doi:10.7289/V5/TM-SWFSC-553

NOAA Technical Memorandum NMFS

FEBRUARY 2016

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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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doi:10.7289/V5/TM-SWFSC-553

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NOAA-TM-NMFS-SWFSC-553

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Summary

The question of where to upgrade and where to decommission aging dams is currently a matter of national debate. Ecological benefits of dam removal are diverse, but a key expected benefit is improved wild fish populations and fisheries, particularly for migratory fish such as anadromous salmonids. However, in general one cannot expect with certainty how strongly or how soon such benefits will materialize after dam removal, due to inadequate data on ecological impacts, unpredictable ecosystem dynamics, or poor understanding of the processes themselves. Each dam removal is thus an experiment, and each expected benefit is an hypothesis to be tested and learned from.

The scientific literature suggests that river restoration in the USA has been impeded because individual projects were not viewed as learning opportunities to help inform and refine future projects elsewhere, but in the past decade this situation has started to improve. Here we outline how to transform a large dam removal project in California into an opportunity to learn about ecological benefits for a threatened population of steelhead trout (anadromous *Oncorhynchus mykiss*) inhabiting one of the distinctive "episodic" type river systems of the state. The Carmel River Re-route and Dam Removal project (CRRDR), now underway near Monterey California, is the largest dam removal project ever in California, and one of the largest in the USA. The principal goals of the project emphasize ecological benefits for steelhead, by improving ecological connectivity to habitat upstream of the dam, habitat-forming processes downstream of the dam, and restoration of habitats within the former dam-site itself. Here we describe a research framework to discern which of these expected benefits are realized, on what timescale, and with what magnitude and effects on steelhead population viability.

A long-established scientific concept is that viable salmonid populations need rivers with abundant habitat and natural (minimally altered) flow dynamics. However, CRRDR is expected to have modest effects on the amount of accessible habitat and on flow dynamics: The amount of accessible habitat upstream of the dam will not increase much because an existing fish ladder already provides passage for migrating adults; and flow dynamics will not change much due to the modest storage capacity of the reservoir.

A broader conceptual framework for steelhead viability emphasizes not just habitat abundance and flow dynamics, but also ecological connectivity and unimpaired habitat-forming processes, and it is improvement of these two latter characteristics that is the focus of the CRRDR. The research program that we outline has applicability to dam removals whose goals are framed within this broader concept of viable salmonid populations.

The Dam Removal and River Reroute

Carmel River has two large dams of similar size, the lowermost of which, San Clemente Dam, is being removed. Storage capacity of San Clemente Dam is small relative to storm flows and has had only weak influence on the Carmel River's wet-season hydrograph. However, it has disrupted downstream habitat-forming processes by trapping bed-load sediments and large woody debris in the reservoir. The dam has also disrupted ecological connectivity of the steelhead population by slowing the passage of spawning adults moving upstream, and by reducing survival and mobility of smolts and juveniles moving downstream. Most fundamentally, it has completely blocked upstream passage of juvenile steelhead, which has probably reduced the resilience and productivity of the local steelhead population.

The CRRDR has a unique design, with ecological effects expected to differ from other dam removals. CRRDR is designed to prevent an unnaturally large pulse of sediment from the former reservoir by sequestering its accumulated sediments in place, and rerouting the river around them through a nearby tributary with a roughly parallel course. The rerouted river will comprise 1030m of constructed channel with a slope that varies from 4.5% to 0.8%. The channel is conceived to function similarly to a natural

channel, with step-pool morphology in the steeper section and pool-riffle morphology in the less-steep section that will respond to high-flows similarly to natural channels with such morphology. It is designed to transport sediment and wood downstream while fostering upstream and downstream migration of all life-stages of steelhead. The project is expected to allow the river to partially resume unimpaired bed-load dynamics, returning the supply of gravel and coarse sands to a level closer to the pre-dam era. It is expected to have little effect on the episodic winter flow dynamics that transport those bed-load materials.

CRRDR is also expected to partially restore large wood to the lower river, with greater abundance, size, persistence, and geomorphic effectiveness. Large wood is broadly recognized to be a key element of fish habitat in rivers due to its geomorphic and biotic effects, and the restoration of normal wood dynamics is expected to improve the survival and growth of juvenile steelhead rearing in the lower river.

