plants and animals are influenced by natural variations in river flow—so much so that they often possess traits that allow them to tolerate or exploit specific seasonal flow conditions. An emerging body of literature supports the notion that there are strong interconnections between flow regime and the species that have adapted to live within the riverine environment. This concept has been investigated and summarized by Poff and Ward (1990), Ligon et al. (1995), Collier et al. (1996), Stanford et al. (1996), Poff et al. (1997), Friedman et al. (1998), Rood et al. (1998), Mahoney and Rood (1998), Richter and Richter (2000), and Richter et al. (2003). By documenting how the Sacramento River responds to changes in flow regime, this study seeks to provide critical information that will help decision makers develop ecologically sound water management strategies for the basin.

1.3 Addressing CALFED Bay-Delta Ecosystem Restoration Program Goals

CALFED documents note that restoring critical components of the flow regime would aid the recovery of at-risk species and restore natural riparian habitats that are dependent on natural ecosystem processes such as seasonal flow variability. CALFED's Draft Stage 1 Implementation Plan acknowledges that "human activities have fundamentally, and irreversibly, altered hydrologic processes in the Bay-Delta ecosystem" (p. 25), including the Sacramento River. To address this problem, the CALFED Ecosystem Restoration Program (ERP) Strategic Goal 2 includes the restoration of natural variability to the flow regime and associated river processes, "as an important component of restoring ecological function and supporting native habitats and species in the Bay-Delta ecosystem."

Other agencies have enacted water-related planning and conservation efforts to balance the water supply needs of people and the environment. Examples include the Environmental Water Account (EWA), the Environmental Water Program (EWP), the Central Valley Project Improvement Act (CVPIA), the Anadromous Fish Restoration Plan (AFRP), the Integrated Storage Investigation (ISI), the North of Delta Off-stream Storage investigation (NODOS), the Water Management Strategy Evaluation Framework (WMSEF), and the Phase 8 resolution of the State Water Resources Control Board's current Bay-Delta Water Rights Hearings (Phase 8).

Despite recent focus on understanding how flow regimes affect ecosystems, both within CALFED and in other programs, few studies have quantified any of the ecologically critical aspects of the natural flow regime for the Sacramento River. Previously, attention focused only on minimum instream flow and temperature requirements for a subset of salmonid species. Quantifying other aspects of the flow regime, in contrast, would facilitate the formulation of more effective water management and ecosystem restoration strategies.

This Study begins the process of quantifying key aspects of an ecologically beneficial flow regime that is compatible with flood damage reduction, agriculture, diversions, storage, and conveyance. A main goal for this Study was to improve our understanding how flow affects the processes responsible for maintaining and creating habitat for anadromous fish and other key species of the Sacramento River ecosystem. To achieve this goal, the Study cooperators created the decision analysis tool (i.e., SacEFT, Task 3), which is designed to provide an integrated assessment of the flow needs of anadromous fish and other Sacramento River riparian and aquatic species.

The results of the Study are not intended as the basis from which to return the Sacramento River to its "pre-regulated" condition. Nor does it identify how best to allocate Sacramento River water to meet human needs. Numerous efforts are already underway to address this topic. The Study does however, bring critical ecological information to decision-making forums. It may be unrealistic to expect to meet all ecosystem and human demands in a system as complex as the Sacramento River basin. However, an important first step towards this ultimate goal is to develop a more complete understanding of the flow regime and its relation to natural processes, habitat conditions, and the population dynamics of key species in order to identify critical aspects of the flow regime necessary to maintain ecosystem function. In this spirit, we have also worked with stakeholder groups to fully utilize information from ongoing water management planning efforts.

1.4 Application of the study's findings

By documenting how flow contributes to the ecological health of the Sacramento River, this Study should be useful for assessing operational impacts and potential opportunities of many ongoing and proposed projects. For example, this Study included a demonstration of a multifaceted analysis of the effects of the proposed raising of Shasta Dam and the proposed North-of-the-Delta Off-stream Storage (NODOS) facility. Other applications of the tools and information developed in this study might include analysis of new diversion and water transfer projects, and the Bureau of Reclamation's re-consultation for the Operations Criteria and Plan (OCAP) for managing the Central Valley Project. Understanding the operational impacts and potential opportunities of each of these projects will require improved understanding of the Sacramento River ecosystem. This understanding should inform the design of projects that provide ecological benefits within the context of the needs of people.

2 Summary of results

In this section, we present brief descriptions of each of the Study's components along with summaries of their principal findings. The results discussed in this section are synthesized in Section 3, where we highlight the key management implications of the Study and identify ways to reduce some of the important uncertainties that remain.

2.1 Linkages between altered riverine processes and biological responses

Our first step was to compile existing information and formulate conceptual models that future Study tasks would build upon. The large body of existing information on species, habitats, and processes of the Sacramento River is synthesized in the Linkages Report (Appendix A, Stillwater Sciences 2007a), which examines ecosystem processes from the perspective of six representative focal species (Table 2-1). The emphasis on a subset of species, rather than on the ecosystem as a whole, was an attempt to conduct a comprehensive yet tractable analysis of key ecosystem processes and management issues.

Table 2-1. Focal species and the habitats and ecosystem characteristics they represent.

Species	Key habitats	Key processes and characteristics of the ecosystem
Chinook salmon (*Oncorhynchus tshawytscha*)	gravel deposits, pools, eddy/point-bar complexes, side channels and sloughs, inundated floodplains	coarse sediment transport and bed surface scour water temperature regime availability of cover and/or slow water during high flows timing and magnitude of flow fish passage barriers
Steelhead (*Oncorhynchus mykiss*)	gravel deposits, pools, eddy/point-bar complexes, side channels and sloughs, inundated floodplains	availability of cover and/or slow water during high flows water temperature regime timing and magnitude of flow fish passage barriers
Green sturgeon (*Acipenser medirostros*)	deep pools, gravel deposits	water temperature regime timing and magnitude of flow fish passage barriers
Bank swallow (*Riparia riparia*)	steep cutbanks	bank erosion progressive meander migration meander bend cutoff timing and magnitude of flow
Western pond turtle (*Clemmys marmorata*)	oxbow lakes, side channels and sloughs, pools, inundated floodplains	progressive meander migration meander bend cutoff timing and magnitude of flow terrestrialization of off-channel water bodies
Fremont cottonwood (*Populus fremontii* ssp. *fremontii*)	point bars, side channels and sloughs, oxbow lakes, inundated floodplains	vegetation succession timing and magnitude of flow meander migration terrestrialization of off-channel water bodies

Collectively, the six species rely on all of the river corridor's major habitat types, including off-channel water bodies, gravel deposits, point bars, and floodplains, as well as aspects of the flow regime (timing, magnitude, frequency, duration, and rate of change) itself. In this section, we summarize the key linkages between management activities, ecological processes, and habitats for each of the focal species.

2.1.1 Chinook salmon

The Sacramento River supports four distinct runs of Chinook salmon, including the endangered winter run, which occurs only in the Sacramento River basin. Because the four runs exhibit a variety of life-history strategies, and because anthropogenic activities in the basin have affected each run differently, each of the runs was analyzed separately in the Linkages Report with the formulation of new conceptual models and hypotheses.

Winter run

Winter-run Chinook salmon are unique in that they spawn during summer months when air temperatures (and thus water temperatures) generally approach their yearly maxima. Because high water temperatures lead to high mortality for early salmonid life stages (Myrick and Cech 2004), winter-run Chinook need to be able to spawn in reaches with water sources that keep temperatures cool throughout the summer. These conditions were historically found in headwater tributaries of the Sacramento River, and now occur in just one short reach below Keswick Dam, due to managed releases of cool hypolimnetic water from Lake Shasta.

By the late 1970s and early 1980s, winter-run escapements had declined substantially relative to historical numbers. The Linkages Report highlights several factors that may have contributed to the population decline:

- the drought of 1976–1977, which led to lethally warm summer flow releases;
- bed coarsening caused by instream mining and dam-related shutdown of sediment supply from headwater sources[1];
- reduced survival at one or more life stages (e.g., due to excessive ocean harvest, effects of Red Bluff Diversion Dam [RBDD], increased predation, and/or water pollution); and/or
- reduced juvenile rearing habitat associated with the reduced frequency and duration of overbank flows.[2]

Over the last several years winter-run escapements have increased. The Linkages Report suggests that this increase may be explained by:

- recent improvements in fish passage at the Anderson Cottonwood Irrigation District (ACID) Dam that increase access to the uppermost reaches preferred by winter-run Chinook;
- recent gravel augmentation efforts (which have focused on the winter-run spawning reach);
- reduced ocean harvest; and/or
- increased hatchery production.

Historical observations (e.g., Yoshiyama et al. 1998) suggest that the winter run population may have been limited by the availability of spawning gravel and that juvenile rearing habitat was probably

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[1] The bed coarsening hypothesis was evaluated at length as part of the gravel study (Section 2.2.1 and Appendix B).

[2] Rearing potential in shallow, seasonally inundated habitats was evaluated in the off-channel habitat study (Section 2.2.4 and Appendix C).

sufficient to support growth and successful outmigration in the pre-dam era. Shasta Dam terminated access to historical spawning grounds while simultaneously creating a new stretch of suitable spawning habitat immediately downstream, due to cold water releases from Lake Shasta and the abundance of spawning-sized sediment in the Sacramento River's main stem (Slater 1963). Over time, however, high-flow releases in winter and the dam-related cessation of coarse sediment supply have degraded the channel bed downstream of Keswick Dam in the winter-run spawning reach (Bigelow 1996). Bed coarsening may have rendered many gravel deposits in the upper river unsuitable for spawning (Section 2.2.1; Appendix B). This may have led to increased competition for spawning habitat, which in turn may now be a key limiting factor for the winter-run population.

Available data also support the hypothesis that the reduced frequency and duration of floodplain inundation in the post-dam era may have contributed to the decline of the winter-run population by limiting opportunities for floodplain rearing (except when bypasses are flooded). Recent research has demonstrated that growth rates of juvenile Chinook salmon are lower in mainstem habitats than in inundated floodplains and off-channel habitats (Sommer 2001, Limm and Marchetti 2003). If lack of access to off-channel habitats has reduced juvenile growth rates relative to historical conditions, then availability of rearing habitat may be an important limiting factor for the winter run, given that slower growth is likely to contribute to reduced survival.

Additional studies are needed before definitive conclusions can be drawn about which (if any) of the proposed mechanisms, or combinations of mechanisms, are responsible for the observed changes in the winter-run population. For example, a redd superimposition field study is a high priority study to shed light on whether spawning habitat is limiting. Also warranted are follow-up analyses with the best available population model to analyze the salmon production data gathered for the Linkages Report.

Spring run

Historically, spring-run Chinook salmon were probably the most abundant salmonid in the Central Valley (Mills and Fisher 1994). Yet viable spawning populations now occur in just three Sacramento River tributaries (Mill Creek, Deer Creek, and Butte Creek). The spring-run population decline was perhaps the steepest of any salmon run in the basin (Fisher 1994). The Linkages Report explains how the decline of the spring run may reflect this particular run's sensitivity to the effects of large, multi-purpose dams in the Central Valley. These large dams blocked the access of all Chinook runs to historical spawning grounds, while simultaneously providing new habitat downstream of Shasta Dam due to cool hypolymnetic reservoir releases. For the spring run, however, the new spawning habitat was inferior, because spawning by fall-run Chinook peaks shortly after the peak of spring-run spawning such that fall-run Chinook often construct their redds on top of existing spring run redds (CDFG 1998). Because spring-run fish migrate upstream when flows are high, they would have historically been able to access spawning grounds much farther upstream than those of the fall run (Vogel 1987a, 1987b), which migrates upstream when flows are too low to permit passage over natural barriers. In the post-dam era, the forced overlap of the two runs on spawning grounds immediately downstream of the dams has apparently led to hybridization, with fall-run Chinook dominating the gene pool.

Population data show that spring-run escapements in Butte Creek have increased significantly. This is not so in Deer and Mill creeks, the other two tributaries that still support spring-run spawning. Increases in Butte Creek escapements may reflect seasonal inundation of the Sutter Bypass, which presumably provides fry rearing habitat for Butte Creek fish and thus may help support relatively high rates of fry survival and outmigration.

Fall run

The fall run has been the most abundant and widely distributed salmon run in the Central Valley, in part because it has been the focus of Central Valley hatchery supplementation for several decades. It may also be more abundant because it has undergone less displacement from its historical habitat relative to other salmonid populations. Even so, fall-run escapements have declined over the past few decades, likely due to the cumulative effects of a number of anthropogenic factors. New analyses presented in the Linkages Report show that a loss of spawning gravel caused by dam-related bed coarsening may have been a primary factor in their decline. Abundant spawning habitat is necessary to produce large numbers of juvenile fall-run Chinook; this may be a necessary buffer from predation mortality. Predation appears particularly detrimental to the fall run; fall-run juveniles typically outmigrate at a relatively small size (<3.5 in [90 mm]) due to water temperature limitations. High predation rates, and the consequent need to produce large numbers of juveniles, suggest that spawning habitat may be limiting to the fall run population.

Late-fall run

The mainstem Sacramento River supports the largest population of late-fall-run Chinook salmon. Analysis presented in the Linkages Report suggests that the run may have arisen almost entirely as an artifact of Shasta Dam operations, which release cold water in the summer and thus create over-summering habitat where it did not previously exist. Late-emerging fall-run fry that historically would have perished from high water temperatures may have been able to survive in the post-dam era by rearing in the river in the summer and emigrating as yearlings the following fall. Thus, by supporting a yearling life-history strategy, the apparent dam-related expansion of over-summering habitat may have allowed for the emergence of a distinct late-season run. This hypothesis was derived in part from new population dynamics modeling efforts as summarized in Section 4.4.5 of the Linkages Report.

2.1.2 Steelhead

Steelhead production in the Sacramento River basin is probably limited by the availability of spawning habitat in steep, high-elevation reaches of the river's tributaries. In the post-dam era, such habitat is no longer widely accessible to anadromous fish, although it still supports large populations of rainbow trout, the resident polymorph of steelhead. Along the mainstem Sacramento River, the key limiting factor for steelhead (and resident rainbow trout) may be the amount of summer and winter rearing habitat for age 2+ juveniles. This hypothesis was derived from the following sequence of observations in the Linkages Report:

1. Upon emergence from redds, steelhead fry require shallow, low-velocity habitat (Hartman 1965, Everest et al. 1986, Fontaine 1988), which is in short supply along the Sacramento River mainstem.
2. The number of age 0+ juvenile steelhead that a reach of stream can support is small relative to the number of eggs (>5,500 per female) that may be deposited.
3. Rearing habitat for age 1+ and 2+ juveniles is limiting, because older (i.e., larger) fish require more cover during high flows (Bustard and Narver 1975; Bisson et al. 1982, 1988; Fontaine 1988; Dambacher 1991).

This suggests that the multi-year juvenile rearing period employed by steelhead imposes a key limitation on numbers of adult steelhead. Additional studies are needed to reduce uncertainties and verify whether this is the case. Two key uncertainties (i.e., the quantity and quality of juvenile rearing habitat) were addressed, in part, in the Off-channel Habitat Study (Section 2.2.4 and Appendix C).

2.1.3 Green sturgeon

The Sacramento River supports one of only three known spawning populations of North American green sturgeon. These fish spend most of their lives at sea and travel hundreds of miles along the west coast of Canada and the United States before migrating upstream to spawn (Adams et al. 2002). Data discussed in the Linkages Report suggest they routinely spawn above RBDD (RM 243), but may hold for a month or more in deep pools near Hamilton City (RM 199), where incidental and intentional angling may be an important source of mortality. Spawning begins in March and peaks between mid-April and mid-June. Closure of the RBDD gates in mid-May prevents at least some late migrants from accessing upstream spawning sites, forcing them to spawn downstream or to forego spawning altogether. Green sturgeon may be suffering from increased egg mortality relative to historical conditions because they have been displaced to relatively low-gradient reaches where bed sediments are generally finer than in the preferred upper reaches. Spawning in fine-grained gravel may make green sturgeon eggs more vulnerable to predation by juvenile steelhead and other fish. Water temperature may be an important limiting factor for green sturgeon, but the river's current temperature regime (designed to protect winter-run Chinook salmon) is probably favorable for downstream-migrating green sturgeon adults and their larvae.

2.1.4 Bank swallow

Bank swallow abundance in the Sacramento Valley has declined substantially relative to historical conditions. The decline appears to be closely related to the loss and alteration of breeding habitat due to bank revetment projects (Schlorff 1997), which now affect nearly 50% of banks along the middle Sacramento River where most of the region's bank swallow colonies are concentrated. Bank revetment projects continue to threaten both existing colonies and unused (but potentially suitable) bank swallow breeding habitat. Other contributing factors in the bank swallow decline likely include destruction of entire colonies during riprap placement, increased nest predation from animals that thrive in and around rural human settlements (e.g., raccoons), and agricultural conversion of riverine floodplains (e.g., grasslands) that formerly provided high quality foraging habitat (Moffatt et al. 2005).

Prime bank swallow nesting habitat is limited to friable soils in vertical bank faces (Garrison 1998, 1999). This makes nesting habitat ephemeral, because steep banks are subject to collapse when undercut by the river during high flows. Such bank erosion is essential for maintaining suitable habitat, because it keeps cutbanks steep and removes burrows that would otherwise degrade and become unsuitable for nesting. The synthesis provided in the Linkages Report documents a strong correlation between recently measured rates of lateral migration (Micheli and Larsen, in preparation) and bank swallow abundance along the Sacramento River (Schlorff 1997). This highlights the critical importance of active channel migration for maintaining a viable bank swallow population along the river. The Linkages Report also discusses the existing habitat suitability model for nesting bank swallows and proposes several potential modifications, including terms that account for proximity to grasslands and changes in river stage associated with summer base flows.

New lateral channel migration data and air photo analyses suggest that there may now be a lower threshold for channel cutoff at many of the Sacramento River's meander bends, relative to historical conditions (Micheli and Larsen, in prep.). This would tend to increase channel cutoffs and reduce average sinuosity in the actively migrating reaches used by nesting bank swallows. Lower average sinuosity would in turn lead to a lower average rate of progressive bank erosion (see Section 2.2.3) and thus a lower overall rate of habitat creation for nesting bank swallows.

Other recent changes to the ecosystem may have affected bank swallows. For example, Shasta Dam and other Sacramento River flood-control measures were important to the extent that they altered the timing and rate of renewal of bank swallow nesting habitat. The timing of bank erosion (and the high flows that induce it) is critical because bank swallow mortality can result if bank collapse occurs during the summer nesting season.

The net effect of anthropogenic factors on bank swallow abundance and population dynamics is not well understood because populations were not monitored on a regular basis until the late 1980s. Since then, annual counts have clearly indicated that bank swallow populations along the Sacramento River are in decline; recent reductions in the number of colonies and overall abundance, and a resurgence of revetment activity combine to make the Sacramento River population vulnerable to extirpation. This has implications for the long-term persistence of bank swallows in the state; roughly 70% of California's bank swallows nest along the Sacramento River.

2.1.5 Western pond turtle

In large alluvial river systems such as the middle Sacramento River, western pond turtles appear to rely predominantly on off-channel water bodies (e.g., sloughs and oxbow lakes) and other floodplain habitats (Holland 1994, Reese 1996, Bettelheim 2005). Off-channel water bodies are eventually colonized by vegetation and filled with sediment and organic detritus from overbank flows, as described in greater detail in the Linkages Report. Natural rates of this “terrestrialization” process typically allow off-channel water bodies to persist in the floodplain for decades to centuries, as documented in the off-channel habitat component of the Ecological Flows Study (Section 2.2.4 and Appendix C).

In comparison, rates of human-induced losses in off-channel habitats have been much higher, far outpacing current (and historical) rates of habitat formation by meander migration and channel-cutoff processes. Since the mid-1800s, for example, nearly all 87,000 ha (214,000 ac) of the Sacramento Valley's historical flood-basin wetlands have been lost. Most of the historical wetland habitat located within the riparian zone has also been lost. Western pond turtle habitat is now mostly limited to isolated areas within a few national wildlife refuges, along canals associated with rice fields, and in remnant wetland and lentic habitat at off-channel sites between Red Bluff (RM 243) and Colusa (RM 143). Below Colusa, levees, bank protection, and agricultural development have eliminated most off-channel habitats. Above Red Bluff, hypolimnetic reservoir releases in the post-dam era have likely rendered water temperatures unsuitably cool for western pond turtles in the few otherwise-suitable off-channel habitats that still remain.

In addition to the large-scale loss of habitat, many other factors have likely contributed to declines in western pond turtle populations. These include introduced predators and competitors, increased numbers of native predators, disease, reduced water quality, habitat fragmentation, permanent and seasonal barriers to movement and gene flow, and habitat alterations caused by invasive plants. Another potentially important limiting factor for the western pond turtle is the relationship between water level and flow in off-channel water bodies. This is because incubating eggs are extremely sensitive to increased soil moisture (Ashton et al. 1997). Flows in the summer incubation season are now higher than they were historically due to irrigation releases during the growing season.

Indications that cutoffs may now initiate at a lower threshold sinuosity relative to historical conditions (Micheli and Larsen, in prep.) suggest that rates of off-channel habitat formation may be increasing, and thus may confer benefits to western pond turtles over the short term. Over the long term, however, such an increase in the rate of cutoff formation is not likely to be sustainable; as bends are cut off, sinuosity is reduced (i.e., the channel becomes straighter), leading to decreased rates of progressive lateral migration (see Appendix D) and thus reducing the potential for future cutoffs. This effect may be exacerbated by the cumulative effects of any future bank revetment projects, which can also lead to decreased rates of progressive lateral migration and production of new off-channel habitats.