The resumption of characteristic bed-load and wood dynamics is expected to be limited by the continuing impact of Los Padres Dam 11 km upstream of CRRDR, which has similar effects on habitat-forming processes as San Clemente Dam. Thus the expected benefit of CRRDR is dependent on sufficient sediment and wood entering the channel from sources (hillslopes, tributaries) downstream of Los Padres Dam.

Lastly, CRRDR is designed to improve ecological connectivity by making passage faster, safer, and more reliable for adult steelhead moving upstream and all life-stages moving downstream. It is also expected to open up upstream passage for immature steelhead, allowing juvenile fish to respond to seasonal changes in the river system, which is expected to increase the resiliency and overall productivity of the population. However, design criteria did not require upstream passage of smaller juveniles (<15cm fork length) through the steep step-pool section, so this benefit may not be fully realized.

<u>Habitat-Forming Processes and Dam Removal</u>

The Carmel watershed has the characteristic California coastal climate of moderate temperatures, dry foggy summers, and highly variable rainfall from large storms in winter. This produces an episodic flow regime, characteristic of California rivers but distinct from the rest of the USA. A key habitat-generating process is the episodic mobilization, transport and deposition of bed-load sediment (sand, gravel) during flow pulses, especially rare extreme flows or flows after wildfire or landslides. During such events large quantities of logs and other large woody debris (LWD) also get transported and deposited in downstream channels, where their subsequent geomorphic and biotic effects create high-quality habitat for many kinds of fish species.

San Clemente Dam and Los Padres Dam 11 km upstream have been disrupting these habitat-forming processes since 1921. Currently the middle and lower river appear deprived of large wood and exhibit features characteristic of lost bed-load: incised channel, scarce gravel substrates, narrowed channel, and disconnection from the floodplain. The channel in the alluvial portion of Carmel Valley downstream of San Clemente Dam is expected to be highly responsive to changes in upstream supply of sediment and large woody debris produced by CRRDR, but the desired response is dependent on flood flows and may take years to fully materialize. In addition, effects of CRRDR on downstream habitat-generating processes must be considered within the context of other anthropogenic impacts such as aquifer depletion, anthropogenic bank alteration and floodplain disconnection.

Intermittency (loss of surface flow) is widespread in tributaries and the lower mainstem in summer, and in the wet season if rainfall is low. Generally, spatial patterns of intermittency in the dry season are linked to spatial patterns of sediment deposition in the wet season, because thicker layers of deposited sediments have greater capacity for subsurface flow and are thus more likely to lose surface flow in the dry season. In the middle and lower river, intermittency is also linked to the state of the water table in the underlying aquifer. Aquifer depletion can override the habitat-generating processes of CRRDR by killing aquatic species and riparian vegetation, the latter leading to channel widening, aggradation when high flows next occur, and alteration of the aquatic community. The effects of CRRDR on ecological connectivity must therefore be considered within the context of natural and anthropogenic processes generating intermittency.

Diversity of benthic macroinvertebrates appears to be low throughout the lower river, with the least diverse conditions just below the two dams. CRRDR is expected to improve invertebrate diversity throughout the lower river, with the largest benefit at the site just below San Clemente Dam.

Los Padres Dam is comparable to San Clemente Dam in terms of size, hydrograph, and geomorphic setting and can therefore serve as an upstream scientific control for evaluation of the effects of dam removal. The existence of such a control provides unique scientific value to the research program outlined here.

Several alien species in the system are problematic because they have similar ecological associations as native species but their spatial expansion is unwanted. Alien brown trout (*Salmo trutta*) occur in the upper watershed and have ecological needs similar to but not identical to steelhead. CRRDR may unintentionally benefit this species and encourage it to expand its range downstream. Alien bullfrogs *(Lithobates catesbiana*) occur throughout the watershed and have ecological needs similar to California red-legged frog (*Rana draytonii*), a threatened native. Bullfrogs and red-legged frogs appear to co-exist through intricate metapopulation dynamics. CRRDR is expected to benefit red-legged frogs through the removal of a large source population of bullfrogs in San Clemente Reservoir. However, the magnitude of this benefit is uncertain since two other large source populations of bullfrog will remain at other sites upstream and downstream of CRRDR.

The seasonal bar-built lagoon at the river mouth is important rearing habitat for steelhead. CRRDR is expected to affect the lagoon by aggrading the bed with sand and/or raising the crest height of the seasonal sandbar barrier. Depending on the relative magnitudes of these two effects lagoon capacity and quality for steelhead could either improve or decline. These bathymetric effects in the lagoon are also expected to interact with sandbar management constraints, predation pressure on steelhead by birds and introduced striped bass, and effects of a planned restoration of floodplain processes to the two southern arms of the lagoon system. Implications for capacity and quality of steelhead rearing habitat are uncertain. The lagoon is intrinsically dynamic and complex, such that effects of CRRDR will be difficult to distinguish from other processes driving lagoon function and structure.

Steelhead Population Viability and Dam Removal

Most steelhead populations on the California coast are thought to be partially anadromous, with some individuals migrating to the ocean and others staying in freshwater to mature. The CRRDR is expected to most substantially affect the anadromous component of the Carmel River steelhead population. Such effects involve conditional smolting strategies evolved by the fish in the context of past habitat dynamics as well as genetic and physiological constraints on growth and development. Conditional smolting strategies are likely to be subtle and complex, involving growth rates, lipid storage, freshwater feeding, local fish density, freshwater movements prior to smolting, and genetic components.

The NMFS conceptual framework assumes that steelhead population viability depends on abundant, high-quality, diverse habitats for each life stage, highly connected by movement corridors. Originally, habitats in middle and lower Carmel River were highly dynamic, probably functioning as productive steelhead nursery habitat in wet years but poor habitat in dry. San Clemente Dam appears to have helped convert the alluvial portion of the river into reliably mediocre habitat by providing narrower incised channels that are deeper and better-shaded, but with simplified structure and poorer feeding resources relative to the pre-dam era.

Various accounts from the 1950s through to 2000 indicate that in the post-dam period, the alluvial section of the river in Carmel Valley was generally sand-bedded, probably due to a combination of trapping of gravel behind the upstream dams; influxes of sand from human-altered riverbanks and floodplains; and contributions of sand from a key tributary at the head of the alluvial valley, Tularcitos Creek. Since the year 2000, large sections of the lower 14 km of river have developed gravel beds for the first time in at least 50 years, probably due to a response of sand dynamics to improved riparian, floodplain and flow management, rather than an increase in gravel supply.

In contrast, upstream between Tularcitos Creek confluence and the CRRDR site, the Carmel River is confined in a narrow V-shaped canyon with minimal floodplain, few sand inputs, and slightly steeper channel gradients, producing a channel bed composed of coarse material (cobbles and boulders).

The response of channels to CRRDR are thus likely to differ upstream and downstream of Tularcitos Creek confluence. Upstream, the coarse sediments are expected to accumulate sand and gravel, leading to smaller mean sediment sizes and greater diversity of sediment sizes overall. This should produce greater habitat complexity for steelhead and increased abundance of spawning habitat. The expected response of the alluvial channel downstream of Tularcitos Creek confluence is likely to be noisier, with complex interplay continuing between sand and gravel dynamics sensitive to floodplain and bank conditions as well as the improved upstream gravel supply. Overall the predictions are for spawning habitat that is highly dynamic and variable, but generally increasing in capacity and quality over time; channel beds that tend to aggrade rather than incise; and increased occurrence and size of large wood that creates greater habitat complexity. Although CRRDR is expected to improve habitat quality on average, it may increase its variability over time and its vulnerability to summer weather and aquifer condition.

A key question is how the expected improvement of survival and growth conditions will affect conditional smolting strategies of steelhead. For example, if improved habitat greatly increases survival but only moderately increases food availability, more fish may survive but with slower growth and fewer actually reaching body sizes that trigger smolting. Thus there is potential for a paradoxical effect in which improved habitat reduces the number of smolts migrating to the ocean. This means the effects of CRRDR on steelhead need to be assessed empirically, in terms of smolt production and anadromous run size, rather than simply as changes in the numbers or genetic composition of *O. mykiss* in reaches affected by the dam.