Anthropogenic changes in rates of terrestrialization of remaining off-channel habitats are another factor to consider. The off-channel habitat study (discussed in Section 2.2.4) was designed, in part, to explicitly measure time-varying rates of terrestrialization, and thus quantify how human disturbance has affected the long-term persistence of off-channel water bodies.

2.1.6 Fremont cottonwood

Fremont cottonwoods are the dominant tree of riparian forests in California's Central Valley. Soon after establishment, they provide ecological structure to the riparian ecosystem by stabilizing substrate, fixing carbon, providing organic matter and large wood to instream and riparian habitats, and providing habitat for a wide range of species. The Sacramento Valley has lost over 98% of its original riparian forests since 1850 (Katibah 1984, Greco 1999). Cottonwood forests are now mostly restricted to the reach between Red Bluff (RM 245) and Colusa (RM 143).

The synthesis provided in the Linkages Report highlights key limiting factors for cottonwoods and other native riparian trees. Willow and cottonwood seedlings are vulnerable to desiccation when the local water table drops too quickly. Reductions in the magnitude and frequency of winter overbank flows in the post-dam era have likely led to an overall decrease in soil moisture available to riparian plants during the growing season (TNC 2003, Morgan 2005, Morgan and Henderson 2005, Stella 2005, Stillwater Sciences 2006). This has contributed to reduced growth rates and has possibly promoted the dominance of species with higher drought tolerances (e.g., box elder and walnut). The reduced magnitude and altered timing of spring flows may have also affected cottonwoods by encouraging recruitment on low-elevation depositional surfaces that become inundated and scoured by subsequent winter floods or by elevated summer base flows.

Three attributes of the current (altered) hydrograph appear to limit cottonwood seedling survival at several middle Sacramento River study sites (Morgan 2005, Morgan and Henderson 2005). These include: (1) decreased spring flow during cottonwood seed release and germination, (2) stage reductions that outpace seedling root growth during the recruitment period, and (3) rapid drops in stage late in the growing season when reservoir releases for summer irrigation cease. Hence, effective management of the timing and magnitude of flow releases appears to be fundamental to maintaining Fremont cottonwood and the species, habitats, and ecological processes that it supports and represents. In addition, maintaining natural channel migration and cutoff processes along the middle Sacramento River is necessary for providing new patches for seedling recruitment and for periodical resetting of riparian vegetation succession, which are both critical for maintaining a diverse, dynamic, and functional riparian-floodplain ecosystem.

2.2 Field and Modeling Studies

This section presents findings of the field and modeling components of the Ecological Flows Study. These components were designed to reduce many of the uncertainties identified in previous studies (e.g., Kondolf et al. 2000) and the Linkages Report (Appendix A, Stillwater Sciences 2007, Section 2.1), and provide data that could be used in the SacEFT modeling effort to assess the ecological implications of several proposed management actions. Management implications of the Ecological Flows Study results are shown in Table 2-3 at the end of Section 2.2. Remaining uncertainties are summarized in Section 3. Section 3 also contains a list of potentially beneficial management actions derived from the overall synthesis of the Linkages Report (Section 2.1) and the targeted studies described in this section.

2.2.1 Gravel resources field study

Gravel is fundamental to aquatic and riparian habitat in rivers and is particularly important for salmonids and other fish because they need gravelly substrates for spawning and egg incubation. Along the Sacramento River, human activity over the last century has dramatically altered the river's flow and sediment transport regimes, which in turn have affected both the quantity and quality of gravel sediments. In recognition of the “keystone” nature of anadromous salmonids in aquatic habitats, and their reliance on sufficient gravels to maintain their populations, several elements of the Ecological Flows Study were designed to quantify the river’s gravel dynamics.

To help document anthropogenic effects on the river's gravel, the Study included a review of existing information, new analyses of existing data, and new field measurements to fill data gaps. For example, the Gravel Study Report (Appendix B, Stillwater Sciences 2007b) includes the first facies maps of the river's gravel resources and includes new grain-size data that were compared with results from previous studies. The gravel study also assessed total area of salmon redds in 2005, enabling the first quantitative analysis of multi-decadal trends in spawning habitat availability in the upper river. A brief synthesis of these efforts follows.

Study objectives and design

The main objectives of the gravel study were to (1) refine estimates of the flow required to mobilize the bed surface, (2) characterize gravel and its habitat value for salmonids, and (3) provide data for reach-specific application of The Unified Gravel-Sand (TUGS) Model, a new sediment transport model discussed in Section 2.2.2 of this Final Report.

The gravel study design was guided by three working hypotheses:

Hypothesis 1. The quantity of spawning gravel has been decreasing over time due to bed-surface coarsening resulting from in-channel mining and dam-related reductions in sediment supply from headwater sources.

Hypothesis 2. Bed-surface coarsening has progressively propagated downstream from the dams.

Hypothesis 3. The quality of any remaining spawning gravel in the upper river has declined due to reduced surface mobility (a consequence of coarsening and the reduced frequency and magnitude of peak winter floods) which has reduced the river's ability to flush fine sediment from the subsurface.

We investigated these hypotheses by quantifying trends in grain-size distributions, bed elevations, gravel permeability, and area used by spawning fish. Data sources included: (1) results from previous studies, (2) observations and measurements from this field study, and (3) sediment transport modeling results.

Key findings

Spawning habitat area

Data from aerial surveys suggest that available spawning area declined substantially from 1964 to 1980 throughout the upper river (CDWR 1980). In 2005, as part of the Ecological Flows Study, Stillwater Sciences conducted a new aerial spawning survey and used it to create a map of spawning area for comparison with preexisting data (Appendix B). Results reveal local increases in spawning area in the uppermost reaches (from RM 298 to RM 302) as of 2005 (Figure 2-1). This is consistent with ongoing gravel augmentation efforts, which began in 1978 and have continued on an annual basis in the reach since 1997 (Figure 2-1). Yet even with the added gravel, the overall loss in spawning area from 1964 to 2005 was significant from RM 290 to RM 302. Total available spawning habitat remained particularly low between RM 292 and RM 298, an important spawning reach for winter-run Chinook salmon. On the other hand, spawning area remained relatively stable over time for short reaches downstream of many of the river's sediment-bearing tributaries (see Appendix B, Stillwater Sciences 2007b). Taken together, these data are consistent with Hypothesis 1: there appear to have been marked dam-related losses in spawning habitat (due to gravel losses), except in short reaches downstream of sediment-bearing tributaries and gravel augmentation projects.

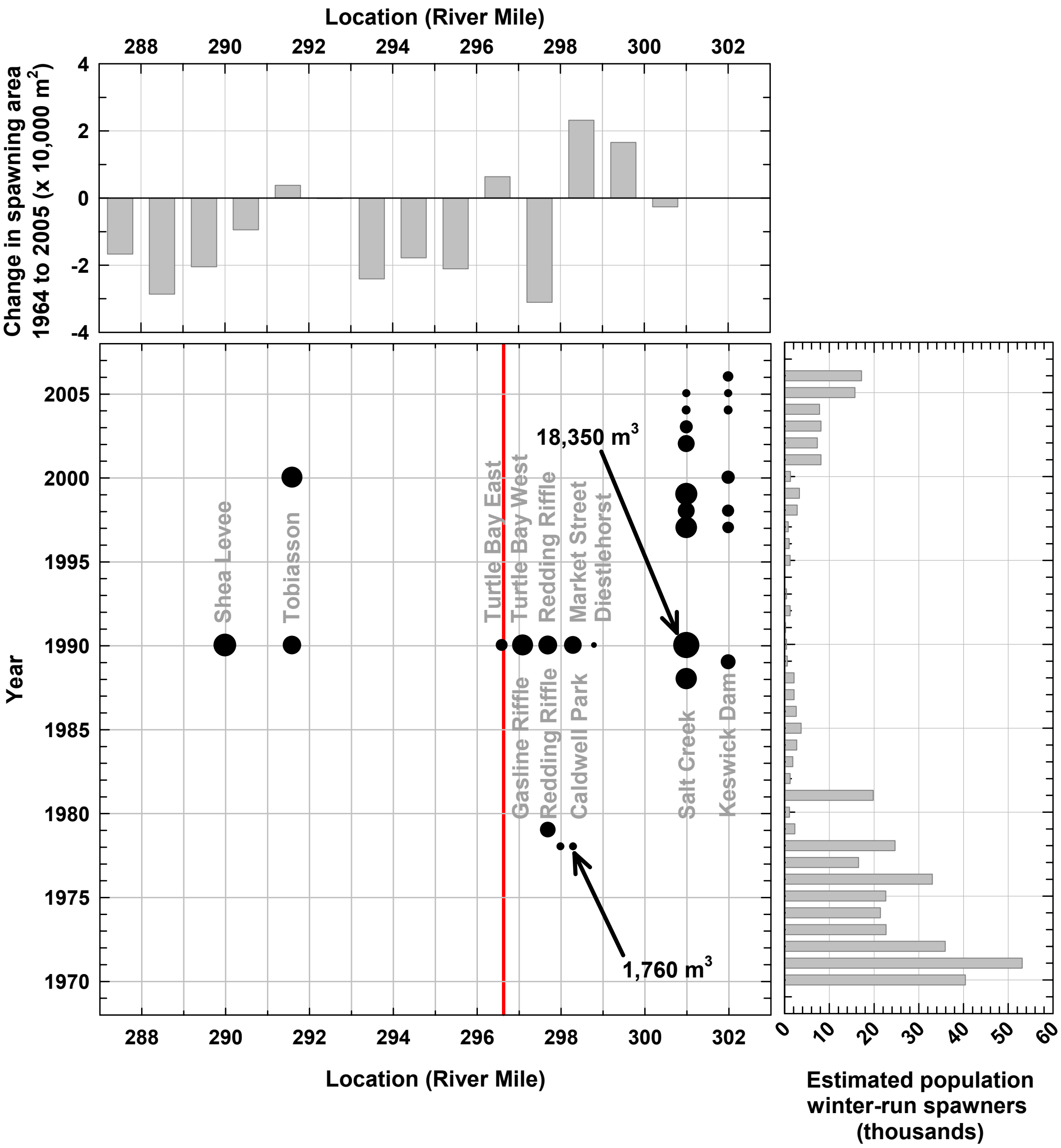

Figure 2-1. Gravel augmentation, spawning area, and winter-run Chinook populations. Bubble plot of gravel augmentation, by year and river mile, for the upper Sacramento River (lower left panel), with histograms showing changes in spawning area from 1964 to 2005 by river mile (upper panel, after Stillwater Sciences 2007, Appendix B) and estimated escapements of winter-run Chinook (lower right panel, after CDFG 2007). Bubble area scales proportionally with volume added (the lowest and highest volumes are labeled for scale). Winter-run escapements declined to a few hundred fish in the early 1990s (lower right), but have rebounded to 10,000–17,000 fish more recently. The recent increase may reflect the effects of several factors, including an increase in spawning habitat upstream of ACID Dam (upper panel) caused by gravel augmentation at Salt Creek and Keswick Dam (lower left). A pronounced decline in spawning area appears to have occurred downstream of RM 298 (upper panel), where gravel additions have been minimal, and where riffles are isolated from effects of upstream augmentation by Turtle Bay (vertical line), a deep, remnant mining pit that acts as a sediment trap. Sediment-transport modeling (Section 2.2.2) suggests that base-level effects of Turtle Bay may be responsible for the spawning area loss immediately upstream, at Redding Riffle (upper panel).

Grain size

Key observations from the grain-size analyses:

- Grain-size distributions show substantial natural variability in grain size at the scale of individual point bars.
- Bulk sampling data from 1980 are incompatible with data from 1995 and 2005, due to differences in sampling methods. There is a similar incompatibility in bulk sampling data between samples taken in 1984 and in 2005.
- Statistical analysis shows that median grain sizes between RM 298 and 284 in 2005 were coarser, on average, than they were in previous years. This is consistent with Hypotheses 1 and 3.
- Statistical analysis also shows that grain-size distributions have become less variable over time. This implies that increases in median grain size are the result of winnowing – the selective transport of relatively finer particles from sediment deposits.

Facies mapping

Key observations from the facies mapping effort:

- Bank erosion appears to be locally important for offsetting the dam-related deficit in coarse sediment supply.
- Fall-run Chinook salmon of the Sacramento River are not apparently able to spawn in deposits where more than 40% of the surface is covered by particles with diameters greater than 130 mm (Figure 2-2).
- Redds were constructed in sediment deposits that were only marginally suitable for spawning, suggesting that virtually all suitable spawning gravel was in use by fall-run salmon during the mapping period. This suggests that redd superposition may have been widespread during the peak of fall-run spawning in 2006.
- At two sites, spawning area has declined to a fraction of its mapped extent in 1964. Areas that no longer support spawning are generally covered by a coarse, immovable bed. This supports Hypotheses 1 and 3.

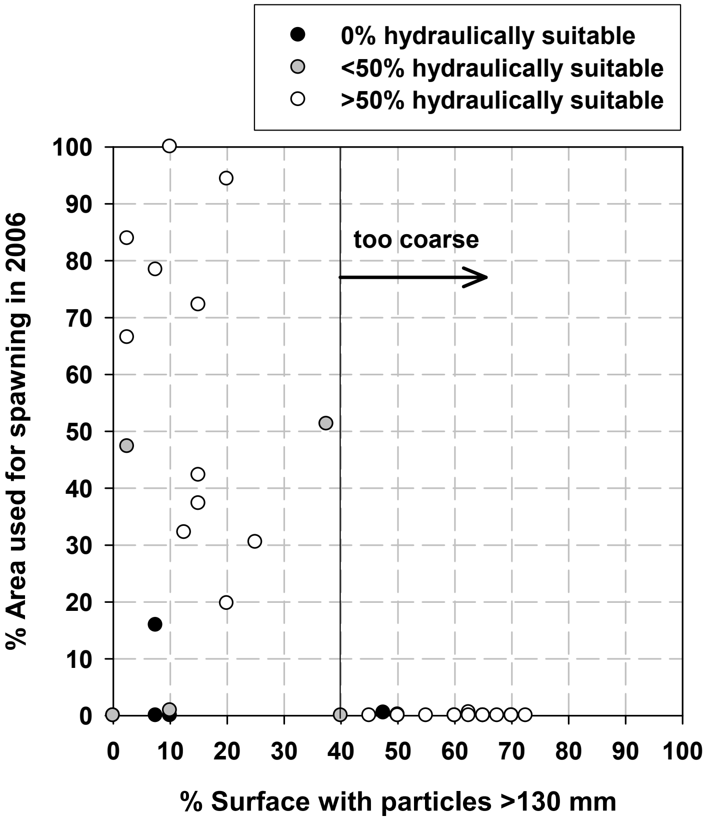

Figure 2-2. Upper limits on particle size for spawning Chinook salmon in the Sacramento River. Plot shows percent of area used by spawning fish in 2006 against percent coverage by particles with intermediate-axis diameters >130 mm for each facies of the gravel study. Hydraulic conditions were judged to be mostly favorable for spawning (at the time of the field work—during the peak of the fall-run spawning season) for sites plotted as open circles. Spawning was scarce or absent in facies where <50% of the area was hydraulically suitable (plotted as gray circles for 1–50% suitable and black circles for 0% suitable). Spawning was also absent in areas with more than 40% coverage by particles with b-axis diameters >130 mm (irrespective of estimated hydraulic suitability). This suggests that 40% coverage by coarse particles represents an upper grain-size threshold for spawning suitability.

Permeability

The permeability data collected in this study are the first of their kind for the Sacramento River and thus provide a baseline for future comparisons. Substrate permeability is greater at a depth of 6 inches than at either 12 or 18 inches, suggesting low rates of fine sediment intrusion in the upper subsurface (Figure 2-3). For salmonids, this means that entombment and suffocation of eggs and fry in newly built redds are probably not significant mortality factors. Nevertheless, permeability-based estimates of survival are almost universally poor for undisturbed gravel at measured sites (Figure 2-3). This highlights the potential importance of redd-building itself as a mechanism for cleaning gravel and making it more suitable for incubation. The permeability analysis did not, however, support or rule out any of the gravel study hypotheses, due to wide site-to-site variability in permeability and a lack of comparative historical data.

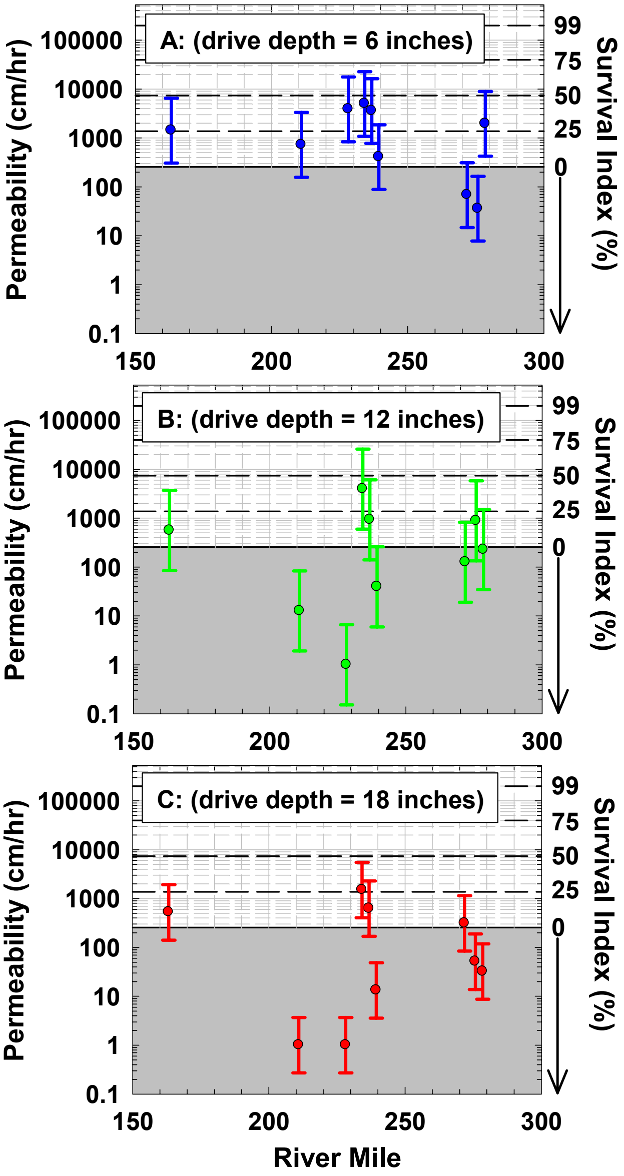

Figure 2-3. Permeability (left axis) and estimated survival index (right axis) as a function of river mile in the Sacramento River. Data were collected in the Ecological Flows study in 2005 for drive depths (permeability sampling depth) of 6 inches (A), 12 inches (B), and 18 inches (C). Permeability is relatively high at 6 inches but shows no clear trend with river mile at any sampling depth. Survival index scaling and units (% survival) are based on available data for coho and Chinook salmon of the Pacific Northwest (Tagart 1976, McCuddin 1977). Shaded regions have an estimated survival index equal to 0%. Low survival indices suggest that many sites would be unsuitable for successful spawning due to low permeability. This seems especially true at depths of 12 and 18 inches (B and C), where Sacramento River Chinook salmon are generally observed to bury their eggs. This highlights the likely importance of redd building as a mechanism for cleaning gravel (and enhancing its permeability) at spawning sites.

Bed mobility

Measurements show that surface mobility of bed sediment can be significant in the middle river, where the propensity for lateral channel migration and sediment delivery from tributaries are both high. Although this does not bear directly on any of the study's hypotheses, observations of mobility in the middle river suggest that the depth of scour can be great enough (>1 m) to disturb redds, killing eggs and alevins if scouring flows occur during incubation. Such scour could particularly affect the fall run, because it is the only run that uses the scour-prone middle river for spawning, and moreover does so in winter when flows can be high enough to mobilize the bed.

Sediment transport modeling

Sediment transport modeling results provide several lines of evidence that are consistent with Hypotheses 1 and 2. The predicted post-dam evolution of sediment transport in the upper river suggest that bed grain size has increased progressively over time due to bed mobilization (caused by successive high flows) and the absence of coarse sediment supply (a result of dam construction). This coarsening is accompanied by a shift in the sediment rating curve: as grain sizes increase, the bed becomes less mobile, reducing the amount of sediment carried by a flow of a given magnitude. This has implications for Hypothesis 3; a coarser, less mobile bed surface should tend to protect sediment in the subsurface layer, which would then be prone to increases in fine sediment (due to a reduced frequency of “flushing” flows). Results from sediment transport modeling of the upper Sacramento River are discussed in greater detail in Section 2.2.2 of this Final Report.

Synthesis

In combination, the data and analyses from the gravel study support Hypothesis 1: the quantity of spawning gravel has been decreasing over time due to bed-surface coarsening. Key evidence includes (1) statistical analyses of grain-size data, (2) changes in total spawning habitat area from 1964 to 2005, and (3) sediment transport modeling results. Evidence is particularly strong for the reach between RM 292 and RM 298, where facies maps of bed material size have been constructed. In other reaches, the picture is complicated by the effects of local sediment supply. For example, coarsening appears to have been reversed in the reach between Keswick Dam (RM 302) and ACID (RM 298.5) due to recent gravel augmentation.

On the basis of grain-size data alone, it is difficult to rule out the possibility that the bed of the entire upper river may have coarsened by 1978, when the first measurements of grain size were collected. This makes assessment of Hypothesis 2 problematic. On the other hand, the sediment transport modeling results show that coarsening propagates systematically in a downstream direction in all modeled scenarios, consistent with Hypothesis 2.

Support of Hypothesis 3 requires evidence to indicate that: (1) bed-surface mobility has decreased significantly throughout the upper river, and (2) fine-sediment concentrations have increased in the subsurface layer. Available data suggest there has been a significant decrease in mobility of the bed over time (as suggested by Hypothesis 1 and Hypothesis 2). There is virtually no support, however, for any increase in fine sediment concentrations in the subsurface. This is because there is no quantitative baseline data (i.e., from before 2005) on permeability in redds. Hence, although Hypothesis 3 is plausible, direct support is lacking.

2.2.2 Sediment transport modeling

As part of the Sacramento River Ecological Flows Study, Stillwater Sciences developed The Unified Gravel-Sand (TUGS) Model (Cui 2007a, 2007b, Appendix E Stillwater Sciences 2007d), which builds on previous sediment transport models in two ways. First, it accounts for the transport and deposition of both fine and coarse sediment; previous models characterized coarse-sediment transport only. Second, it explicitly accounts for the interchange of sediment between the surface and subsurface layers of the channel bed, a previously ignored process that is crucial for predicting changes in spawning gravel quality. Hence, the development of TUGS represents a significant advance in the ability to predict how management-related changes in flow, sediment supply, and bank erosion are likely to affect aquatic habitats, including quantity and quality of salmonid spawning gravel.

The TUGS modeling effort is a good demonstration of the interrelatedness of the Study tasks. TUGS was developed and applied using historical hydrologic data (Linkages Report, Section 2.1), as well as simulated hydrologic conditions both with and without gravel augmentation (with input from data collected in the other targeted studies). The results of TUGS were in turn used as key inputs for the SacEFT (Section 2.3 of this Final Report).

The SacEFT, TUGS, and the meander migration model (Section 2.2.3) have all been developed with capability to use flows derived directly from CALSIM-SRWQM hydrologic and operational simulations of proposed management strategies. CALSIM SRWQM data is monthly time-step output data that has been “disaggregated” into daily time-step data. These date are used because:

- Monthly flows are too coarse for predicting geomorphic and ecological consequences.
- Historic flow data implicitly includes historic facilities and operations. Facilities (e.g. Shasta Dam) and modified operations over time (such as flood control operations) have led to significantly altered flow conditions during the historic period of record.
- It has been used to evaluate water planning projects throughout the state, and thus helps make the Study consistent with the concepts of the “Common Assumptions Group” while helping to make ecological outputs relevant to, and readily integrated with, existing analyses of other projects.
- It allows with and without project analysis to determine (to the extent required by environmental documentation processes) the positive and negative effects of water planning projects.

Prior to interpreting results of comparative analyses conducted with the models utilized in this project (TUGS, meander migration, and SacEFT) it is important that the reader understand the draft nature of the comparisons. Comparisons were conducted utilizing the CALSIM and SRWQM data available at the time of the study as inputs to our models. Therefore, these data sets may or may not be representative of affects of water projects as they are finally formulated. The data sets do however, represent the utility of the tools applied to in fact provide a comparison once final formulations of water projects become available.

Similarly, if a management action (such as a water-storage project) were to affect hydrology differently than predicted by CALSIM SRWQM, the ecological issues considered with these models would need to be reevaluated in light of the actual (measured or modeled) changes in hydrology. Subsequent water-planning processes that use the various model outputs would also need to be re-evaluated in light of the revised model output.

Study objectives and design

As part of TUGS model development, sediment transport simulation results were shown to be consistent with laboratory data (Cui 2007a) and field observations from two geomorphically distinct reaches of the Sandy River, Oregon (Cui 2007b). This result supports the expectation that TUGS can realistically evaluate sediment transport under a wide range of anthropogenically altered and natural conditions.

The model was applied to the mainstem Sacramento River between Keswick Dam (RM 302) and its confluence with Clear Creek (RM 290), a reach with no major sediment-bearing tributaries. Key objectives of the TUGS modeling exercise were to simulate sediment transport under historical hydrologic conditions and a series of potential future operational scenarios. These included raising the elevation of Shasta Dam to increase storage capacity and diversion of water to Sites Reservoir, a proposed off-stream storage site (Section 2.3). Future scenarios were evaluated both with and without gravel augmentation to predict whether it is likely to be effective at replenishing spawning gravel. Results were then fed directly into SacEFT as a demonstration analysis of the physical and ecological implications of the proposed management scenarios (see Section 2.3). More specifically, the tools can be used by planners to evaluate the likely effects by comparing results from project and no project data and analyses.

Key findings

Run 0: Historic sediment transport dynamics from 1941 to present

Historic sediment transport dynamics were simulated by: (1) cutting off upstream sediment supply to reflect post-dam conditions; (2) reproducing the effects of the dredging pit in Turtle Bay in the initial channel profile to mimic aggregate mining during dam construction; (3) running the model with historical (WY 1941–2005) discharges from the Keswick gauging station; and (4) providing gravel augmentation at documented rates within the study reach. This type of analysis is especially helpful in calibrating the model and verifying model performance. In addition, this type of historic simulation can help investigators understand, in greater detail, what has happened to the river channel since construction of Shasta Dam.

TUGS simulations reveal that:

- bed-surface coarsening and significant losses in sediment storage occur throughout the reach (Figure 2-4), but they are especially pronounced upstream of Turtle Bay (RM 296.5) due to base-level effects of the mining pit;
- biological implications of bed-surface coarsening may be severe, as reflected in substantial increases in coverage by particles >130 mm, which may be an important limiting factor for redd building by Chinook salmon females (see Figure 2-2); and
- gravel augmentation projects have resulted in local improvements to spawning habitat (Figure 2-4).

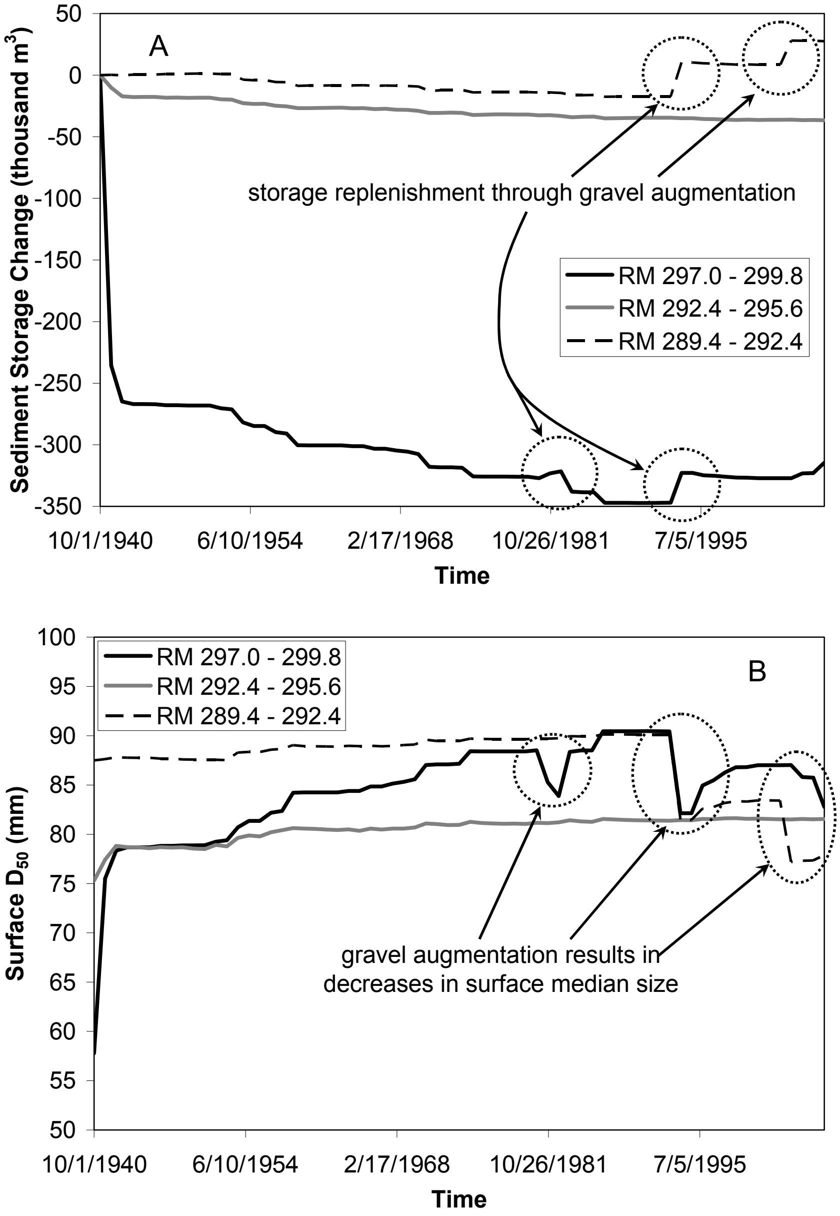

Figure 2-4. Simulated changes in coarse (>2 mm) sediment storage (A) and median grain size of the surface (B) for three reaches of the upper Sacramento River (black, gray, and dashed lines) over 6 decades (x-axis). TUGS predicts progressive losses in sediment storage and surface coarsening from 1941 to present in all reaches. Offsetting effects of gravel augmentation are localized and temporary.

Run 1: Hypothetical sediment transport dynamics using a repeat of historic hydrologic conditions

This run is hypothetical because an historic repeat of the facilities and operations of the CVP and SWP is no longer possible. The facilities and operational rules and objectives were significantly different in 1941 than in 2005 and changed significantly during that time period.

Hypothetical sediment transport dynamics were simulated using (1) the evolved channel from Run 0 as a starting point and (2) historical (WY 1941–2005) discharges from the Keswick gauging station.

TUGS simulations reveal that:

- grain size and sediment storage remains roughly stable for more than 50 years in the alluvial reach immediately upstream of Turtle Bay (RM 297.0–299.8), even without any additional gravel augmentation, due to the downstream propagating legacy of gravel that has already been added upstream at the Salt Creek and Keswick Dam injection sites (note, however, that gains in RM 297.0–299.8 would come with the potentially undesirable expense of 55,000 m^3 of gravel from the area upstream of RM 300, which now supports abundant spawning by both the fall and winter runs); and
- sediment storage decreases, and bed coarsening continues, downstream of Turtle Bay because no bedload from upstream can pass through Turtle Bay (this highlights the importance of conducting new gravel augmentation activities downstream of Turtle Bay).

Run 2: Geomorphic analysis of a 18.5-ft (5.6-m) increase in Shasta Dam height

Future sediment transport dynamics were simulated using (1) the evolved channel from Run 0 as a starting point and (2) daily average discharges estimated from CALSIM simulations, which are based on the WY 1939–1994 hydrologic record, with a projected post-construction operation rule for Shasta Lake.

For the hypothetical analysis, TUGS simulations reveal that:

- sediment storage in the main stem is more stable if Shasta Dam is raised, relative to what it would be under the “unaltered” conditions of Run 1 (because the biggest difference in hydrology is the reduced magnitude of peak flows, which are the primary movers of coarse sediment in the river); and
- the rate of bed coarsening will decrease after the height of Shasta Dam is increased, although surface grain sizes will nevertheless become increasingly coarse immediately upstream of the Sacramento River’s confluence with Clear Creek.

Run 3: Geomorphic analysis of the proposed NODOS-AF2B reservoir

Future sediment transport dynamics were simulated using (1) the evolved channel from Run 0 as a starting point and (2) daily average discharges estimated from CALSIM simulations, which are based on the WY 1939–1994 hydrologic record under projected operation rules for the NODOS reservoir, the Central Valley Project and State Water Project systems, and the Central Valley's flood-control system. TUGS produces essentially identical results for Run 2 and Run 3, because the simulated hydrologic record for NODOS (Run 3) is very similar to that of the increase in Shasta Dam height (Run 2).

Run 4: Geomorphic analysis of the FNA2 (Future No Action) scenario

Future sediment transport dynamics were simulated using (1) the evolved channel from Run 0 as a starting point and (2) daily average discharges estimated from CALSIM simulations, which are based on the WY 1939-1994 hydrologic record, assuming current operation rule for Shasta Lake.

- TUGS simulation indicates that, without any future gravel injection, sediment storage will continue to decrease and bed surface will continue to coarsen in all the subreaches except that immediately upstream of Turtle Bay, which continue to benefit from the early gravel augmentation farther upstream.
- Simulation of the gravel injection and comparison with the results of no gravel injection indicates that all the subreaches except that immediately upstream of Clear Creek confluence benefited significantly from gravel injection with increased gravel storage and decreased surface median size.

Effects of initial gravel injection

To evaluate whether gravel augmentation is likely to be effective at improving and maintaining spawning habitat, TUGS was used to simulate the effects of an initial injection of 583,000 metric tons (477,000 yd^3) of gravel for each management scenario. Simulated effects of the gravel injection suggest long-term (i.e., >50 year) increases in sediment storage coupled with decreases in grain size for sub-reaches that initially receive part of the injected gravel. The benefits of gravel augmentation would last about the same duration if Shasta Dam were raised (Run 2), or if an off-stream reservoir were installed and operated as proposed (Run 3).

Synthesis

TUGS simulations predict a progressive decline in sediment storage and an overall coarsening of the bed surface due to the system-wide, dam-related blockage of sediment supply to downstream reaches (Figure 2-4). Lack of data on tributary sediment inputs precluded application of the model to the reach from RM 290 to Colusa (RM 143); it also precluded assessment of the dynamics of fine sediment transport.

Increasing the height of Shasta Dam and operating an off-stream reservoir may both reduce peak flow, which would likely in turn reduce rates of sediment depletion and bed-surface coarsening within the study reach. Reductions in peak flow magnitude would also likely reduce bank erosion (Section 2.2.3) and thus have potential impacts on spawning gravel availability, especially if little gravel is added in the future. Reductions in bank erosion might also affect lateral channel migration, which is essential for creating the off-channel habitats important to many Sacramento River species. Hence, in the overall assessment of the various flow management options, it is very important to consider the many other factors that are at play besides sediment storage and bed surface coarsening.

Remaining data needs

To expand the application of TUGS to the entire project area (i.e., downstream to Colusa at RM 143), it will be necessary to better define rates of sediment supply from tributaries that join the river downstream of Clear Creek (RM 290). Measurements of fine sediment inputs, in particular, are necessary to fully exploit the potential management utility of TUGS.

2.2.3 Meander migration modeling

Meander migration[3] is a key regulator of the quality and quantity of near- and off-channel habitats for a diverse array of species, including most of the focal species of the Linkages Report (Table 2-1). Hence, to ensure that the riparian ecosystem is managed in a way that meets the needs of humans as well as those of the riparian ecosystem), it is important to understand how meander bends evolve over time. It is particularly crucial to quantify how meander migration may change in response to proposed changes in flow management.

Numerical modeling of meander migration can predict the evolution of off-channel habitats under a range of management scenarios. However, the predictive capability of meander migration modeling has been limited by the need to simplify bank erosion in terms of a single formative discharge. To overcome this limitation, and improve understanding of how the Sacramento River is likely to evolve over time, this

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[3] Meander migration and bank erosion occur by two processes: progressive channel migration, in which flows erode banks incrementally, and episodic meander-bend cutoff, in which the channel locally avulses to a new course. The meander migration model discussed here deals primarily with progressive channel migration, which has been responsible for roughly 80% of the river's lateral change over the last 100 years (Appendix A Stillwater Sciences 2007a). A separate effort to model cutoff processes was conducted as part of the off-channel habitat study (Section 2.2.4 of this Final Report; Appendix C Stillwater Sciences 2007c).

meander migration study was designed to (1) incorporate a variable hydrograph into an existing meander migration model, and (2) use that model to evaluate how a suite of potential management scenarios may affect channel migration in the middle section of the Sacramento River. Management scenarios considered in the meander migration study included revetment (riprap) removal at key sites and changes in flow rates that would result from the proposed construction of water storage facilities. The full study report is included in Appendix D (Larsen 2007). Key observations and implications are summarized below.

Key findings

Simulations were conducted for three sub-reaches between RM 222 to RM 179 under three flow scenarios and two bank-revetment scenarios (one with existing revetment in place and one with selected revetments removed).

Prior to interpreting results of comparative analyses conducted with the meander migration it is important that the reader understand the hypothetical nature of the comparisons. Comparisons between scenarios with the meander migration model are less appropriate as those conducted with the other models within the study and are for demonstration only. Unlike the other modeling efforts, the meander migration analysis was limited by availability of appropriate data sets to compare, namely a “no action” data set to an “action” dataset. A no action data set was not available for comparison with the meander migration model. Therefore, the action scenario was compared to the historic, or calibration, dataset. Although demonstrative, this is an incorrect use of this dataset because the historic data set already includes modification of the flow regime by Shasta Dam. With that understanding, the reader realizes that the comparisons represent the utility of the tools but not to place confidence in the comparative results of the meander migration analysis.

Simulations were generated using CALSIM data as input for the period from 2005 to 2059. The *hypothetical* flow scenario was based on historical flows for WY 1939 to WY 1993 recorded at three different gauges on the Sacramento River and current geomorphic and meander conditions. Synthetic flows for two other model scenarios were provided by CALSIM-SRWQM (see Section 2.2.2 for caveats about use of CALSIM-SRWQM flows): (1) the proposed 18.5-ft (5.6-m) increase in Shasta Dam height and (2) installation and operation of an off-stream reservoir (the proposed North-of-the-Delta Off-stream Storage facility).

The model output included (1) evolution of the channel centerline, (2) area reworked by lateral migration (e.g., Table 2-2), (3) changes in migration rate over time, (4) cumulative effective stream power (e.g., Table 2-2), and (5) (in one case) length of abandoned channel due to a predicted chute-cutoff event.

Table 2-2. Change in stream power and area reworked for the Woodson Bridge reach with existing revetment.

Model Scenario	Cumulative effective stream power	Floodplain area reworked
NODOS reservoir	-10%	-5%
raise Shasta Dam	-16%	-8%

As noted in Section 2.2.2, peak flows are noticeably reduced under both of the “modified” flow scenarios, relative to the historic, or calibration, flows in this *hypothetical* comparison. Cumulative effective stream power shows a decrease of up to 16% in the Woodson Bridge reach (Table 2-2). Although cumulative effective stream power ultimately drives meander migration and the reworking of the floodplain, the correlation between percent change in stream power and percent change in reworked area is not one-to-one (Table 2-2). This partly reflects the fact that migration rates are affected by the channel’s context (i.e., the initial planform geometry and distribution of revetments and natural constraints), which is largely decoupled from cumulative effective stream power.

For all three segments combined, the reduced peak flows of the “raise Shasta Dam” scenario correspond with a simulated decrease in reworked area of 425,000 m^2 (8%) relative to historical conditions in this hypothetical comparison. For the off-stream reservoir scenario, the decrease in total area reworked was somewhat lower (375,000 m^2 or 5%)[4].

Four revetment-removal scenarios were modeled in the three channel segments (Figure 2-5 and Figure 2-6). The resulting simulated increase in area reworked between WY 2005 and WY 2059 was 575,000 m^2 or 8% relative to historic conditions in this hypothetical comparison (i.e., with revetments remaining in place). The modeled removal of the revetment at Ord Ferry resulted in a slight decrease in area reworked, because the predicted response is the creation of a new 2,500-m-long abandoned channel due to a cutoff (Figure 2-6), which leads to relatively low mainstem sinuosity and therefore slow progressive lateral migration for the reach. Excluding the Ord Ferry revetment removal, there was a total increase in 600,000 m^2 of area reworked by lateral migration under the revetment-removal scenarios.

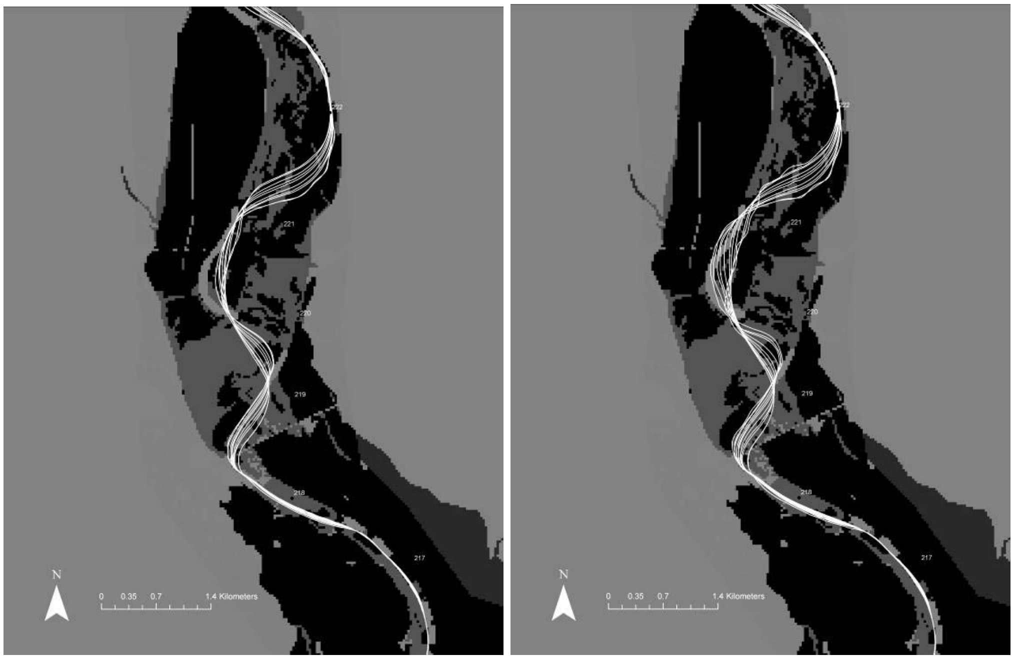

Figure 2-5. Predicted evolution of Woodson Bridge site for hypothetical flow scenario with existing (left) and altered (right) revetment conditions. Altered condition corresponds with revetment removal at RM 220–222 (right bank) at Kopta Slough.