CRRDR is expected to improve anadromous migrations by improving traverse times through the former dam site and by reducing injury to downstream migrants (smolts and kelts). The most substantial benefit in terms of viability may be improved population resilience in dry years.

The new constructed reroute channel will include approximately 60 rock “step-pool” sets that will reconnect the lower river to the elevation of the former reservoir’s sediment fill (an 18 m rise). The channel will have an average slope of 3% and typical step of 0.3 m, and will incorporate approximately 7 larger “resting” pools separating channel reaches with steep climbs. Passage times for migratory life-stages of steelhead are expected to be faster relative to the old fish ladder, a benefit expected to provide resilience most strongly in dry years when migration opportunities may be limited to brief windows of time after storms.

The reroute channel was not specifically designed to allow upstream passage of juvenile steelhead smaller than 15 cm fork length. Depending on how suitable the reroute channel is for upstream passage of juvenile steelhead, CRRDR may restore the capacity of the river to support two important steelhead life-history tactics: upstream retreat of age 0 fish from vulnerable spawning habitats to reliable rearing habitats, and an advance-and-retreat tactic by which rearing fish adaptively respond to changing habitat conditions in the lower river. This could potentially relieve a source-sink structure forced on the population by San Clemente Dam, increasing and stabilizing smolt production.

Some benefits of CRRDR may not be realized until aquifer depletion is also fixed and/or floodplain processes are restored to the lower river and estuary.

<u>*Recommended Research System*</u>

The predicted ecological benefits of CRRDR for steelhead can be usefully framed as three general questions:

1) How well do restored bed-load and wood dynamics improve downstream habitats?
2) Does the reroute channel function as intended?
3) How much does increased ecological connectivity improve steelhead viability?

To address the first question we recommend tracking key habitat-forming processes, and establishing a system of permanent indicator reaches on the river in which to measure physical and biotic response. To ask the second question we recommend intensive study of geomorphic, hydrologic, and biotic processes in the reroute channel, especially the combined-flow reach. To ask the third question we recommend establishing a systematic effort to electronically tag juvenile steelhead and monitor their movements and fates in the river system. Finally, we recommend developing an integrated population model that would translate these data into analyses of steelhead viability consistent with the NMFS Viable Salmonid Population framework.

Habitat-Forming Processes should be tracked by quantifying sediment and wood transport and deposition in the river. For sedimentary and geomorphic change, we recommend standard methods for measuring suspended sediment transport and quantifying topographic and plan-form change in the river channel downstream of CRRDR. For wood transport we recommend recurrent large wood censuses downstream of CRRDR, using methods established by Smith and Huntington (2004).

Basic Response of Indicator Reaches should be tracked by establishing a system of 14 indicator reaches (IRs) in which there is recurrent collection of 5 basic performance metrics (channel geometry; grain size in the channel bed; characteristics of LWD; characteristics of the local assemblage of benthic macroinvertebrates (BMI); and characteristics of rearing steelhead).

To support a causal interpretation between dam removal and river response, the recommended system of indicator sites was designed according to principles for Before-After/Control-Impact studies. However, the system lacks elements of classic experimental design such as random, replicated assignment of experimental treatments (dam removal in this case). Consequently, one can test for predicted effects of dam removal, but cannot necessarily use formal probabilistic reasoning to reject alternative explanations for those effects. A unique scientific strength of the Carmel River system, absent in most studies of dam removal, is the existence of a true scientific control: an upstream dam of similar size and ecological setting that is *not* being removed. We recommend establishing indicator reaches downstream of this dam as well as CRRDR because the resulting data will help distinguish effects of dam removal from other drivers of environmental variation in the river. This will improve scientific rigor and the basis for causal interpretation of the data.

Additional event-based data should be collected after wet seasons or individual flood events judged to produce significant reworking of the channel, transport of sediment, or deposition of wood. After such events, we recommend 1) establishing additional IRs where there has been significant new deposition of large wood; 2) repeating the longitudinal channel profiles conducted between Via Mallorca and Robinson in the past (years 1997, 1999, 2001, and 2007); and 3) quantifying changes in river plan-form and riparian vegetation using aerial imagery.