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[4] Following the completion of the Draft Final Report, DWR provided two updated scenarios: NODOS-AF2B and FNA2, to allow more comparable simulations of different hydrosystem facilities and configuration. For time and budgetary reasons, it was not possible to update the revetment simulations using these new simulations. Therefore there are no corresponding revetment simulations for the FNA2 scenario, and the NODOS-AF2B scenario makes use of an earlier NODOS scenario.

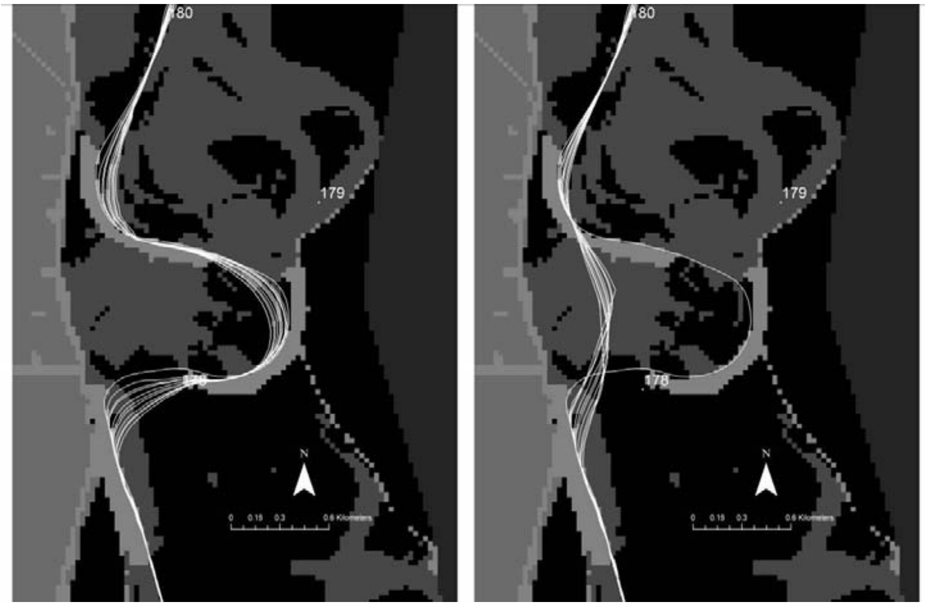

Figure 2-6. Predicted evolution of Ord Ferry site for hypothetical flow scenario with existing (left) and altered (right) revetment conditions. Altered condition corresponds with revetment removal at RM 179 (right bank) at the Llano Seco Riparian Sanctuary. Revetment removal leads to a new cutoff, which in turn leads to reduced sinuosity and slower lateral migration in the new mainstem channel. This highlights an important trade-off to consider: the prospect of a reduced meander migration rate (which might reduce the creation of bank swallow habitat) must be balanced against the prospect of creating new oxbow habitats (which might benefit western pond turtles).

Synthesis

For this *hypothetical* application, the meander migration model was used to evaluate trade-offs associated with proposed flow and revetment changes along the middle Sacramento River. Results suggest that the total added area of reworked floodplain induced by selected revetment removal may be roughly equivalent to the reduction in reworked area that results from raising Shasta Dam or operating NODOS relative to historical flows[5].

For one of the four simulated revetment removal options, the model also predicted that a meander-bend cutoff would occur. The simulated cutoff would produce about 8,200 feet (2,500 meters) of abandoned channel while reducing the meander migration rate of the segment in question (Figure 2-6). This highlights a trade-off in ecological function when cutoffs occur—abandoned channels provide habitat for some species (e.g., western pond turtles), whereas active meander zones provide habitat for others (e.g., cutbanks for bank swallows). Such trade-offs are important considerations for evaluating the benefits of various management actions. There may be other sites where cutoff potential could be encouraged if revetments or natural constraints were removed. Identifying such sites should be a priority for future research.

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[5] Following the completion of the Draft Final Report, DWR provided two updated scenarios: NODOS-AF2B and FNA2, to allow more comparable simulations of different hydrosystem facilities and configuration. For time and budgetary reasons, it was not possible to update the revetment simulations using these new simulations. Therefore there are no corresponding revetment simulations for the FNA2 scenario, and the NODOS-AF2B scenario makes use of an earlier NODOS scenario.

2.2.4 Off-channel habitat study

In large rivers such as the Sacramento River, understanding the natural processes that create, maintain, and eventually destroy off-channel habitats is crucial for effectively managing ecological resources within the context of human needs. The Ecological Flows Study included an off-channel habitat component (Appendix C: Stillwater Sciences 2007c) that focused on reducing uncertainties about how natural and anthropogenic factors affect three key processes:

- chute cutoff, a poorly understood mechanism for generating off-channel water bodies (OCWBs) on the floodplain;
- inundation of seasonally inundated secondary channels, a source of habitat for many species, including juvenile Chinook salmon and Central Valley steelhead; and
- terrestrialization, the process by which OCWBs are modified by sediment deposition, vegetation colonization and succession, and accumulation of organic debris from aquatic vegetation.

The off-channel habitat study was a collaborative effort led by an interdisciplinary team of researchers from Stillwater Sciences, UC Berkeley, and the *Centre National de la Recherche Scientifique* (in Lyon, France) (see Appendix G). One outgrowth of the study is that ongoing research on off-channel habitats along the Sacramento River is now more effectively aligned to achieve complimentary goals. Another product of the study was the development of a provisional classification system for shallow-water, seasonally inundated habitat that occurs within the bankfull channel. Such habitats have received little attention in ecological studies, but they are important as rearing habitat for many of the river's native fish species.

Study objectives

The goal of the off-channel habitat study was to identify potential management actions (e.g., changes in flow releases, removal of bank revetments, or excavation of off-channel habitats) that could help maintain and restore the ecological value of habitats in OCWBs and secondary channels. To achieve this overarching goal, four tasks were identified:

- identify the physical processes that create chute cutoffs;
- evaluate how flow and sedimentation affect the persistence of OCWBs and secondary channels;
- survey aquatic vegetation and monitor water quality in secondary channels and OCWBs to identify factors that affect the composition and distribution of aquatic vegetation; and
- identify flows that create shallow-water, seasonally inundated habitats that are likely to support juvenile salmonid rearing within the bankfull channel.

The original scope of the study included developing a model to predict the formation of OCWBs by chute-cutoff processes under various discharges and riverbank conditions. After a significant investment of time and effort, including a workshop with experts on chute cutoff processes, the modeling objective was deemed infeasible and was abandoned. The problems encountered in the chute-cutoff modeling effort are described in Appendix C in an effort to guide future studies of the physical processes that drive channel cutoff in large gravel-bedded rivers.

Key findings

Sedimentation rates

Radiometric data and depths of sediment within the OCWBs reveal that sedimentation rates tend to even-out over time, with the volume of slower-filling OCWBs (which are typically less well-connected to the main channel) tending to “catch up” to faster-filling OCWBs over a period of decades. There is a strong relationship between planform channel geometry and infilling rates of oxbow lakes along the Sacramento River, with higher rates for OCWBs whose inlets more closely parallel the course of the mainstem (Figure 2-7). Oxbow lakes whose inlets diverge significantly from the course of the mainstem appear to function as long-term sinks for fine sediment in the floodplain and may also serve as storage sites for adsorbed pollutants.

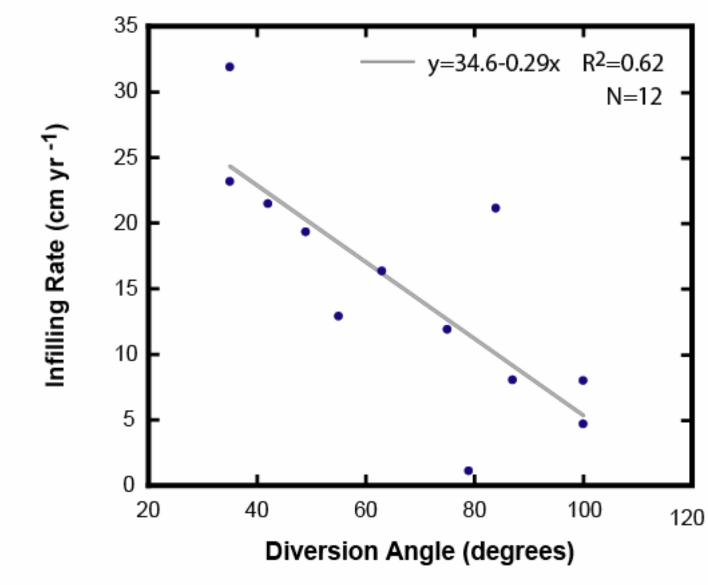

Figure 2-7. OCWB Infilling rate as a function of diversion angle, defined as the angle between the mainstem channel centerline and the centerline of the off-channel water body. Lower angles correspond with higher delivery of water and sediment, which leads to faster infilling rates.

Water quality

Average dissolved oxygen content was >90% saturated at 11 out of 29 OCWB study sites. In contrast, water samples at ten of the other sites had dissolved oxygen concentrations of less than 55% saturation, concentrations that could be limiting for many aquatic organisms. Appendix C includes a table that summarizes the presence/absence data for aquatic macrophytes and fish species that were observed in the OCWBs over the course of the study.

According to Environmental Protection Agency (EPA) standards for streams with “good,” mixed fisheries, conductivity should be between 150 and 500 µhos/cm (EPA 2006). Our measurements indicate that five of the OCWB sites had average conductivities greater than 500 µhos/cm, which is high enough that it might affect aquatic species composition and diversity. Conductivity was highest in an OCWB adjacent to agricultural land; this may indicate that salt-rich agricultural runoff is entering the water body. Average conductivities at seven of the OCWB sites were between 100 and 150 µhos/cm, below the EPA threshold for good fisheries. Low conductivity may be indicative of high hydrologic connectivity with the mainstem.

Secondary channels

Aerial photograph assessment of morphometric differences in OCWBs led to the following simple classification system for seasonally inundated secondary channels that lie within the bankfull main stem:

Type 1: Scour channels along the bank, behind and often across active point bars; typically with perched inlets and the most ephemeral outlet connections of the three types; these channels typically become connected at their inlets at flows from 11,200 to 12,500 cfs.

Type 2: Abandoned mainstem channels (or flow scars) on the insides of meander bends; most similar to OCWBs but have outlets connected to the mainstem; have pools ephemerally connected to outlets due to rising water table because their inlets are plugged with sediment and require overbank flows to connect to the mainstem.

Type 3: Former mainstem channels on the outside of a meander bend or at a previous bend that has straightened; inlets with a higher degree of connectivity that typically begin to disconnect at flows below 8,500 cfs, outlets typically remain perennially connected, but pools along axial length will desiccate as inlets disconnect.

Shallow secondary channels exhibit substantial increases in inundated area when mainstem Sacramento River discharges exceed 11,500–12,000 cfs (Figure 2-8), which is also the approximate threshold for higher-elevation inlet connection between the mainstem and Type 1 channels. Another significant mainstem flow threshold appears to be about 8,500 cfs (Figure 2-8). Below this discharge, the inlets of Type 2 channels become disconnected from the main stem, and isolated pools within all types of shallow-water channels significantly contract or desiccate completely.

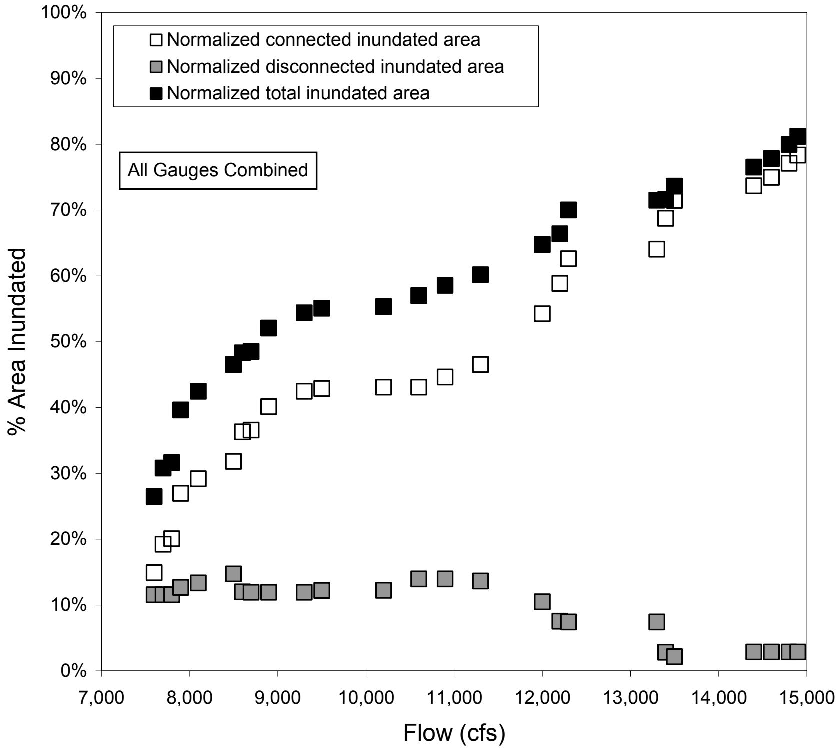

Figure 2-8. Normalized connected (white symbols), disconnected (gray symbols), and total inundated area (black symbols) averaged over all study sites for varying flows on the Sacramento River. Each site is normalized by the maximum potential inundated area, such that they each have equal weight in determining average percent inundated area. The stepped pattern of area versus flow highlights what appears to be a significant river-wide increase in inundated area at about 12,000 cfs. A significant decrease in inundated area appears to occur at roughly 8,500 cfs.

Water temperatures in seasonally inundated secondary channels tend to be significantly lower when inlets are connected to the main stem and thus are receiving fresh, cool water; temperatures tend to rise when these channels are disconnected at their inlets. Temperature modification via outlet connection to the main stem appears to affect only a small area of the secondary channel nearest the outlet. In 7 out of 13 instances during the study, water bodies with disconnected inlets had temperatures that exceeded 22°C, the reported lower threshold for mortality in Central Valley fall-run Chinook salmon fry (Moyle 2002). In contrast, water temperatures never exceeded 22°C at sites with inlets that remained connected to the main stem. This suggests that juvenile Chinook salmon that become stranded in shallow OCWBs would likely suffer high mortality rates from temperature alone. We did not observe any instances of stranded salmon or steelhead in this study, but suspect that it could easily occur and could be an important source of impaired survival. Stranded fish are also extremely vulnerable from both avian and mammalian predators. Additional assessment of this hypothesis is warranted.

Synthesis

In the off-channel habitats study we tried to reduce key uncertainties regarding the processes that create, maintain, and eventually eliminate OCWBs and seasonally inundated shallow-water areas along the mainstem Sacramento River, as well as create a classification system with management utility. Measurements of several chemical indices of biological suitability suggest that water quality varies widely across the OCWBs, and in several cases may be sufficiently degraded to impair species diversity.

Sedimentological data show that infilling rates are faster for oxbows whose inlets more closely parallel the course of the mainstem. This appears to highlight the importance of channel geometry as a regulator of OCWB persistence and suggests that divergence angle and other indices of planform geometry may be useful indicators to quantify in meander-migration and chute-cutoff modeling studies.

Thermograph data from shallow-water seasonally inundated secondary channels show that inundated area generally increases at a threshold mainstem discharge of around 12,000 cfs. As flows recede below 8,500 cfs, the inlets of the secondary channels become increasingly disconnected from the main stem and inundated area rapidly declines. Hence, results of this study appear to show that the extent and timing of inundation of shallow-water habitats are regulated by at least two key discharges. This has important implications for stranding of fish. Additional studies are needed to quantify how inundation and habitat quality relates to discharge across the full potential range of summer flows and from site-to-site along the main stem. Another remaining uncertainty is the effect of antecedent conditions, particularly whether extended droughts or wet periods affect the seasonal inundation and desiccation of shallow-water habitats.

2.2.5 Effects of bank revetments

Study rationale and key questions

Bank erosion is a fundamental riverine process that drives lateral migration and helps create and maintain off-channel habitats. It also affects recruitment of sediment and large woody debris from eroding banks, riparian areas, and floodplains and so is a key regulator of aquatic habitat in the main stem. Bank erosion also disrupts human activity, however, and this has prompted land owners and government agencies to armor extensive lengths of the Sacramento River's banks with riprap. For the past two decades, resource agencies have expressed concern that bank armoring reduces the extent and quality of aquatic and terrestrial habitats by affecting the processes that create and maintain them.

To date, there have been no definitive studies of how bank armoring affects aquatic habitat. Proposed indices of the effects of armoring are channel depth and the amount and quality of spawning and rearing habitat, but a clear assessment of how these features differ in armored and eroding (i.e., unarmored) bends has remained elusive. In the Ecological Flows Study, we sought to address uncertainties about armoring by answering the following questions:

- Do channel depth and cross-sectional geometry differ in armored and eroding meander bends?
- How does bank armoring affect habitat area for various fish species of interest?

- How does the density of LWD differ between armored and eroding bends? How does bank armoring affect large wood in the channel?
- How do variations in the size of riprap affect aquatic habitat and cover?
- Do zones where slow and fast water meet (i.e., “eddy fences,” where juvenile salmon may feed) differ in extent between armored and eroding bends?

Study objectives and design

To examine the effects of bank armoring on aquatic habitat in the middle Sacramento River, we selected a paired series of eroding and armored bends and measured channel depth, details of the three-dimensional flow-velocity field, and the extent of cover. Depth, velocity, and cover were selected because they are all thought to be important regulators of habitat suitability for aquatic species (e.g., salmon and steelhead).

Flow velocities and water depths were measured at a discharge of roughly 7,800 cfs using an Acoustic Doppler Current Profiler (ADCP) at five pairs of eroding and armored banks (10 sites total) on the middle Sacramento River. Velocities were measured a second time at two pairs of sites at a discharge of about 12,500 cfs. Large wood and the size of riprap pieces at armored bends were qualitatively assessed as measures of cover at each site. Zones where slow and fast water meet were mapped onto aerial photographs and also characterized by ADCP measurements.

Key findings

Preliminary observations indicate that maximum and average water depths along armored bends are greater than along eroding bends when similar locations are compared. Preliminary observations also indicate that the channel’s cross-section adjacent to armored bends tends to be narrower and more incised and often lacks the extended shallow zone typically found on the insides of eroding bends. This is generally consistent with conventional wisdom about the effects of armoring on hydraulic geometry, as well as other studies conducted for the Sacramento River.

On the other hand, results from the preliminary velocity analyses are not entirely consistent with expectations about effects of armoring on habitat suitability for fish. Although more abundant rearing habitat might be expected in channels with eroding banks, the paired comparisons failed to reveal any statistically significant differences in suitable habitat between armored and unarmored bends for any of the fish species considered in this study.

These results may, in part, be artifacts of the methods chosen and/or the range of flows sampled. The ADCP deployed in this study cannot measure velocity if depth is less than about 2.5 feet (0.8 meters). On the Sacramento River, such shallow areas often have depths and velocities that provide ideal rearing habitat for many species of concern. Such areas were prevalent in eroding bends at the flows sampled in this study. This may have led to a systematic underestimation of prime rearing habitat in the eroding bends. In contrast, the relatively incised hydraulic geometry of armored bends is such that we were able to measure ADCP-based velocities across almost the entire wetted channel width for the flows sampled in this study. Hence, the ADCP-based approach appears to have introduced a bias into our comparison of habitat distributions in armored and eroding bends. This bias limits or precludes altogether a statistically rigorous comparison, at least with the information collected in this study.

In the armored bends, much of the apparently suitable habitat arises from an abundance of deep areas that function similarly to pools, with low velocities at low discharges. As flow increases, wetted area likely remains relatively constant in armored bends while velocities increase, because the hydraulic geometry of incised channels at armored bends is generally such that the channel can't readily expand its wetted width onto the adjacent point bar. In contrast, eroding bends, with their less confined hydraulic geometries, are presumably able to expand greatly in width and thus substantially increase wetted area available as rearing habitat. The “high flow” survey portion of this study suggested that eroding bends may start to exhibit significant gains in suitable area at flows of around 12,500 cfs.

Data from this study sheds light on other uncertainties as well. At low flows, armored and eroding banks appear to have roughly similar lengths of eddy fences (i.e., lengths of low-velocity water and back eddies that are adjacent to high-velocity flow). Large wood density was higher at eroding bends than at armored bends; it was also higher at eroding bends with adjacent mature riparian forests than at those with orchards or other agricultural crops.

Hence, preliminary observations suggest that the extent and quality of aquatic habitat probably differs between channels with armored and unarmored bends. However, the full range of goals articulated in the original study scope cannot be achieved with the data collection methods chosen.

Additional research needs

Despite the abundant field data generated by this study, the challenges inherent in quantifying velocities and depths in the high-velocity, near-bank environment of the Sacramento River (and consequent limitations in data-collection techniques) placed statistically defensible conclusions beyond reach. Future work should include techniques that enable additional velocity surveys at higher discharges than those surveyed here. Flow depths and velocities would also need to be measured in shallow areas to supplement the existing ADCP data. Such a study could enable several important advances:

- test the hypothesis that differences in habitat area between armored and eroding bends vary with the magnitude of discharge;
- document flow parameters and flow structure at discharge(s) that exhibit progressively greater differences in velocities between the outsides and insides of bends; and
- document how discharge varies with wetted channel width and habitat area.

Also needed is a better characterization of the physical habitat preferences of the species that utilize meander bends.

2.2.6 Management implications of field and modeling study results

Results from the field and modeling components of the Ecological Flows Study have many implications for effectively managing the river's ecological resources within the context of human needs. Key results and implications are summarized in Table 2-3.

Table 2-3. Observations and management implications from the Sacramento River Ecological Flows Study.