Lagoon response to CRRDR will be difficult to interpret because the estuary is highly responsive to multiple influences and has no comparable second lagoon to serve as a control. This places an emphasis on sufficient repeated sampling in the "before" period to characterize the background variation prior to CRRDR. Thus it is makes sense to maintain certain existing data collections with long time series in the pre-removal era: annual bathymetric surveys at 4 cross sections in the lagoon; continuous monitoring of water surface elevation and water temperature; vertical-profiling at 5 water-quality sites; and vegetation composition in quadrats on the North Arm. In addition, we recommend developing additional methods that focus 1) on interpreting this data record; 2) on clarifying links between lagoon structure / dynamics and the ecology of striped bass, an introduced predator on steelhead in the lagoon; 3) on estimating abundance of juvenile steelhead themselves in the lagoon; and 4) on evaluating the suitability of the aerial photo record for estimating various other performance metrics. Finally, we recommend event-based surveys in the lagoon for occurrence of large wood and for lagoon bathymetry.

Function of the Reroute Channel should be evaluated by 1) monitoring flow, water temperature and potentially other water quality parameters on channels above and below the site, and in the combined-flow reach; 2) detailed geomorphological measurements of the combined-flow reach after completion of the project and after winters with large flow events; 3) establishing indicator reaches in the reroute channel; and 4) use of PIT-tagging techniques to evaluate upstream and downstream passability of the channel by adult, juvenile, and smolt life-stages of steelhead.

Changes in Ecological Connectivity in the steelhead population should be tracked by 1) establishing an integrated scheme for sampling steelhead from stream reaches and tagging them with PIT tags, and 2) establishing a system of electronic detection stations on the river, to track movements, survival, and smolting rates of the tagged fish. Tagging steelhead and observing their movements supports tests of three kinds of predicted effects of CRRDR: First, predictions that migrating smolts and adult steelhead will experience similar movement speed and survival through the CRRDR site as in other parts of the river; second, that improved connectivity at the CRRDR site allows juvenile movements that are associated with greater survival and smolting rate; and third, that changes in habitats downstream of CRRDR are associated with greater smolt production.

Changes in steelhead population viability in response to CRRDR can be estimated by constructing an integrated population model that translates the fish data from indicator reaches and tagging efforts into the response of the steelhead population as a whole. Integrated population models (IPMs) use quantitative techniques to integrate diverse sets of data into a single, process-based model of population dynamics and trajectory (Schaub and Abadi 2011). Such models allow for population-level assessment of viability (extinction risk) and other key population traits (adult run size, anadromous fraction, etc.). A suitably designed tagging effort and IPM, in combination with existing data collection efforts on Carmel River steelhead, would allow for formal evaluation of the response of steelhead extinction risk to CRRDR.

Together the above recommendations comprise a basic research system to which sites and performance metrics could be added or subtracted through time to address other ecological questions of interest, including the responses of other species such as California red-legged frogs or alien fish species; and to determine how effects of dam removal interact with other restoration actions such as aquifer restoration or management of problematic alien species. Toward this end we outline a comprehensive set of performance metrics that would extend the basic system described here.

NMFS, USGS, CSU Monterey Bay and the Monterey Peninsula Water Management District have begun implementing some elements of this research system, but additional resources are necessary to adequately answer the principal questions about ecological benefits for steelhead.

Contents

Introduction

The question of where to upgrade and where to decommission the Nation's aging dams has now entered the national debate (e.g. Brewitt and Holl 2014, Chouinard 2014, Ciocci 2014, Lovett 2014, Waldman et al. 2014), weighing the services of existing dams against their ongoing loss of capacity and the benefits of removal. Although benefits of dam removal are diverse, a key factor frequently driving the discussion is the long-term ecological benefit expected from removal, especially for wild fish and fisheries. On the US Pacific coast the focus is often on the benefit for endangered wild salmon.