Study Results	Management Implications
Gravel Study Report	
Gravel augmentation may have led to rapid increases in spawning habitat and use in the upper river.	Gravel augmentation may provide substantial benefits for Chinook salmon where spawning habitat appears to be limiting
Changes in fish passage at diversion structures may have played a crucial role in increases in spawning use in the upper river.	It may be possible to further modify fish passage for increasing benefits to the winter run and possibly the spring run.
Chinook salmon of the Sacramento River do not appear able to readily spawn in deposits where more than 40% of the bed is covered by immovable particles (i.e., >130 mm in b-axis diameter).	Assessing the percent coverage by immovable particles, together with hydraulic conditions, can provide a quick, powerful, diagnostic tool for assessing the suitability of spawning gravel in rivers where spawning may be limited by the abundance of very coarse material on the surface. Managers should use this criterion, together with historical data on spawning use, to identify areas that have recently become too coarse for spawning and to prioritize sites for future gravel augmentation/restoration projects.
In the middle river, the depth of scour in typical winter flows can be significant enough (>1 m) to excavate redds, killing eggs and alevins if scouring flows occur during incubation.	Such scour could have significant effects on the fall run, because it is the only run that uses the scour-prone middle river for spawning, and moreover does so in winter when flows may be high enough to mobilize the bed.
Permeability measurements suggest that the upper part of the bed is relatively free of fine sediment.	Fine sediment infiltration is probably not sufficient to cause substantial entombment or suffocation of eggs and alevins in any given year; additional monitoring is nevertheless warranted.
Sediment Transport Modeling	
Base-level effects of Turtle Bay are the single biggest regulator of the coarsening and loss of gravel at Redding Riffle, which is immediately upstream.	Restoring historical spawning conditions at Redding Riffle may be difficult, which suggests managers may need to focus on other sites where restoration feasibility is higher.
Predicted coarsening leads to increasing immobility of the bed surface.	Infiltration of fine sediment may become a problem in the long term as the frequency of flushing flows continues to decrease.
The proposed raising of Shasta Dam and the proposed operation of the NODOS reservoir would reduce sediment transport and preserve existing gravel resources (including gravels from past augmentation projects) as compared to a Future No Action alternative.	The proposed management scenarios may help preserve spawning habitat for Chinook salmon, but only if reduced mobility is not accompanied by increased infiltration of fine material; further study of the latter possibility is warranted.
Off-channel Habitats Study Report	
Infilling of off-channel water bodies is regulated fundamentally by planform geometry of the channel and water bodies.	Divergence angle and other indices of planform geometry may be key parameters to consider when assessing the relative merits of management scenarios via meander migration and chute-cutoff modeling .
Water quality in off-channel water bodies shows some correspondence with proximity to agricultural lands.	After further investigation of this relationship, managers should consider whether agricultural use should be limited, and/or best management practices implemented, to improve water quality in the vicinity of key off-channel water bodies.
Pools within shallow-water, seasonally inundated channels contract significantly and begin to exhibit increased temperatures once inlets disconnect from the mainstem. Depending on the type of channel, two thresholds were identified for inlet disconnection: 8,500 and 12,000 cfs	Flows less than 12,000 or 8,500 cfs may pose a significant stranding risk for juvenile salmon and other fish that use the channels for seasonal rearing.
Meander Migration Report	
Removal of revetment may sometimes cause the channel to avulse to a new, straighter course with a slower rate of progressive migration.	In selecting revetment removal sites, managers must balance the potential benefits of increased progressive migration against the benefits of the new off-channel habitats that would be created by the cutoff.

Study Results	Management Implications
Hypothetical comparisons revealed that the proposed raising of Shasta Dam and the proposed operation of the Sites Reservoir are expected to reduce progressive migration by approximately 10%.	Loss of meander migration potential should be mitigated.
Hypothetical comparisons revealed that Removal of revetment may increase progressive meander migration by approximately 10%.	Removal of bank revetment mitigate effects of raising Shasta Dam or installing/operating the Sites Reservoir.
Effects of Bank Revetment	
Bank revetments alter channel geometry, deepening flow along the outside of the bend, which may confine channels to narrow wetted widths, even at high flows.	Revetments should either be designed to reduce this effect or avoided altogether if possible within the context of human needs.
Bank revetments reduce large wood recruitment to the channel.	Mitigation measures and/or additional riparian vegetation restoration should be implemented for future bank revetment projects (and those already installed) or revetment should be avoided altogether.

2.3 Sacramento River Ecological Flows Tool (SacEFT): Integrated trade-off analysis for select management alternatives

Subsequent to the completion of the first version of this report, DWR provided revised flow and water temperature simulations that included a Future No Action (FNA2) baseline scenario that can be used in comparisons with modified hydrosystem operations. The NODOS-AF2B scenario includes select restoration targets and constraints in its alternative operation plan; and the FNA2 scenario provides a "Future No Action" alternative in order to make internally consistent comparisons with the NODOS-AF2B scenario. As a rule, SacEFT comparisons of focal species response under the NODOS-AF2B alternative must, by definition, be only made versus the FNA2 scenario. This comparison includes common assumptions, and Appendix F results are updated to reflect this consistent scenario comparison. The Shasta alternative is not compared to anything as we were not provided a future no action Shasta scenario against which to compare the Shasta alternative. Therefore, due to differences in hydrosystem operations and demands between both the historical and Shasta scenarios and the FNA2 scenario, it is understood that direct comparisons can only be made between the FNA2 and NODOS-AF2B scenarios. Readers are advised that this document may show SacEFT results for historical flows to illustrate the results used in calibrating species performance measures' hazard threshold boundaries.

Allocation of scarce water resources to meet the needs of people and ecosystems is a significant challenge. In the Central Valley of California, a number of programs exist to implement water-related conservation strategies that attempt to balance the needs of humans and ecological systems. These include the Environmental Water Account (EWA), Environmental Water Program (EWP), Central Valley Project Improvement Act (CVPIA), Anadromous Fish Restoration Program (AFRP), and the CALFED Ecosystem Restoration Program. Despite much study, ecological considerations that are included in water planning exercises are most often still limited to meeting minimal in-stream flows, meeting basic temperature requirements, or limiting periods of pumping during times when sensitive species are present. Although these considerations are likely beneficial, more transparently relating additional attributes of the flow regime to multiple focal species life-history needs contributes to more effective water operations and ecosystem restoration. In addition, there was a need to integrate requirements of multiple ecological targets into a single framework. This framework needed to be structured to make accessible the disparate existing information for individual species contained in stacks of separate reports and in separate modeling tools.

The second challenge of this framework was not only to integrate this disparate information but also to translate any analyses into easily understandable results. When expanding the number of ecological targets considered, practical synthesis and integration becomes a challenge to disseminate, especially to an audience with multiple levels of understanding. For instance, trade-off analysis results must make it clear whether actions implemented for the benefit of one area or ecological target negatively affect another. A clear need among all the aforementioned water management and planning programs was a set of tools that integrate (not re-invent) multiple sources of information on the ecosystem effects of alternative management actions and boil down performance and trade-offs across multiple indicators. While new information is being generated daily by ongoing research, effective synthesis tools to integrate and clearly communicate multi-species, multi-scale trade-offs have not kept pace.

2.3.1 Study rationale and key questions

In response to these needs, The Nature Conservancy and ESSA Technologies developed a computer model that incorporates physical models of the Sacramento River with biophysical habitat models for six focal species in an attempt to improve the ecological representativeness of water operation targets and to reflect ecosystem responses to alternative scenarios of discharge, water temperature, gravel augmentation and channel revetment actions. The resultant tool, named the Sacramento River Ecological Flows Tool (SacEFT) is a database-centered software system that links flow management actions to focal species outcomes on the mainstem Sacramento River (details provided in ESSA Technologies 2007, available from the “SacEFT Design Guidelines” link on http://www.delta.dfg.ca.gov/erp/docs/sacriverecoflows/Task%203_SacEFT%20Design%20Guidelines.pdf).

The vision for SacEFT was to create software that makes it easy to expand the ecological considerations and science foundation used to evaluate water management alternatives on the Sacramento River. To meet this vision, the system leverages existing physical and biological datasets and models rather than reinventing wheels, and selectively “builds-in” functional relationships for focal species performance measures. The SacEFT design workshop SacEFT Backgrounder Report link on (http://www.delta.dfg.ca.gov/erp/docs/sacriverecoflows/Task%203_SacEFT%20Backgrounder%20Report.pdf) describes in detail the process used to develop functional relationships between focal targets and management actions. The functional relationships selected reflect both existing data availability and the current level of quantitative evidence for linkages between species’ responses and habitat characteristics. While for some focal species a considerable amount of quantitative information was available (e.g., Chinook salmon), in other cases there are major gaps in both data and scientific understanding (e.g., green sturgeon). Details of functional relationships included in the current SacEFT model are provided in the SacEFT Design Guidelines link on http://www.delta.dfg.ca.gov/erp/docs/sacriverecoflows/Task%203_SacEFT%20Design%20Guidelines.pdf

Use of existing planning models is a key aspect of the system; this includes both common water-planning tools like the CALSIM-SRWQM-HEC5Q modeling complex, and geomorphic simulation models such as the meander migration model developed by researchers at UC Davis (Larsen 2007, Appendix D) and The Unified Gravel-Sand model (TUGS) developed by Stillwater Sciences (Cui 2007a, 2007b, Appendix E). SacEFT possesses unique strengths that compliment and advance other tools like the Ecosystem Functions Model (EFM) (USACE 2002) and Indicators of Hydrologic Alteration (IHA) (Richter et al. 1996).

Considering that our goal with this work is to facilitate the inclusion of a broader suite of ecological considerations into water-planning exercises, we developed a series of questions to guide an evaluation of SacEFT's benefit to planning forums. We formulated the questions to test whether the effects of potential water infrastructure projects, and their effects on hydrology and water temperature (as reflected by CALSIM-SRWQM-HEC5Q output) would be revealed through our focal species and associated functional relationships. These "proof of concept" questions were as follows:

1. Of the two internally consistent flow management scenarios considered in the Study, how much difference do they make to the six focal species? Re-stated, how sensitive are the focal species performance measures to the NODOS-AF2B scenario relative to the FNA2 baseline?
    - What do we learn about focal species sensitivity by looking at the variation in historical flows *alone* from 1939 to 2004?
2. How much difference does 'no channel action' vs. 'full channel action' make? Is gravel augmentation more significant than channel revetment? For what focal species?
3. What are the most and least sensitive focal species performance measures? To what actions? For focal species which appear to be insensitive, is this likely to occur in nature, or is this due to simplifying assumptions in the SacEFT models?
4. Does SacEFT suggest directions for adaptive management experiments and/or research to test the real-world benefits of different actions for focal species? Are there any glaring differences with leading hypotheses and management advice identified in the Linkages Report (Appendix A)?

The summary of findings with regard to these four questions is not intended to be definitive. There are a number of considerations, outlined in the next section, that explain why this is the case.

2.3.2 Scenarios evaluated

In the initial demonstration application of SacEFT, we developed and carried out 14 simulations based on availability of required inputs. A required input to a SacEFT simulation are daily flows (e.g., daily streamflow data taken directly from the historic record or SRWQM daily flow time-series disaggregated from CALSIM II). Therefore, the choice of our demonstration simulations was very much driven by available historic and CALSIM-SRWQM data. In partnership with the Department of Water Resources and the Bureau of Reclamation, four daily flow output data sets were used in our simulations of the ecological outcomes. These are described below and include

Scenario 1 (Historical):
Historical flows (WY 1939–2004) used principally to calibrate and assist in the identification of thresholds between condition levels (i.e. good, fair, poor) for a target. Most indicators and hazard thresholds are currently broken down into terciles and this is further discussed in Appendix F (ESSA Technologies 2008), Section 1.1.5. While historical flows embed a range of hydrosystem configurations, operations and levels of human water demands and thus do not have internally consistent assumptions, they nevertheless illustrate the true measured flow regime. These flows typically provide the widest range of contrasts, a desirable property when calibrating hazard threshold boundaries.

Scenario 2 (NODOS Future No Action, or FNA2):
As part of the Surface Storage Investigations, the CALFED Bay-Delta Authority, California Department of Water Resources and U.S. Bureau of Reclamation developed a Common Assumptions process to provide peer review of analytical tools and baseline conditions for planning analysis, including a NEPA Future No Action (FNA2) simulation of 2020 operations and hydrology (based on an 80 year historic

streamflow record). The FNA2 scenario includes the current Common Assumptions FNA assumptions, documented as Common Model Package 8d.

Scenario 3 (NODOS Future Action Alternative, or NODOS-AF2B):
The North-of-the-Delta Off-Stream Storage Investigation AF2B (NODOS-AF2B) scenario is a hydrosystem simulation developed jointly by the California Department of Water Resources and Bureau of Reclamation, to evaluate the potential benefits and consequences of the new off-stream Sites Reservoir near Maxwell, California. The investigation is evaluating a number of multi-objective scenarios[6] for improved water supply reliability and Delta water quality, and enhanced survival of anadromous fish. The AF2B scenario was selected based on its emphasis on select restoration targets and constraints in its scenario operation plan. The NODOS-AF2B operational rules and hydrology are the same as FNA2 (2020 facilities, demands, and operations), but includes the new offstream Sites Reservoir. This allows a direct comparison of AF2B and FNA2 scenarios by providing a dataset depicting common assumptions about the streams, reservoirs, Delta, and operations of the central valley water resources systems including the Central Valley Project and State Water Project.

Scenario 4 (Shasta):
In this scenario (WY 1922–1994) the Bureau of Reclamation is investigating the water delivery consequences of raising Shasta Dam 18.5 feet to increase the reservoir's storage capacity.

These scenarios included permutations of other management actions such as gravel augmentation and channel revetment actions in various combinations. As shown in Table 2-4, 4 simulations were developed using the historic streamflow data set. An additional ten simulations included CALSIM-SRWQM output from the Shasta, NODOS-AF2B and FNA2 scenarios.

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[6] These restoration objectives include (J. Wieking, CDWR, pers. comm.):

- Improve the reliability of cold-water carry-over storage at Shasta Lake.
- Increase supplemental flows for cold water releases for salmon and steelhead between Keswick and Red Bluff Diversion Dam.
- Reduce diversions at Red Bluff to provide water into the TC Canal and at Hamilton City to provide water into the GCID Canal during July, August, and September. Priority is to reduce diversions at GCID. This concept is designed to minimize diversion effects to fish during identified critical periods.
- Improve the reliability of cold water carry-over storage at Folsom Reservoir and stabilize flows in the American River.
- Modify spring flows into a "snowmelt pattern" in years with peak storm events in late-winter and early-spring, from Red Bluff to Colusa. The snowmelt pattern would be designed to increase the success of cottonwood cohorts, specifically.
- Stabilize fall flows to avoid abrupt reductions from Keswick to Red Bluff to avoid adverse conditions for spawning fall-run Chinook salmon (i.e., egg desiccation).
- Provide a flow event by supplementing normal operating flows from Shasta and Keswick Dams in March during years when no flow event has occurred during winter or is expected to occur. Flow events would be provided only when sufficient inflow to Lake Shasta was available to sustain the prescribed releases. This action could be refined by evaluating its indirect costs and the overall effectiveness of achieving objectives, which are 8,000 – 10,000 cfs in dry years and 15,000 – 20,000 cfs in below-normal years.
- Provide a March Delta outflow from the natural late-winter and early-spring peak inflow from the Sacramento River. This outflow should be at least 20,000 cfs for 10 days in dry years, at least 30,000 cfs for 10 days in below-normal water years, and 40,000 cfs for 10 days in above-normal water years. Wet-year outflow is generally adequate under the present level of development.
- Provide a minimum flow of 13,000 cfs on the Sacramento River below Sacramento in May of all but critical years.
- Maintain X2 West of Collinsville during May – December (summer/fall).

Table 2-4. Summary of initial simulation runs conducted using SacEFT. TUGS = The Unified Gravel-Sand Model (Stillwater Sciences 2007b, Cui 2007.). MM = Meander Migration Model (Larsen 2007).

Flow Scenario		**Channel Actions**			
		Gravel Augmentation: TUGS		**Channel Revetment: MM**	
		No Gravel	**Preferred Gravel ††**	**Current Channel (No revetment)**	**Select Revetment Removal**
		ng	**g+**	**cc**	**r^2**
H – Empirical Historical flow (WY 1939-2004)		**H-ng**	**H-g+**	**H-cc**	**H-r^2**
Future State	**FNA2**	**F-ng**	**F-g+**	**†**	**†**
	NODOS-AF2B	**N-ng**	**N-g+**	**N-cc †**	**N-r^2 †**
	Shasta	**S-ng**	**S-g+**	**S-cc**	**S-r^2**

† Following the review of the first version of this report DWR provided two updated scenarios: NODOS-AF2B and FNA2, to allow directly comparable simulations of different hydrosystem facilities and configuration. For time and budgetary reasons, it was not possible to update the revetment simulations using these new simulations. Therefore there are no corresponding revetment simulations for the FNA2 scenario, and the NODOS-AF2B scenario makes use of an earlier NODOS scenario.

†† The Anadromous Fisheries Restoration Program (AFRP) has defined the most ambitious abundance objectives for Central Valley salmonid populations. The g+ scenario uses the AFRP "doubling" target (doubling the average escapements of each run of Chinook salmon and steelhead from the reference period 1967 and 1991 (USFWS 1995)) to guide the gravel augmentation rules used in SacEFT modeling. It is important to note that the AFRP doubling targets are production goals, rather than escapement goals. As a result, Stillwater Sciences estimated annual harvest rates for each run in order to define a complementary escapement goal to the Sacramento River basin. It is also important to note that the AFRP doubling goals apply to all tributaries in the Central Valley, not just the Sacramento River mainstem included in our study area. In short, we are assuming that gravel augmentation must accommodate an additional 54,400 redds to achieve the AFRP doubling goal. Assuming a defended area of 100 ft^2/redd, the concomitant spawning habitat area to be added to the modeling reach is 5.44 million ft^2. Assuming gravel will be graded in the channel to a depth of 1.5 ft, then the 8.2 million ft^3 (300,000 yds^3) of spawning sized gravel will need to be injected as part of the initial augmentation, assuming that all added gravel results in spawning habitat. This is an unrealistic assumption, so we increased the volume of augmented gravel by 60% (to 480,000 yds^3) assuming that a significant portion of the injected volume will result in the additional spawning habitat that is being targeted. For this exercise, we are assuming that a one-time equal volume addition of gravel will be injected within each TUGS modeling reach at the beginning of the simulation except within the Turtle Bay area, which is a sediment trap. Additional details on the g+ gravel augmentation scenario are available in Stillwater Sciences (2007b).

	ID	**Notes**
Historical	**H-ng**	**TUGS: Historical Flow, No Gravel** – based on historical discharge with no gravel augmentation. TUGS simulations are initialized from an equilibrium state determined by a calibration run (or "zero run") that uses approximate historical gravel augmentation. This scenario says: "if you were to repeat the sequence of past flows, facilities and operations again, but didn't add any gravel, what would happen to substrate conditions and focal species performance over time?"
	H-g+	**TUGS: Historical Flow, High Gravel** – based on historical discharge with the high gravel augmentation scenario. This simulation is likewise initialized using the same calibration results as in the H-ng simulation. This scenario says: "if you were to repeat the sequence of past flows, facilities and operations again, but did add gravel at a rate believed to meet salmon spawning requirements[δ] in the study reach, what would happen to substrate conditions and focal species performance?"

	ID	Notes
	H-cc	**MM: Historical Flow, Current Channel** – based on historical discharge. MM simulations assume the current revetment configuration on the mainstem Sacramento River. This scenario says: “if we had an approximate 2004 channel configuration, and encountered the past sequence of flows, facilities and operations again, what would happen to channel migration dynamics and associated focal species performance?”
	H-r^2	**MM: Historical Flow, Revetment Removal** – based on historical discharge. MM simulations assume that rip rap is removed at selected locations on the mainstem. This scenario says: “if we had a modified channel configuration, with rip rap removed at select sites, then encountered the past sequence of flows again, what would happen to channel migration dynamics and associated focal species performance?” Details on simulated rip rap removal sites is provided in Larsen (2007).
FNA2	**F-ng**	**TUGS: FNA2, No Gravel** – based on the FNA2 no future action scenario with no gravel augmentation. TUGS simulations are initialized as before, no gravel is added, but the sequence of daily flows is now based on a hydrosystem configuration without additional development.
	F-G+	**TUGS: FNA2, High Gravel** – based on the FNA2 no future action scenario with the high gravel augmentation scenario (see †† footnote above). TUGS simulations are initialized as before, no gravel is added, but the sequence of daily flows is now based on a hydrosystem configuration without additional development.
	F-cc	*Not available with FNA2 flow scenario.*
	F-r^2	*Not available with FNA2 flow scenario.*
NODOS-AF2B	**N-ng**	**TUGS: NODOS-AF2B, No Gravel** – based on the NODOS-AF2B scenario with no gravel augmentation. TUGS simulations are initialized as before, no gravel is added, but the sequence of daily flows is now based on a hydrosystem configuration and operation including Sites Reservoir and restoration actions.
	N-g+	**TUGS: NODOS-AF2B, High Gravel** – based on the NODOS-AF2B scenario with the high gravel augmentation scenario (see †† footnote above). TUGS simulations are initialized as before, a large one-time amount of gravel is added, but the sequence of daily flows is now based on a hydrosystem configuration and operation including Sites Reservoir and restoration actions.
	N-cc	**MM: NODOS, Current Channel** – based on the *earlier* NODOS flow scenario. MM simulations assume the current rip rap configuration on the mainstem. The encountered flows are based on an alternative hydrosystem configuration and operation that includes Sites Reservoir.
	N-r^2	**MM: NODOS, Revetment Removal** – based on the *earlier* NODOS flow scenario. MM simulations assume that rip rap is removed at selected locations on the mainstem. The encountered flows are based on an alternative hydrosystem configuration and operation that includes Sites Reservoir. Details on simulated revetment removal sites is provided in Larsen (2007).
Shasta	**S-ng**	**TUGS: Shasta, No Gravel** – based on the Shasta scenario with no gravel augmentation. TUGS simulations are initialized as before, but the model encounters this alternative hydrosystem configuration and operation.
	S-g+	**TUGS: Shasta, High Gravel** – based on the Shasta scenario with the high gravel augmentation scenario (see †† footnote above). TUGS simulations are initialized as before, but the model encounters this alternative hydrosystem configuration and operation.
	S-cc	**MM: Shasta, Current Channel** – based on the Shasta scenario. MM simulations assume the current revetment configuration on the mainstem.
	S-r^2	**MM: Shasta, Revetment Removal** – based on the Shasta scenario. MM simulations assume that revetment is removed at selected locations on the mainstem. Details on simulated revetment removal sites is provided in Larsen (2007).

As mentioned above, SacEFT simulations rely on CALSIM-SRWQM output data and the model was designed specifically to leverage the significant investments in the CALSIM-SRWQM model itself. However, the reliance on CALSIM-SRWQM output results in three primary considerations to bear in mind.

First, ecological effects of management actions such as additional water storage facilities can only be derived based on the flow conditions reflected by CALSIM-SRWQM output. Therefore, if the CALSIM-SRWQM model is not able to accurately approximate flow conditions, then ecological effects based on these inaccurate approximations of flows will likely be different than the ecological effects of the actual flow regime. Because CALSIM is a recognized and accepted method for evaluating large water projects in California, we chose to leverage that acceptance. Future improvements in CALSIM and SRWQM will also increase the accuracy of SacEFT output with no required changes to SacEFT.

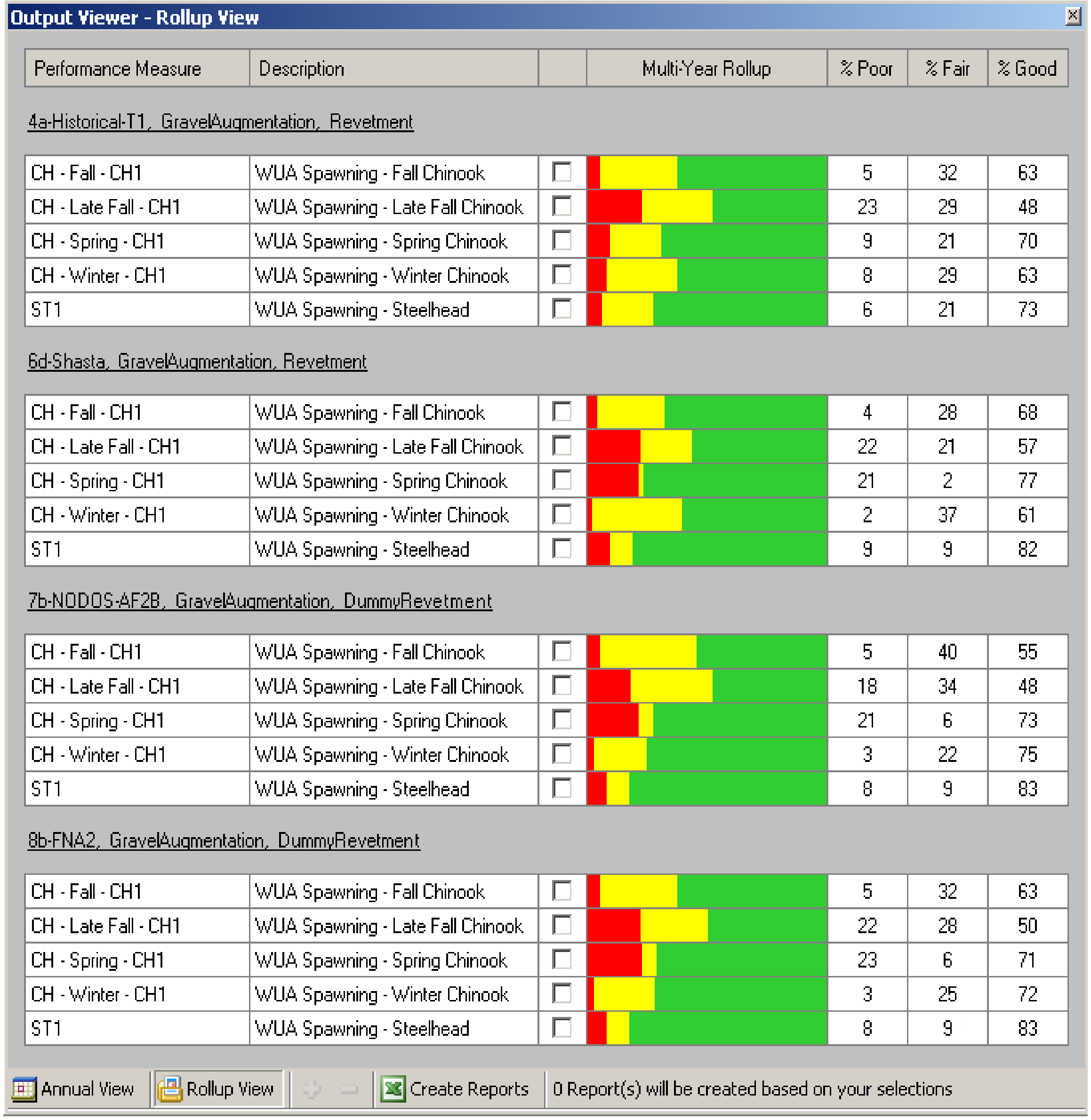
Second, the CALSIM II model functions at a monthly time-step. This is a recognized shortcoming of the model in a number of ways and DWR is working to disaggregate monthly data to a daily time-step in a realistic way. This is particularly important for ecological analyses as a monthly time-step glosses over natural variability that has a bearing on ecology. DWR has developed a disaggregation method in SRWQM for use in assessing water temperature and water quality characteristics associated with the Upper Sacramento River CVP system. For the FNA2, NODOS-AF2B and Shasta scenarios, the daily flow disaggregations *below* Red Bluff Diversion Dam used in our study (from CALSIM-SRWQM) were known to be flawed and do not remain consistent with monthly time-step totals. Our study effort has the same limitations as all other efforts utilizing these data. In this report, these data are therefore used for testing and demonstration purposes only. Disaggregated daily time-step data above Red Bluff Diversion Dam remain consistent with monthly time-step totals and therefore provide a more legitimate basis for comparing performance measures calculated at sites above Red Bluff Diversion Dam. DWR is currently developing a Sacramento River Daily Operations Model that disaggregates CALSIM II monthly data, and this model will replace the SRWQM disaggregation approach in the near future.

Finally, CALSIM II model runs contain numerous assumptions that are built into the CALSIM-SRWQM analysis: these same assumptions are therefore carried forward into SacEFT analyses, even if they are not always explicit in the flow and temperature data. Since CALSIM planning and analysis require the use of a consistent common set of internal assumptions coupled to with/without project (or equivalently: action/no action) scenarios, the FNA2 (Future No Action) scenario was provided as the basis for comparison with the NODOS-AF2B scenario. The analyses shown here and in Appendix F include results from the empirical historical data (used primarily for model calibration, see Appendix F – Section 1.1.5), the Shasta scenario, and the paired FNA2 and NODOS-AF2B scenarios.

2.3.3 SacEFT overview and key findings

The format of SacEFT was driven by two competing needs: making the review of a large amount of integrated information as simple as possible for decision-makers and for considerations in group planning forums, and providing the necessary transparency and detail for technical specialists to understand how results were derived.

The first need: simplicity of output – was accomplished by using a “traffic light” hazard approach, or a simple indication of ecological conditions as red (poor), green (good), or yellow (fair). These characterizations, called hazard thresholds, can be displayed at a level of detail appropriate for a variety of audiences. Displays can be varied by the water years included (the entire 66-year period of analysis or any combination of years of interest), and the focal targets selected (up to the total of 35 built into the model), as well as varying the selection of management scenarios evaluated. For example, Figure 2-9 below shows SacEFT output in one of the more simplified formats. It displays the evaluation of Chinook and steelhead spawning habitat during the entire period of simulation summarized as percentages of good (green), fair (yellow), or poor (red) conditions. The figure displays this ecological indicator for historical (Scenario 1: Historical) conditions and for NODOS Future No Action (Scenario 2: NODOS FNA2) vs. NODOS Future Action Alternative (Scenario 3: NODOS-AF2B) scenarios as affected by NODOS.

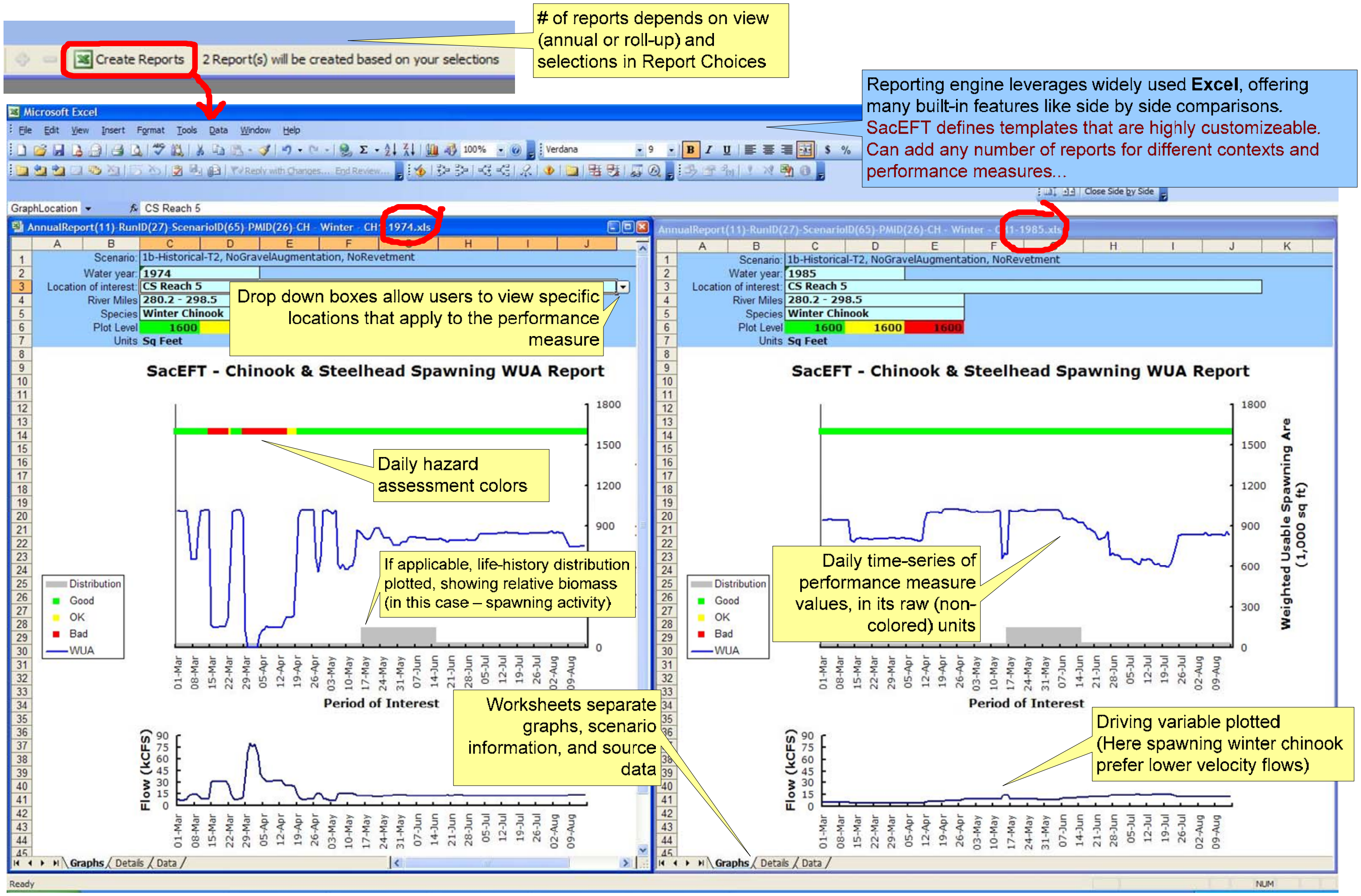


Performance Measure	Description		Multi-Year Rollup	% Poor	% Fair	% Good
4a-Historical-T1, GravelAugmentation, Revetment						
CH - Fall - CH1	WUA Spawning - Fall Chinook	☐	🟥🟨🟩	5	32	63
CH - Late Fall - CH1	WUA Spawning - Late Fall Chinook	☐	🟥🟨🟩	23	29	48
CH - Spring - CH1	WUA Spawning - Spring Chinook	☐	🟥🟨🟩	9	21	70
CH - Winter - CH1	WUA Spawning - Winter Chinook	☐	🟥🟨🟩	8	29	63
ST1	WUA Spawning - Steelhead	☐	🟥🟨🟩	6	21	73
6d-Shasta, GravelAugmentation, Revetment						
CH - Fall - CH1	WUA Spawning - Fall Chinook	☐	🟥🟨🟩	4	28	68
CH - Late Fall - CH1	WUA Spawning - Late Fall Chinook	☐	🟥🟨🟩	22	21	57
CH - Spring - CH1	WUA Spawning - Spring Chinook	☐	🟥🟨🟩	21	2	77
CH - Winter - CH1	WUA Spawning - Winter Chinook	☐	🟥🟨🟩	2	37	61
ST1	WUA Spawning - Steelhead	☐	🟥🟨🟩	9	9	82
7b-NODOS-AF2B, GravelAugmentation, DummyRevetment						
CH - Fall - CH1	WUA Spawning - Fall Chinook	☐	🟥🟨🟩	5	40	55
CH - Late Fall - CH1	WUA Spawning - Late Fall Chinook	☐	🟥🟨🟩	18	34	48
CH - Spring - CH1	WUA Spawning - Spring Chinook	☐	🟥🟨🟩	21	6	73
CH - Winter - CH1	WUA Spawning - Winter Chinook	☐	🟥🟨🟩	3	22	75
ST1	WUA Spawning - Steelhead	☐	🟥🟨🟩	8	9	83
8b-FNA2, GravelAugmentation, DummyRevetment						
CH - Fall - CH1	WUA Spawning - Fall Chinook	☐	🟥🟨🟩	5	32	63
CH - Late Fall - CH1	WUA Spawning - Late Fall Chinook	☐	🟥🟨🟩	22	28	50
CH - Spring - CH1	WUA Spawning - Spring Chinook	☐	🟥🟨🟩	23	6	71
CH - Winter - CH1	WUA Spawning - Winter Chinook	☐	🟥🟨🟩	3	25	72
ST1	WUA Spawning - Steelhead	☐	🟥🟨🟩	8	9	83

0 Report(s) will be created based on your selections

Figure 2-9. SacEFT multi-year rollup results for Chinook and steelhead spawning weighted useable area (WUA) for historical and 3 flow scenarios. Note that the Historical simulation (top panel) was principally used for calibration and that the 2 lower panels (NODOS-AF2B, FNA2) are more directly comparable as Future Action Alternative (NODOS-AF2B) and Future No Action (FNA2) scenarios. (Abstracted from Appendix F, Figure F-6.)

Because a huge amount of underlying information supports the summary display, we also sought to add transparency to this background information, to enable and simplify thorough reviews by technical specialists. We therefore developed other detailed output reports for technical specialists, allowing them to see the actual data and interpretations that result in the final hazard rating colors. Figure 2-10 shows an example of the detail necessary for a specialist to gauge their confidence in the displayed hazard ranking. The figure shows a report for Chinook and steelhead spawning that is location- and year-specific (daily), and displays the underlying data with corresponding hazard rankings. More detailed results such as those shown in the example below "roll up" into the summarized version of results in the example above.



2 Report(s) will be created based on your selections

Scenario: 1b-Historical-T2, NoGravelAugmentation, NoRevetment
Water year: 1974
Location of interest: CS Reach 5
River Miles: 280.2 - 298.5
Species: Winter Chinook
Plot Level: 1600
Units: Sq Feet

Scenario: 1b-Historical-T2, NoGravelAugmentation, NoRevetment
Water year: 1985
Location of interest: CS Reach 5
River Miles: 280.2 - 298.5
Species: Winter Chinook
Plot Level: 1600 1600 1600
Units: Sq Feet

# of reports depends on view (annual or roll-up) and selections in Report Choices

Reporting engine leverages widely used **Excel**, offering many built-in features like side by side comparisons. SacEFT defines templates that are highly customizeable. Can add any number of reports for different contexts and performance measures...

Drop down boxes allow users to view specific locations that apply to the performance measure

Daily hazard assessment colors

If applicable, life-history distribution plotted, showing relative biomass (in this case – spawning activity)

Daily time-series of performance measure values, in its raw (non-colored) units

Worksheets separate graphs, scenario information, and source data

Driving variable plotted (Here spawning winter chinook prefer lower velocity flows)

Figure 2-10. SacEFT provides detailed output on a scenario × year × performance measure basis in custom Excel reports. Here, managers and scientists can examine the detailed results in the performance measure's raw units, alongside its driving variable (e.g., flows). (Abstracted from Appendix F – Figure F-16)

These figures are taken from Appendix F, where a more detailed discussion of model capabilities, underlying assumptions, and pilot analyses results are available. For clarity, interpretations of the large body of detailed output provided in Appendix F are summarized for the reader in this section and in the synthesis section of this Final Report.

Detailed answers to the 4 key questions for the SacEFT study (see Section 2.3.1) are provided in Appendix F. The following list briefly summarizes the key findings from the pilot application of the SacEFT modeling framework:

- With varying degrees of significance, many focal species indicators improved under NODOS-AF2B scenario, relative to the FNA2 (No Action) scenario; while others worsened (Table 2-5). For the NODOS comparison, this may reflect the affects of ecosystem actions built into the modeled scenario. While different in form, location and assumptions, the NODOS-AF2B and Shasta scenarios had qualitatively similar effects on SacEFT performance measures. Results for historical flows show a wider envelope of expected outcomes, under a less constrained past hydrosystem state and operation. As the historical flows arising from past operations and hydrosystem configurations are different from what exists today these results are in large measure, "academic"[7].
- When considering the various focal species trends in Table 2-5 and Appendix F it is critical to have in mind SacEFT's assumptions on the average timing of select life-history events (see Table 2-6.).
- Of the indicators included in SacEFT, Fremont cottonwood initiation success, Chinook and steelhead rearing WUA and Chinook and steelhead redd scour risk were the indicators most sensitive to flows.
- For the indicators we used, gravel augmentation had more significant effects (on Chinook and steelhead spawning) than did selected rip-rap removal (on bank swallow nesting habitat and western pond turtle habitat creation).
- Under the current flow regime, larger scale rip-rap removal and levee setback actions will be required to promote significant channel migration and generate associated focal species improvements.
- A small percentage of focal species performance measures were insensitive to the flow and in-channel actions we investigated. While this finding may be true for select indicators (e.g., green sturgeon egg/larvae temperature preferences), it more likely reflects limitations in indicator formulation (i.e., the only functional relationship for green sturgeon is temperature effects on eggs/larvae) or that the indicator was not the most limiting. Where limiting factors are poorly understood, use of *multiple* indicators for each focal species (as done for Chinook and steelhead) is recommended. Furthermore, physical driving datasets (especially meander migration) must be properly matched to the scale and resolution required by the focal species indicator (e.g., bank swallow habitat suitability and new area of off-channel habitats for western pond turtles).
- The potential for improving conditions to limit redd scour was high, especially for fall Chinook. Redd dewatering was another indicator that received a relatively high incidence of poor and fair ratings.

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[7] We note that this greater range of contrast is critical for calibrating hazard threshold boundaries in SacEFT in order to avoid a "self-fulfilling prophecy".

Table 2-5. Direction of change in indicator ratings for NODOS-AF2B hydrosystem operations vs. the FNA2 “Future No Action” scenario. A ‘+’ indicates the relative strength of the improvement (or decline: ‘–’). An absence of a ‘+’ (or ‘–’) sign indicates the directional change was small, and may be an artifact of the initial demonstration thresholds chosen.

	Change Relative to FNA2 (Future No Action) scenario	
	Improved	**Worsened**
NODOS-AF2B	▪ + Egg-to-fry thermal mortality (CH3) – esp. steelhead, spring and late-fall Chinook ▪ + Redd dewatering – esp. spring Chinook (CH6) ▪ + Fremont cottonwood initiation (FC) ▪ Juvenile stranding (CH4) ▪ Redd scour (CH5) ▪ Bank swallow flow suitability (BASW2)	▪ – WUA rearing – except late fall Chinook and steelhead (CH2) ▪ Spawning WUA – fall Chinook (CH1) ▪ Redd dewatering – steelhead and late fall Chinook (CH6)

Table 2-6. Summary of the life-history timing information relevant to the focal species performance measures being integrated into SacEFT. Details related to this table are available in ESSA Technologies (2007). Darker orange squares represent the predominant period for a given life history stage; lighter orange squares are the full range of that stage.