In general the National Marine Fisheries Service (NMFS) evaluates impacts of human activities on endangered Pacific salmonids using a two-pronged conceptual framework of 1) viable salmon populations (McElhany et al. 2000); and 2) habitats maintained by natural fluvial processes (Beechie et al. 2010). This framework provides a consistent, scientifically grounded basis for evaluating how a project such as a dam removal or upgrade affects the local salmonid population.

However, in general one cannot expect certainty from such evaluations, due to inadequate data, unpredictable dynamics, or poor understanding of processes. Each dam removal is thus an experiment, and each expected benefit is an hypothesis to be tested and learned from. In the broader context of river restoration and salmon recovery, what is learned from one dam removal can then serve to refine the conceptual framework and expected benefits of the next proposed removal, creating a social-learning process (Palmer and Bernhardt 2006, Kibler et al. 2011). The lack of such project-by-project social learning has been one of the principle roadblocks to ecologically effective river restoration in the USA (Bernhardt et al. 2005, Palmer et al. 2005, Bernhardt et al. 2007, Palmer 2009), although the scientific and management communities are making a concerted effort to synthesize lessons learned from recent large dam removals (e.g., O'Connor and East 2014).

In this report we outline a strategy for using the ongoing removal of San Clemente Dam on Carmel River as a learning tool for dam removals in California. In 2013, NMFS, Federal, state and local partners began removing this 32m-high dam at a cost of $84 million, with key objectives of improving habitat and ecological connectivity to benefit steelhead (National Marine Fisheries Service 2013a), a Federally threatened salmonid.

This is the first removal of a large dam on California rivers, whose distinctive Mediterranean climate, episodic flow regimes and high sediment loads make unclear the applicability of lessons learned from dam removals elsewhere in the country (Hecht 1993, Kondolf et al. 2013). Thus the San Clemente project offers a unique opportunity to learn about the effectiveness of large dam removal as a tool for salmon recovery in California.

The San Clemente Dam removal also provides a unique opportunity to evaluate specific aspects of the NMFS conceptual framework for salmon recovery. A long-established view in the scientific literature is that resilient salmon populations require rivers with abundant habitat and natural (minimally altered) flow dynamics. However, the NMFS framework reflects broader view that salmonids need river systems with these attributes but also two additional attributes: good ecological connectivity and unimpaired habitat-forming processes.

It turns out that the removal of San Clemente Dam is in effect "doing the experiment" to ask if the broader view truly outperforms the established view. The dam has always had a fish ladder providing upstream passage to migrating adults, so its removal will not open up new habitat. But it will improve the connectivity of existing habitat by allowing non-migratory life-stages of steelhead to begin moving freely between the upper and lower river. This gives an unprecedented opportunity: to examine the benefits of ecological connectivity that is not confounded by changes in amount of accessible habitat.

In addition, due to the relatively modest total capacity of reservoirs on the system, the existing winter flow regime is minimally altered from its natural state. However, for 9 decades the dam has been trapping most of the coarse sediments and large woody debris being transported by the river. With dam removal the river will finally resume two key habitat-forming processes: the downstream transport of gravel and of large woody debris. Moreover, as part of the project the existing sediment field in the reservoir is being stabilized in-situ and the river rerouted around it. In short, dam removal will not much alter the existing episodic flow regime, nor create a large unnatural pulse of reservoir sediments downstream, unlike other recent examples of large dam removals (Wilcox et al. 2014, East et al. 2015). This gives a second unprecedented opportunity: to examine the benefits of habitat forming processes that are not confounded by changes in flow regime and artifacts of dam removal. A third opportunity is to evaluate the benefit of adding over 1000 m of new gravelly step-pool channel and riparian habitat where there is now a very steep fish ladder with no spawning or rearing habitat.

Meanwhile, another dam on the river system, of similar size and ecological effect, is not being removed and can serve as a scientific control for the experiment. What is needed to complete the experiment is to collect data in the post-dam period, and evaluate whether or not dam removal has produced measureable and significant benefits to habitats and the local *O. mykiss* population.

In this report we outline a strategy of data collection and analysis that would test whether such benefits materialize from dam removal on the Carmel River. The seeds of the strategy were developed in a workshop on the expected ecological benefits of the Carmel River Reroute and Dam Removal, held in November 2012 at the NMFS SW Fisheries Science Center in Santa Cruz, California, and spearheaded by Trish Chapman of the California Coastal Conservancy, Joyce Ambrosius of the NMFS West Coast Region, and Thomas Williams of the NMFS SW Fisheries Science Center. We are grateful to the local biologists and physical scientists who participated in the workshop and shared their expertise, as well as additional participants who have studied dam removals elsewhere in the USA and shared their recommendations and lessons learned from their work (see acknowledgements for a complete list). The workshop led to an extended series of discussions among the authors of this technical memorandum, the outline of the scientific strategy described in this text, and first steps at implementation.

The first section below provides background on the Carmel River and the unique aspects of the Carmel River Reroute and Dam Removal project (CRRDR project). The second section is a review that synthesizes a conceptual model of habitat-forming processes in the river, identifying past impacts of the dam, expected response of the river to CRRDR, and key uncertainties about the expected response. The third section is a review of steelhead population viability concepts, identifying expected benefits and key uncertainties about the response of Carmel River steelhead to CRRDR. Finally, the fourth section outlines the recommended data collection a follow-up analyses to test if the expected benefits of CRRDR for steelhead materialize.

The CRRDR is expected to have myriad ecological benefits, but here we focus on benefits for steelhead as a kind of organizing principle for a very complex topic. By this we do not wish to underrate other ecological benefits expected from the dam removal, but a comprehensive treatment of ecological benefits expected from CRRDR and how to assess them is well beyond our scope and expertise. However, the fundamental system of indicator reaches, performance metrics, and integrative ecological modeling that we recommend below is intended to be flexible and extensible so that it can accommodate extensions to other focal species or biotic communities.