Performance Measure & Timing Relevance		**Jan**				**Feb**				**Mar**				**Apr**				**May**				**Jun**				**Jul**				**Aug**				**Sep**				**Oct**				**Nov**				**Dec**			
CS – 1	**Spring Chinook** Spawning																															▨	▨	▨	▨	■	■	▨	▨	▨	▨								
CS - 3,5,6	Egg Development Period	▨	▨	▨	▨	▨	▨	▨	▨	▨																						▨	▨	▨	▨	▨	▨	▨	▨	▨	■	■	■	■	■	■	■	▨	▨
CS - 2,4	Juvenile Period	▨	▨	▨	■	■	■	■	■	■	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																▨	▨	▨	▨	▨	▨	▨	▨
CS – 1	**Fall Chinook** Spawning																																					▨	▨	▨	▨	■	■	■	■	▨	▨	▨	▨
CS - 3,5,6	Egg Development Period	■	■	■	■	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	■
CS - 2,4	Juvenile Period		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	■	■	■	■	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨															
CS - 1	**Late fall Chinook** Spawning	▨	▨	■	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨																																		
CS - 3,5,6	Egg Development Period	▨	▨	▨	▨	▨	▨	▨	▨	■	■	■	■	■	■	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																					
CS - 2,4	Juvenile Period																		▨	▨	▨	▨	▨	▨	▨	■	■	■	■	■	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨					
CS - 1	**Winter Chinook** Spawning									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨																		
CS - 3,5,6	Egg Development Period									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	■	■	■	■	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨							
CS - 2,4	Juvenile Period	▨	▨	▨	▨	▨	▨	▨	▨	▨														▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	■	■	■	■	■	■	■	■	■	▨	▨	▨
CS - 1	**Steelhead** Spawning	■	■	■	■	■	■	■	■	■	■	■	■	▨	▨	▨	▨	▨	▨																									▨	▨	▨	▨	▨	▨
CS - 3,5,6	Egg Development Period	▨	▨	▨	▨	▨	▨	▨	■	■	■	■	■	■	■	■	■	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												▨	▨	▨	▨	▨	▨
CS - 2,4	Juvenile Period												▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	■	■	■	■	■	■	■	■	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	
GS1	**Green Sturgeon** Spawning									▨	▨	▨	▨	▨	▨	■	■	■	■	■	■	■	■	▨	▨	▨	▨	▨	▨																				
BASW2	**Bank Swallow** Nesting Period											▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																						
FC1	**Cottonwood** Seed Dispersal															▨	▨	▨	▨	▨	▨	▨	▨	▨																									

2.3.4 Management implications

Carefully targeted restoration of natural flow characteristics are generally accepted to provide ecological benefits (Poff et al. 1997, Postel and Richter 2003, as cited in Richter and Thomas 2007). Perhaps the biggest challenge in the practical implementation of ecological flows, from the ecosystem perspective, are the wide range of objectives and focal species that need to be considered. Ecologists and biologists realize that these various objectives cannot all be simultaneously met in any given water year. Fortunately, flow characteristics that benefit various life history aspects of the targets investigated here are usually required on a periodic basis and not every single year. In nature, conditions sometimes benefit one target or species to the potential detriment of another in any given year (as illustrated in Table 2-5). In managed systems, these trade-offs involve making choices year to year (realizing there will be winners and losers), and being careful to keep track of "neglected" physical process and focal species objectives over time. By not requiring a given set of flow objectives year after year, flexibility is provided to these operators and decision makers. For example, it may only be necessary to implement a cottonwood forest recruitment flow every 5 to 10 years, and even then only if one does not occur naturally within that timeframe. Taking advantage of different water year types for achieving different ecosystem objectives (e.g., using wet and very wet years for geomorphic objectives, while focusing on temperature objectives in dry and very dry years) is a cost-effective approach and a cornerstone of the Trinity River Restoration Program (USFWS and HVT 1999). The downside of this flexibility is that water operators will not always be able to rely on fixed rules or an ultimate ecological "objective function". Instead, year to year judgment and an evolving ecological ledger will be needed in order to realize *multiple* focal species benefits.

Figure 2-11 provides a target and avoidance flow range synthesis for SacEFT outputs. Upon further refinement to SacEFT's hazard threshold boundaries, this type of synthesis result can be used to improve focal species conditions on the Sacramento River (i.e., begin to inform development of an "ecological ledger"). Appendix F provides the same information on an indicator by indicator basis, but with plot resolutions that can be more precisely read. These draft target and avoidance flow ranges were derived by taking the historical flow scenario (water years 1939-2004) and selecting all the good (green) performing years ('target' or 'desired' flow) or poor (red) performing years ('avoidance' flow)[8]. "More suitable" flow lines represent the median of all good (green) performing years found in the historical model simulation. We are currently working to refine this concept, noting that our "envelopes" (Figure 2-11) are presently too wide to be useful in practice due to our decision to bound their range using the minimum and maximum flow found on any given day from the multiple years that fit the 'good' or 'bad' criteria. Future versions of these plots will likely use a more informative measure of dispersion, such as the 25th and 75th percentiles. Moreover, until our hazard threshold boundaries have been peer reviewed for biological significance, presentation of these envelopes will remain 'illustrative' of the type of synthesis output available from SacEFT. This is one of our highest short-term priorities for SacEFT modeling.

It is very likely the status quo will contribute to further species declines and increasing regulation undesirable for all interests. Hence, adopting 'reasonable and prudent' actions now such as SacEFT flow targets (once further refined) is advised in parallel with purposeful adaptive management experiments and monitoring programs aimed at further understanding the biological significance of flow alterations and in-channel actions.

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[8] The method for setting indicator rating thresholds is defined in Appendix F.

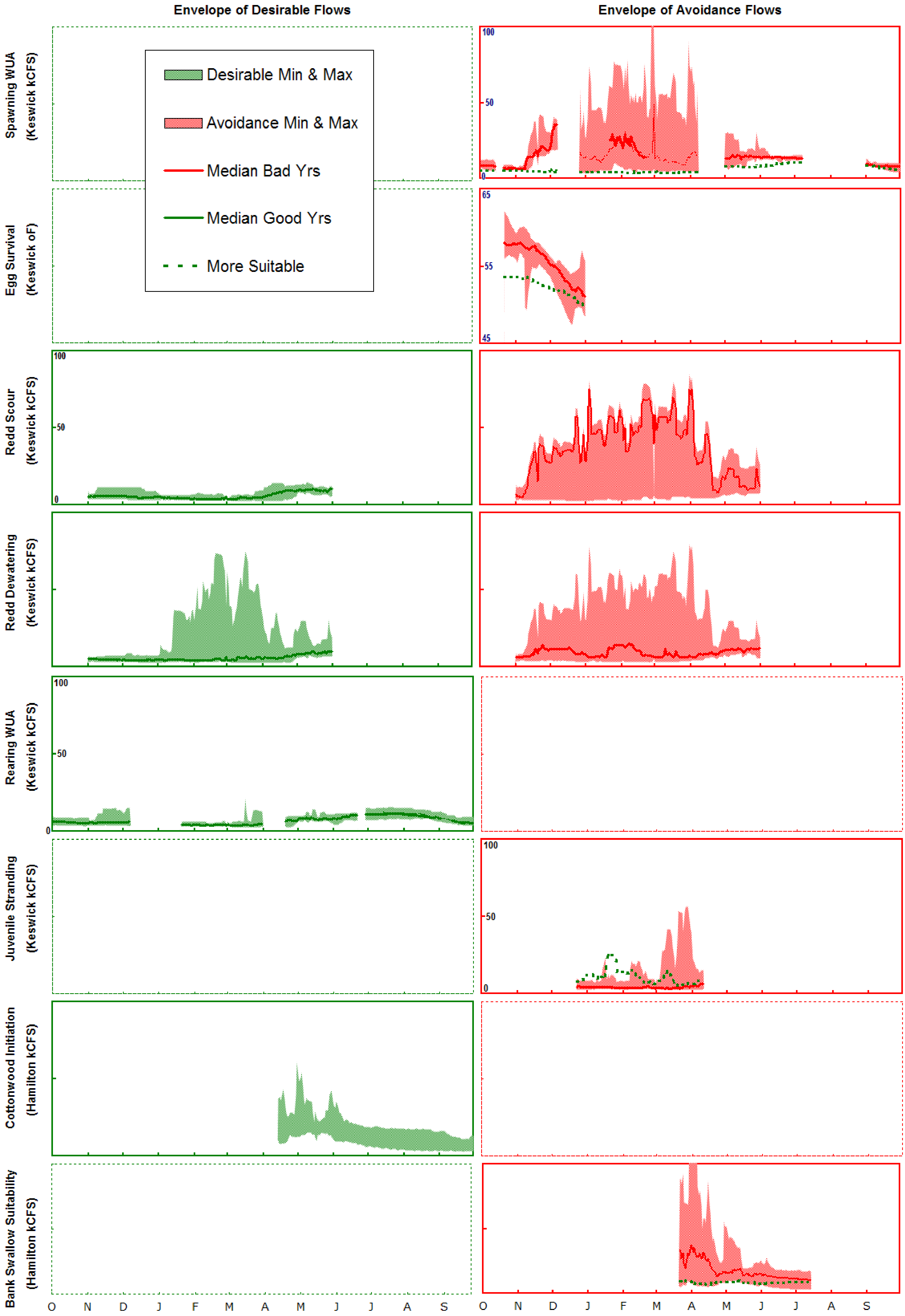

Figure 2-11. Desired (left) and avoidance (right) Sacramento River flow ranges for SacEFT focal species indicators. Note: redd dewatering and juvenile stranding do not lend themselves well to this mode of presentation, as these indicators are driven by patterns of flow reduction under 8,000 - 10,000 cfs. Appendix F provides the same information, but at a 'zoom' resolution that can be read more precisely. Plots in this appendix also differentiate Chinook and steelhead run types.

3 Synthesis

In this section, we synthesize the species-specific results discussed in Section 2. The implications of the Sacramento River Ecological Flows Study findings and SacEFT outcomes on river management are identified along with recommendations for further reducing some of the key uncertainties that remain.

3.1 Goals and tasks of the Sacramento River Ecological Flows Study

This Synthesis section distills the most significant findings of the numerous stand-alone documents that were generated in the Sacramento River Ecological Flows Study (the "Study"). The reader may wish to review the individual documents (Appendices A–F) in addition to this Final Report for further details.

As stated in the introduction (Section 1) to this report, the Study was designed with the following goals:

1. Synthesize existing interdisciplinary information on linkages among habitats, biota, and hydrogeomorphic processes along the river;
2. Improve understanding of how flow corresponds to ecological needs, and thus improve decision making in projects that seek to balance human land and water use with the needs of the ecosystem;
3. Evaluate trade-offs among different ecological objectives for different management scenarios; and
4. Propose strategies for achieving conservation benefits for multiple species.

The means to accomplish these goals were grouped into four tasks, also as described in the introduction (Section 1):

Task 1. Synthesize existing information and produce the "Linkages Report."
Task 2. Develop plans for five studies that address remaining uncertainties, and then conduct those studies and produce technical reports that summarize their findings.
Task 3. Develop a new decision-analysis tool and a new sediment-transport model to evaluate flow-related management strategies.
Task 4. Conduct outreach, complete reporting, hold a final stakeholder review workshop, and release a Final Report.

Recent advances in ecological river restoration have challenged conventional ways of managing human interactions with rivers. There is a growing body of scientific knowledge about utilizing a river's flow regime, and other management actions, to restore ecological functions that benefit river-dependent fish and wildlife. It is a rapidly progressing science and a variety of approaches gained from practical experience are developing around the world. We reviewed many of those efforts in formulating this project in an effort to learn from previous successes and challenges.

The scope of this study was larger in scope and more ambitious than many other similar projects. It integrates a framework for existing information with new field studies that reduce key uncertainties, and then leverages the combined database into a tool that supports an overarching decision-analysis framework. The approach is consistent with scientific understanding of physical and ecological processes, and it seeks to adapt fundamental scientific tools and understanding to resolve persistent needs for ecosystem recovery recognized throughout the Sacramento River system.

Below we present the activities and key findings associated with each of these goals and their associated task.

Goal/Task #1. *Synthesize existing interdisciplinary information on linkages among habitats, biota, and hydrogeomorphic processes along the river (Linkages Report, Appendix A)*

This integrated effort contributes to conservation of natural resources on the Sacramento River by increasing the existing knowledge base needed to manage river flows and implement other management actions to benefit ecological targets. The approach taken to accomplish this goal was to select a suite of representative (“focal”) species from the aquatic and terrestrial domains, and to examine their habitat and life-history needs as affected by alterations in flows and physical processes. This approach allowed us to examine complex physical and ecological interactions while avoiding the pitfalls of taking too narrow of a view that would result from a focus on one species alone. The range of species included both terrestrial and aquatic species, all of which share a connection to the riparian and instream habitats. In two cases, the bank swallow and western pond turtle, species were selected in order to represent the important physical river processes and ecological functions provided by channel meandering and cutoffs (which both depend, fundamentally, on the river's flow regime).

Key contributions:

- Compiled the most comprehensive review of ecological information to date on the Sacramento River.
- Synthesized existing data on Chinook spawning redds and conducted analysis of multi-decadal trends.
- Developed a new state-space model and used it to formulate hypotheses about limiting factors for winter-run Chinook.
- Developed conceptual models for anthropogenic effects on each of the six focal species.
- Convened a group of approximately 60 specialists who contributed to the Draft Linkages Report; received and responded to over 350 comments to produce the Final Linkages Report.
- Identified key assumptions and significant gaps in our understanding of the functional relationships between the river and the ecological needs of focal species.
- Recommended specific studies to reconcile knowledge gaps.

The Linkages Report (Appendix A) provides an historic and a current view of the river and describes the sequence of events and ecological consequences of flow-management decisions at broader scales of time and space than has usually been considered. For this river, existing information on these ecological relationships was not available in a single repository; the Linkages Report provides a starting point for such a repository. Persistent fundamental uncertainties about several of the focal species were identified during the compilation of the Linkages Report. For example, in the case of green sturgeon, we still know very little about the migratory habitat requirements of adults and juveniles, and how they are affected by operation of diversion structures and other management actions (see Section 3.3.1).

Goal/Task #2 *Improve understanding of how flow corresponds to ecological needs through five field and computer simulation studies that address identified uncertainties.*

Key contributions:

Task 2.1: Quantify and refine the relationship between flow and sediment transport (see Appendices B and E).

- Measured scour and mobility directly in the middle Sacramento River during a period that included sustained flows >50,000 cfs and peak flows >85,000 cfs
- Developed TUGS, which includes significant advances in management utility relative to existing sediment transport models; used TUGS to quantify the relationship between flow and sediment transport to show how sediment dynamics have changed over time in response to bed-surface coarsening in the upper Sacramento River

Task 2.2: Quantify fluvial geomorphic processes that create and maintain off-channel habitats and characterize ecological attributes of these habitats (see Appendix C).

- Measured rates of infilling of off-channel habitats for a series of sites in the middle Sacramento River using radiometric dating and depths measured in sediment cores; showed that infilling rates correlate with planform geometry (with higher rates for OCWB's whose inlets are more tightly aligned with the course of the mainstem)
- Documented occurrence of aquatic vegetation and fish species in OCWB's
- Quantified several indices of water quality in OCWB's
- Measured relationships between discharge and stage in secondary channels, which provide important sources of seasonally inundated shallow-water habitat within the bankfull channel
- Began development of a chute-cutoff model but failed to fully resolve complexities of routing flow and sediment in bifurcated channels

Task 2.3: Characterize channel substrate composition and permeability (see Appendices B and E; includes original contract Task 3.1).

- Quantified grain size via bulk sampling and pebble counting at a series of sites across the study area; overlap with sites from previous studies was sufficient to enable comparative, time-series analyses, which show that bed-surface coarsening has been occurring in the upper river
- Created facies maps of grain size, the first of their kind for the upper Sacramento River, and used these data, together with historical and recent observations of spawning use, (1) to quantify the upper limits on gravel size for spawning suitability and (2) to identify areas that appear to have become too coarse for spawning over the last several decades
- Quantified permeability for the first time at a series of sites, providing a baseline for comparison with results from future monitoring efforts and highlighting the importance of the redd-building process itself for making gravel suitable for spawning
- Used TUGS to estimate how surface and subsurface grain sizes are likely to have changed in the upper river over time since construction of Shasta Dam

- Quantified spawning use in the upper river in 2005 via helicopter survey; incorporated spawning-area data from previous studies (CDWR 1980) and the new helicopter survey into a GIS framework for comparative analysis of spatial changes over time; analyzed changes in spawning area over time

Task 2.4: Assess and compare the effects of bank protection on in-channel habitat conditions (see Section 2.4);

- Quantified water depths and velocities at a paired series of armored and eroding bends in the middle Sacramento River
- Quantified grain size of riprap in armored bends to document whether site-to-site variations in riprap are indicative of differences in ecological cover
- Characterized LWD at armored and eroding bends as an index of site-to-site differences in ecological cover

Task 2.5: Refine a meander migration model (see Appendix D)

- Incorporated variable discharge into an existing model of meander migration, thus providing a significant advance in management utility over previous applications that were limited by the need to simplify flow in terms of a single "formative" discharge
- Applied the model to historical and two flow scenarios with two different revetment conditions to provide input for SacEFT
- Recognized revetment-related reductions in channel sinuosity, which presumably lead to simplification and reduction of riverine habitats over time

In general, the field and modeling studies were successful in addressing several data gaps identified in the Linkages Report. However, some studies raised as many questions as they answered, and the unresolved issues or data gaps that arose from the Linkages Report were not fully addressed. Taken together, however, the targeted studies did help clarify the limits of existing data. This was crucial as the team moved on to Task 3, the assessment of alternative management scenarios with the new decision analysis tool.

Goal/Task #3. *Develop a decision-analysis tool (SacEFT) to evaluate trade-offs among different ecological objectives and flow-release scenarios.*

There are many demands on the water resources of the Central Valley, and the Sacramento River provides much of the water to supply those demands. We recognized early in the project-formulation phase that consideration of ecological flow needs could not be conducted without consideration of those other demands. We reviewed many of the existing water-planning tools and forums during the project formulation and found that many other efforts were already accounting for other uses such as agriculture, power, and domestic supply. In order to avoid duplication of these other efforts, we purposely omitted consideration of other human-associated water demands in our project. This approach was supported and preferred by water users in a meeting organized by CALFED ERP staff in 2002 specifically for the purpose of addressing any potential concerns of water user with the project.

As this is the first analytical application of SacEFT, there are a number of caveats to consider when interpreting the demonstration output (see Appendix F and Table 2 therein), because some of the model assumptions were constrained by limited data or other input. For instance, the spatial extent of the river with relevant input data was limited in the case of the meander migration model and the TUGS sediment transport model. Consequently, results may or may not always be representative of the larger river. Input values to the functional relationships for some performance indicators are sometimes based on interpolated or extrapolated model results which may (or may not) produce inaccuracies. The daily discharge scenarios input to SacEFT also have limitations. The non-historical daily flow data scenarios were generated by disaggregating CALSIM II monthly output using SRWQM, a model of the Sacramento River and reservoir system developed by Reclamation. SacEFT also uses the water temperature predictions made by the USBR's temperature modeling system (SRWQM-HEC5Q). Also, the CALSIM and SRWQM datasets used in this Study are comprised for only 4–5 nodes between Keswick and Colusa. As improved daily physical datasets become available (whether from CALSIM or any other hydrosystem model capable of generating daily flows), SacEFT has been designed to easily absorb this new information.

Despite caveats and remaining uncertainties, the model in its current form can already be used to facilitate the inclusion of ecological considerations in water operation decision-making. In fact, the first set of SacEFT simulation runs was deliberately chosen to clearly demonstrate that ecological trade-offs can be evaluated using the same tools and data used by managers and decision makers to formulate water planning projects. Three broad categories of model simulations were tested: historical flow; a scenario with increased storage behind Shasta Dam; and a pair of scenarios in which flow augmented by storage from the North-of-the-Delta Off-Stream Storage Investigation is compared to a Future No Action scenario. SacEFT simulations were run for each of these in turn with two types of gravel inputs and revetment removal levels[9] designed to enhance progressive channel migration. Results (Section 2.3 and Appendix F) illustrate the types of trade-off analyses that are possible, and they also display the model's ability to link numerous biophysical processes for multiple focal species with alternative flows and other management actions, a novel capability not previously available.

Key contributions:

- Improves the basis for evaluating flow alternatives on the Sacramento River with a single computer program that expands focal species considerations, linking performance of 6 species (35 habitat-centered performance measures) from Keswick to Colusa with flow, water temperature, gravel, and channel revetment actions
- Provides for multiple levels of communication of information ranging from simplified formats for managers and decision-makers to in-depth displays of detail functional relationships and transparent assumptions for review by technical experts
- Leverages existing systems and data sources (CALSIM-SRWQM-HEC5Q modeling complex; historical gauging station records, the meander migration model, and TUGS). SacEFT does not reinvent their functionality but acts as an "eco plug-in" compatible with major water-planning models
- Catalyzes exploration of new alternatives and helps promote the development of needed flexibility in the water management system.

Goal/Task #4. *Identify strategies for achieving conservation benefits for multiple species, and disseminate findings through meetings and reports.*

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[9] Following the review of the first version of this report DWR provided two updated scenarios: NODOS-AF2B and FNA2, to allow more comparable simulations of different hydrosystem facilities and configuration. For time and budgetary reasons, it was not possible to update the revetment simulations using these new simulations. Therefore there are no corresponding revetment simulations for the FNA2 scenario, and the NODOS-AF2B scenario makes use of an earlier NODOS scenario.

This goal was achieved through a variety of means, including development of SacEFT, development of a new sediment transport model, and conducting a variety of field studies. In combination, these exercises produced a suite of potential management actions (summarized in Section 3.2). In addition, SacEFT provides a framework to communicate and synthesize much of the information developed through this project. Taking advantage of SacEFT as a decision-support tool will require users to understand its utility as well as current limitations. For example, currently, thresholds for some focal species conditions conveyed as a red (poor) or yellow (fair) are a function of a designation based on terciles obtained from a historical analysis used to reveal that indicator's range of quantitative values over 66 years. Further informing these "hazard thresholds" is a critical next step for the results of SacEFT to be truly useful.

A primary undertaking in this project was to engage as many specialists and managers as possible at different steps throughout the project to provide feedback and guidance. We conducted a variety of workshops as well as individual meetings with specialists. A summary of these in chronological order is as follows:

- On December 5 and 6, 2005, the Study team held a model design workshop to evaluate a preliminary conceptual design of the Sacramento River Ecological Flows Tool (SacEFT). Forty scientists and other technical experts on the focal species or physical submodels on the Sacramento River were invited to attend the workshop to discuss and prioritize aspects of the project. Prior to their attendance, a backgrounder on SacEFT was provided to workshop participants that described the candidate submodels to be evaluated at the workshop (ESSA Technologies 2005). Participants also assisted in the evaluation of functional relationships between focal species and habitat in the form of designating the appropriate indicators and identifying the level of rigor represented by the selected indicator. After recognizing the infeasibility of "including everything," we facilitated a discussion of essential elements that would ensure that SacEFT reflected a reasonable level of breadth and depth across the six focal species. The resulting workshop advice is documented in detail in the final design of SacEFT (ESSA Technologies 2007).
- The Study team held a one-day public workshop to review the Draft Linkages Report (then called the Draft State of the System Report) in Sacramento on December 12, 2006. Over 100 scientists and decision-makers from various state and federal agencies and other interested parties were invited to review the draft report and provide comment during the public workshop. The primary objectives of the workshop were to:
    - Provide an overview of the draft Linkages Report
    - Solicit comments and questions on the draft Linkages Report
    - Solicit ideas for future studies and exploratory modeling runs of SacEFT to increase insights and reduce uncertainties regarding flow and habitat-management options.

  We obtained extensive feedback through verbal comments provided during the workshop and in subsequent written comments. These comments helped improve the final version of the Linkages Report and provided additional guidance on the management scenarios explored in modeling runs of SacEFT. Individual meetings with technical experts conducted under this task included various discussions of fish and aquatic ecology issues with Peter Moyle and Ron Yoshiyama at UC Davis and Wim Kimmerer of the SFSU Romberg Tiburon Center.

<u>Department of Fish and Game</u>: For the past several years, The Nature Conservancy has attended the annual Upper Sacramento Monitoring Project Work Team where DFG, among other agencies, have been updated on the progress of this Study. TNC and Stillwater Sciences staff also met with DFG staff in the Redding office during the information-gathering phase for Task 1 (the Linkages Report) and have shared

drafts of the Study's reports for DFG review and comment. Managers and staff at Stillwater Sciences have retained a strong working relationship with CDFG and have engaged in numerous one-on-one discussions both with individuals and in group settings regarding specific elements of the project.

Department of Water Resources: The Nature Conservancy worked closely with the Department of Water Resources to align the products of this Study with DWR's planning work for the North-of-the-Delta Off-Stream Storage (NODOS) investigation. TNC staff were part of the NODOS Technical Advisory Group and met with DWR surface storage staff on several occasions. Additionally, TNC and DWR staff made a presentation on this Study and NODOS progress at a joint TNC-Reclamation workshop in Boulder, Colorado.

Bureau of Reclamation: The Nature Conservancy met with the Bureau of Reclamation on numerous occasions to keep Reclamation staff informed of the Study's progress. This included field visits, meetings with the Director of the Mid-Pacific Region, and a presentation by TNC and Reclamation staff at a joint TNC-Reclamation workshop in Boulder, Colorado.

Over the course of the project, we received input from approximately 60 specialists and managers and responded to approximately 350 comments. The last of the Task #4 activities are this Final Report and a final presentation of results, planned for January 29, 2008.

3.2 Management implications of study outcomes

3.2.1 Context for evaluating management implications

The results of the Sacramento River Ecological Flows Study should help inform the management of flows in the Sacramento River, and they can help strike a balance between ecosystem needs an those of the people relying on water resources within California. Arguably, this study is the most comprehensive look to date at the relationships between existing flows in the Sacramento and the ecological functions they have influenced and provide. The completion and operation of Shasta Dam in 1945 imposed the most significant changes in the flow regime (Kondolf et al. 2000), reducing the magnitude and frequency of winter and spring peak flows while increasing summer and fall base flows. This is consistent with the purpose of the dam, which is to impound water for release during the irrigation season and to increase flood protection during the rainy season. By increasing the magnitude of summer base flows, dam operations have changed the shape of the hydrograph from a gradual recession limb to an artificially rapid decline and a return to an unnaturally elevated plateau. This has had significant ecological consequences—including changes in the establishment, distribution, composition, and survival of naturally recruited riparian vegetation; and changes in the timing and distribution of migration, spawning, and rearing of green sturgeon, Chinook salmon, and steelhead.

The results of the Ecological Flows Study provide a new foundation of knowledge to continue development of a comprehensive ecological view of the river, and a tool that facilitates the inclusion of ecological considerations into management decisions. More work needs to be done, but the initial findings presented here should nevertheless be immediately useful to managers and may even help address some of the functional shortcomings of the current, "status quo" approach to river management.

3.2.2 Compilation of management implications across all study components

Our synthesis of the results from the various study components leads to a consistent series of management implications for hydrology, gravel augmentation, and other actions. These are outlined in Table 3-1, which shows how the recommendations are linked across the Linkages Report, the field studies, and SacEFT.

Table 3-1. Cross-walk of recommendations that arise from the Study as it relates to river process category of focal species.

Category of Recommended Actions	Integration of recommendations
Hydrology	High value is evident in evaluating the ecological outcomes of changes in flow frequency, duration, and magnitude. Chinook • Evaluate changes in discharge during emergence and fry-to-juvenile life stages to limit risk of stranding and/or inadequate rearing habitat, especially by use of conservative ramping rates and sufficient summertime flow. • Moderated wintertime flow important for avoiding redd scour of fall Chinook but will conflict with forming bank swallow and pond turtle habitat if pursued too vigorously in every year. Green Sturgeon • Absence of data suggests that more basic research on green sturgeon spawning locations and rearing habitat preferences is needed. Bank Swallow, Western Pond Turtle, Freemont Cottonwood • Discharge flows that seasonally reconnect both off -channel and in-channel features to allow cottonwood colonization and riparian vegetation succession, promote western pond turtle habitats. Recognize and resolve potential conflicts with wintertime redd scour. • Higher spring flows followed by gradual stage recession rates in wet years are important to promote cottonwood seedling establishment, but recognize potential adverse impacts of such flows on nesting bank swallows.
Gravel augmentation /modification	Importance of spawning gravel is clear from all studies and models, although relative importance to specific species not fully resolved. Experimental manipulations should address: • Removal of coarse gravel layers at specific locations. • Increased gravel augmentation with monitored use by target populations. Other recommended actions include: • Use bed-particle size analysis to rank potential spawning areas to set restoration priorities. • Conduct redd-superimposition study. • Identify spatial extent of upriver spawning gravels.
Bank revetment	Revetment removal plus flow management that allows occasional high flows are apparently both necessary and sufficient for habitat creation and persistence. In consort with flow management, experiment with rip-rap removal at selected sites to encourage migration meander and recruit or replenish off-channel areas.
Fish passage	Importance of fish passage improvements is strongly suggested by past studies; assessment of benefits only possible through implementation with monitoring.

These generalized actions can be further broken down into more specific hypothesis driven management actions developed from the Study's efforts. Adaptive management is a well-suited approach for organizing a collective effort to restore ecological components to water-management activities in the Sacramento River. At the very least, the Study should support a more coordinated research and complimentary monitoring program to inform and reduce key uncertainties, driven by explicit hypotheses and formulated to take advantage of existing efforts, research dollars, and natural flow events.

Here we identify potential management actions that would serve two purposes: 1) to fill in the gaps in our scientific understanding, and 2) to test hypotheses regarding the effectiveness of recommended remedial actions. The SacEFT decision support model can provide guidance on both target flows (to maximize ecological benefits) and avoidance flows (to minimize negative consequences), bracketing the range of discharges to be evaluated experimentally. Some of the more significant recommended actions are listed in Table 3-2.

Table 3-2. Provisional list of potential management actions to advance conservation objectives.

Type of action	**Potentially beneficial action**	**Habitats and processes affected**	**Focal target benefited**
Change in dam operations	extend the "gates out" period at RBDD or replace it with a new water-diversion structure	upstream fish passage	spring-run Chinook, green sturgeon
Change in flow regime	implement flows that improve or extend the duration of access to low-velocity shallow-water habitats while minimizing the risk of stranding	eddy/point-bar complexes, side channels, sloughs, oxbows	steelhead, Chinook salmon
Change in flow regime	manage flow regime to promote natural bank erosion, meander migration, and channel cutoff ensure that bank erosion occurs before bank swallow nesting season begins promote channel migration to create new seedbeds for cottonwood recruitment	steep cutbanks, off-channel habitats, point bars, timing and magnitude of flow, bank erosion, veg. succession	bank swallow, western pond turtle, cottonwood
Change in flow regime	manage flows during the summer pond turtle nesting season to reduce risk of nest inundation	timing and magnitude of flow	western pond turtle
Change in flow regime	in wet water years, manage the recession limb of spring high flows and discharge fluctuations in summer flows to promote cottonwood seedling establishment	point bars, vegetation succession	cottonwood
Change in public use regulations	impose season- and reach-specific angling restrictions to protect green sturgeon that hold near Hamilton City	harvest	green sturgeon
Habitat enhancement	promote strategic horticultural restoration on floodplain surfaces that are too high to support passive recruitment	floodplains, vegetation succession	cottonwood
Habitat enhancement	prioritize actions to eradicate/control invasive plants	vegetation succession	cottonwood
Habitat enhancement	mitigate for lack of LWD recruitment in armored bends with riparian vegetation at future bank revetment projects (and those already installed)	rearing habitat, abundance of cover	steelhead, Chinook salmon, other fish
Habitat enhancement	design revetment projects to maximize cover afforded by riprap	rearing habitat, abundance of cover	steelhead, Chinook salmon, other fish
Instream habitat enhancement	change design of existing (and future) revetments to reduce effective deepening of bends	rearing habitat, abundance of shallow, slow water	steelhead, Chinook salmon
Habitat enhancement	conserve banks, remove riprap, setback levees, and retire bank revetments (especially at sites where meanders are likely to create bank swallow habitat)	steep cutbanks, off-channel habitats, point bars, bank erosion, veg. succession	bank swallow, western pond turtle, cottonwood
Instream habitat enhancement	increase gravel augmentation rate in the reach between Keswick Dam (RM 302) and ACID Dam (RM 298.5)	gravel bars, pools	Chinook salmon (all runs)
Instream habitat enhancement	restructure the coarse surface layer of armored beds between ACID Dam (RM 298.5) and Clear Creek (RM 290) to expose spawning-sized gravel in the subsurface	gravel bars	Chinook salmon (all runs)
Instream habitat enhancement	construct structures that provide suitable velocity refugia during high flow, improving overwinter survival	access to overwintering habitat	steelhead, Chinook salmon
Instream habitat enhancement	conduct new gravel augmentation activities downstream of Turtle Bay (RM 297)	gravel bars	Chinook salmon (all runs)

3.3 Future directions and next steps

3.3.1 Research and monitoring required to address key uncertainties and fill data gaps

Taken together, the Linkages Report, field studies, modeling exercises, and the SacEFT analysis, highlight significant knowledge gaps that, if addressed, would contribute to more effective river management. These knowledge gaps are briefly highlighted in the points below.

- Salmonid habitat – There is still more to be understood about salmonid spawning, rearing, and adult holding habitats for the four runs of Chinook and steelhead in the Sacramento River. Most importantly, we cannot definitively say whether spawning habitat is limiting for winter-run and fall-run Chinook. We also still don't fully understand the temporal and spatial availability of rearing habitats for overwintering juvenile Chinook and steelhead.
- Other physical habitat issues – The role of tributaries in the life history of steelhead is important but was beyond the scope of the present study. Understanding how migration through the Delta contributes to adult return is another significant gap and will stymie our ability to plan effective recovery strategies until it is filled.
- Temperature issues – We do not understand how temperature affects the spatial distribution and life-history type of steelhead, Chinook salmon, or green sturgeon. Hence, the implications of any changes in the temperatures of the river through flow-release strategies on these species should receive further study.
- Green sturgeon – There are significant gaps in what we know of the distribution, habitat selection, and environmental tolerances of the green sturgeon in the Sacramento River. Without further study, there is a risk of prescribing a flow pattern that benefits salmonids at the expense of green sturgeon. SacEFT, for example, incorporates temperature effects on eggs and larvae only.
- Bank swallows and bank-erosion processes – Further developing our understanding between aspects of the flow regime and back erosion processes would provide better guidance for managed flow events. We also are not currently able to identify whether predicted bank erosion is likely to lead to expansion of bank swallow habitat, and so future studies should identify floodplain soils that would be suitable for nesting were bank erosion to occur within them.
- Western pond turtle life history issues – The life history and ecology for the Sacramento River population of western pond turtles is poorly understood. Additional field work is recommended to verify assumptions and expand on the existing knowledge base.
- Meander-bend cutoff processes – We still do not have a workable model for predicting the occurrence of meander bend cutoffs, a critical process for the formation of off-channel habitats.
- Sediment delivery rates – We lack a quantitative database of sediment delivery rates from tributaries and from bank erosion. In particular, existing data are not sufficient to fully exploit the management utility of the sediment transport model that was developed during the Study. Long-term monitoring of the delivery of both fine and coarse sediment should be a priority of future research.

Table 3-3 provides a provisional list of studies that would help address some of these basic information gaps highlighted above and identified in Appendices A-D. In addition to the studies recommended below, the continuation of basic status and trends monitoring in the Sacramento River (e.g., salmon carcass surveys, aerial redd surveys, RBDD rotary screw trapping, bank swallow surveys, bank erosion monitoring) will be important to improve our understanding of process-habitat-biotic linkages in the Sacramento River and system response to management interventions.

Table 3-3. Provisional list of research needs.

Topic/Species	Potentially beneficial study	Uncertainty addressed
Fall- and winter- run Chinook	The occurrence and extent of superimposition and its effects on Chinook salmon (analyze existing information and initiate regular monitoring)	spawning habitat limitation
Fall- and winter- run Chinook, gravel resources	Quantify post-dam loss of gravel and assess its effects on Chinook salmon	spawning habitat limitation
Spring- and winter-run Chinook	Study potential for operating ACID fish passage facilities: • to keep winter-run salmon downstream of the dam after gravel upstream of the dam is saturated with spawning fish, and • to create a spring-run salmon spawning sanctuary above the dam by excluding fall-run Chinook salmon	effects of changes in upstream passage
Spring-run Chinook	Evaluate possibilities for new flood bypasses that would be inundated annually, thus increasing fry rearing habitat	effects of restoring inundated floodplains; potential for stranding risk
Steelhead, winter-run Chinook	Initiate study of over-wintering habitat and use by juvenile steelhead and winter-run Chinook along the mainstem	rearing habitat limitation
Green sturgeon	Initiate new research on spawning preferences and juvenile habitat use	life history and distribution on the Sacramento River
Bank swallow	Survey soils and river dynamics to locate sites where prime nesting habitat (with suitable soils) could be generated via natural (or restored) meander migration	potential for generating suitable habitat at specific sites
bank swallow	Evaluate stage-discharge relationships at key bank swallow nesting sites	local thresholds for bank erosion
Bank swallow	Conduct an updated population viability analysis using the most recent techniques and data collected since the original analysis was conducted by CDFG in 1992.	addresses data gap
Bank swallow	Conduct more intensive surveys periodically to calibrate burrow (nest) occupancy and nest survival rates	addresses data gap
Western pond turtle	Survey abundance and distribution of western pond turtle (and non-native turtles)	life history and distribution on the Sacramento River
Riparian vegetation	Conduct long-term monitoring of cottonwood recruitment and riparian vegetation dynamics	Germination and colonization of cottonwood
Chinook salmon production	Estimate the amount of spawning gravel needed to meet AFRP production goals for Chinook salmon (e.g., using gravel area measurements and stock-production modeling, under the assumption that the fall and winter run are spawning habitat limited)	management target for gravel augmentation
Chinook salmon spawning	Test the hypothesis that Chinook salmon cannot readily spawn in deposits with more than 40% coverage by particles >130 mm; Conduct water temperature modeling to assess limitations on spawning and rearing habitats for salmonids	upper limits on size of spawning gravel & temperature suitability limitations
Aquatic habitat, Chinook salmon	Document changes in substrate permeability over time	changes in spawning gravel quality
Winter-run Chinook salmon	Document the extent of spawning gravel in the winter-run spawning reach (e.g., quantified in a field study that focuses on mapping the percent coverage of immovable particles)	spawning habitat limitation

Topic/Species	**Potentially beneficial study**	**Uncertainty addressed**
Bed-surface coarsening	Document grain-size distributions at key riffles, particularly in the vicinity of RM 284 and farther downstream	the downstream limit of bed surface coarsening
Sediment transport	Quantify sediment supply from tributaries	crucial input for expanding application of TUGS
Sediment transport	Quantify inputs from agricultural runoff and other fine sediment sources	expands utility of TUGS, enabling estimation of dynamics of fine sediment transport
Chute-cutoff modeling	Develop algorithm for modeling flow in bifurcated channels	flow and sediment transport in incipient cutoffs
	Improve estimates of sediment dynamics in incipient cutoffs	
	Manipulate off-channel water bodies to study rates of terrestrialization	
Rearing habitat	Expand assessment of stage-discharge/inundation relationship for seasonally inundated habitats across the full range of plausible summer flows	stranding risks
Aquatic habitat	Quantify how water quality in OCWB's varies with land use, drainage pathways, and connectivity with the mainstem	limiting factors on ecological potential of OCWB's
Terrestrialization of OCWB's	Continue to document rates of infilling using radiometric methods especially for oldest OCWB's	long-term sedimentation history
Discharge	Expand flow gauging network in the mainstem and in OCWB's	hydrologic interactions between mainstem and OCWB's
Chute-cutoff processes	Inventory and characterize the length of armored and unarmored banks on the mainstem	local propensity for meander bend cutoff
Aquatic habitat and bank revetment	Measure cross-stream distribution of depths and velocities at progressively higher flows for paired eroding and armored bends	effects of armoring on habitat suitability in the mainstem
Aquatic habitat and bank revetment	Quantify the length and characteristics of eddy fences (where fast and slow water meet) across a range of flows for paired eroding and armored bends	effects of armoring on habitat suitability in the mainstem

3.3.2 Next steps for SacEFT

SacEFT represents a major step forward for improving the tools available to plug-in and expand ecological considerations in water management decisions on the Sacramento River. Model complexity and ease of understanding was balanced with providing a reasonable representation of the complexity of the ecosystems. As with any first iteration of a model, improvements would increase the model's utility and effectiveness. We highlight the highest priority next steps for the model's development below.

The most important next steps for SacEFT involve:

- reviewing focal species indicators for the demonstration scenarios and refining them (including obtaining final NODOS-AF2B, Shasta and FNA2 daily flow datasets for the reach below Red Bluff),
- convening several small technical meetings with qualified biologists to refine the indicator (or hazard) thresholds used to signify the biological significance of different outcomes ('poor', 'fair', 'good'),
- considering whether other focal species indicators (including life-history components) and important biophysical linkages not presently represented in SacEFT should be added based on Linkages Report (Appendix A) and Field Study results (Appendices B, C, and D). Examples of potential improvements to the model include:
  - adding management actions related to operation of ACID and Red Bluff Diversion Dam to reflect the benefits of spatial segregation for certain Chinook run type
  - adding an indicator for flow in off-channel water bodies during summer incubation for western pond turtles based on accurate site specific stage discharge information (currently lacking)
  - improving the indicator of Chinook/steelhead spawning weighted useable area to reflect the quantity and relative depth of spawning gravel, in addition to substrate grain-size suitability
  - adding a redd superimposition indicator for Chinook using appropriate field research that quantifies the functional details

Despite the necessary refinements discussed above, the model in its current form serves an immediate purpose. It is very likely that the status quo (or waiting for perfect knowledge) will contribute to further species declines and increasing regulation undesirable for all interests. Hence, considering SacEFT flow targets and other suggested actions once they are further refined, is still advised in parallel with additional research efforts. It may also be worth considering application of SacEFT elsewhere or building onto the existing model to include components that were beyond the scope of the initial iteration.

Early in project development, we purposely excluded the Bay-Delta as a consideration. However, approximately 80% of the Bay Delta's freshwater inflow arrives from the Sacramento River. We stated earlier in Section 3.1 that further consideration of ecological targets into water planning and decision making could not occur without consideration of the many other demands on the water storage and delivery system. Now that the initial version of SacEFT is functional, yet in need of refinement, perhaps inclusion of Bay Delta targets is now a reasonable goal. This would be a cost-effective approach to build on the considerable investment in developing both SacEFT and Delta ecosystem models. The design of SacEFT facilitates the inclusion of new information, hypotheses, and models. Therefore, the Project team believes it is feasible to expand SacEFT to incorporate performance measures specific to Delta focal species, developed through a series of workshops with Delta stakeholders and experts. This would permit an exploration of intra- and inter-regional ecological tradeoffs under different linked flow management scenarios (landscape scale, ecosystem management).

By integrating with other users and planning efforts, we hope to inform more fully the existing water-planning efforts with ecological considerations. SacEFT provides a framework that can house and integrate new ecological information as it is developed in the long term; it is designed with the flexibility to both alter existing linkages between management actions and biological response as well as incorporate new linkages as they are developed. Ultimately, an additional long-term goal of this project is to work with leaders in these other planning forums to continue the development of SacEFT to best meet the needs of these groups.

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