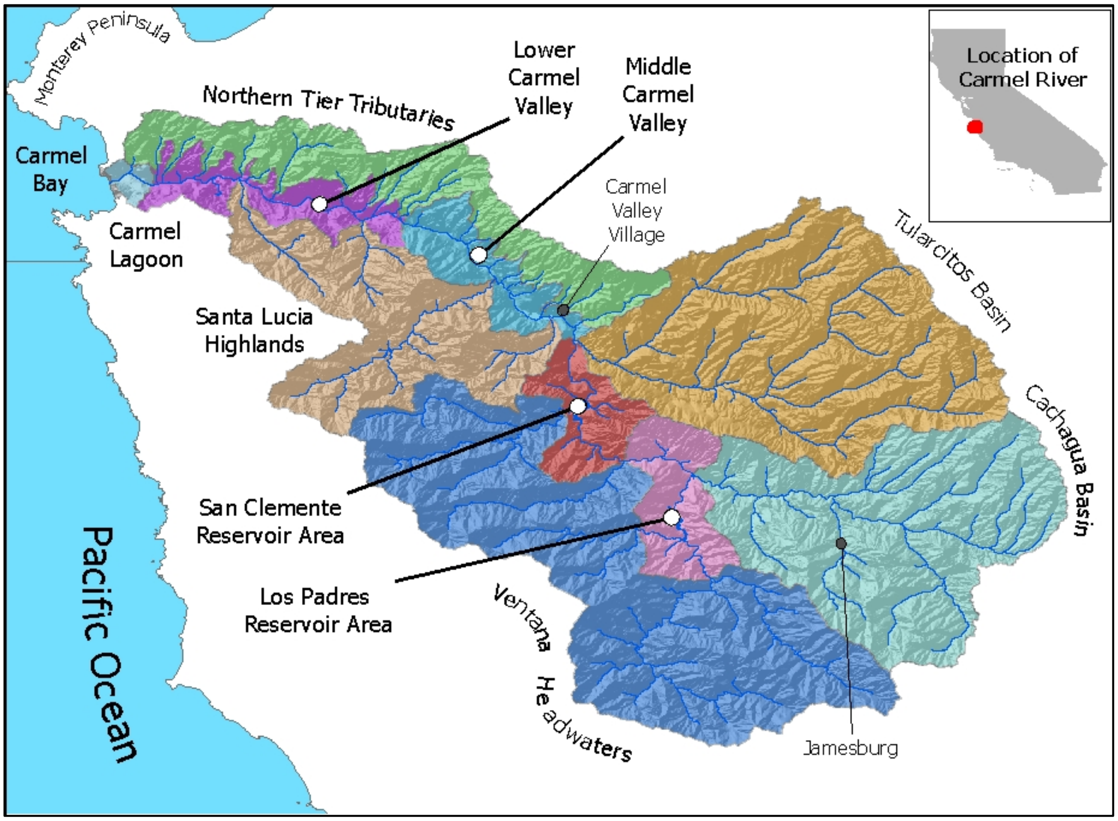

Figure 1. Carmel River system, its major landscape domains and tributaries

The Carmel River

Carmel River (Figure 1) drains a watershed at the northern end of the Santa Lucia Mountains of the south-central California coast. The river flows about 65 km from headwaters in Ventana wilderness, northwest through mountainous, unstable terrain with several active faults, then west to the Pacific Ocean through the alluvial Carmel Valley, where its water supports the people and economy of Carmel Valley and Monterey Peninsula (Smith et al. 2004).

Due to local demand for water and environmental amenities, the Carmel River system is intensively managed. Key features of this management system historically were three dams on the main-stem upriver from Carmel Valley, two aquifers under Carmel Valley, conveyance systems to an aquifer outside the watershed used for remote water storage, and extensive mitigation programs to benefit riparian vegetation, aquatic biodiversity, and in particular, Carmel River steelhead (MPWMD 2006). Carmel River steelhead (anadromous *Oncorhynchus mykiss*) are part of a distinct population segment that is threatened with extinction and a focus for Federal recovery efforts under the US Endangered Species Act (National Marine Fisheries Service 2013b).

Over the past three decades, NMFS and Federal, local and state partners have invested heavily in the recovery of Carmel River steelhead. Riparian restoration in the lower 25 km of river was initiated locally in 1983 by concerned citizens and the local water district. Extensive changes in water management were also started in 1989, leading to less reliance on San Clemente Dam as a primary point of diversion for municipal supply, and eventually to a requirement from the State Water Resources Control Board to reduce unauthorized water withdrawals from the river. Mitigation efforts include ongoing relocations and captive rearing of steelhead stranded by dewatering of the river channel, as well as restoration of streamside habitat. The Carmel Estuary Lagoon Enhancement Project, completed in 2004 by Federal, state, and local partners, expanded the volume of the estuary by 30% and restored wetland vegetation, with the aim of benefiting steelhead and California red-legged frog (*Rana draytonii*), another endangered species.

Dam sites on the mainstream are Los Padres Reservoir in the upper watershed, San Clemente Reservoir in the middle watershed (Figure 1); and Old Carmel River Dam, a small diversion dam about 0.5 km below San Clemente Dam.

Los Padres Dam (b. 1948) and San Clemente Dam (b. 1921) both currently have capacity too low to provide significant flood control or even to provide much alteration to wet-season hydrographs, and are currently used to support river flows in summer. Los Padres Reservoir has lost about half its storage capacity to accumulated sediments, and San Clemente has lost 95%. Old Carmel River Dam is a much smaller, older structure that no longer functions as a water turnout.[1]

The principal mechanism by which San Clemente Dam has disrupted habitat-generating processes in the Carmel River has been to trap nearly all of the bed-load sediments and reduce the volume and size of large woody debris being transported by the winter hydrograph. Due to its small capacity, the dam has always had a relatively modest impact on the winter hydrograph itself, and this has only diminished with time as accumulated sediments reduced the water storage capacity to only 5% of its original $1.76 \cdot 10^6$ m^3 (1425 acre-feet).[2] Passage of large wood is impeded by the spillway, which is composed of 24 gated bays 1.7 m wide each (National Marine Fisheries Service 2013a, p. 50). The bays restrict the passage of large wood pieces over the dam during high flows; in the past the accumulated wood has typically been either allowed to sink into the reservoir, or cut to smaller pieces and pushed through the bays.

The principal mechanism by which San Clemente Dam has disrupted spatial structure and diversity of Carmel River steelhead has been to impede downstream passage of most life-stages and to completely block upstream passage of all life-stages except migrating adults. A 21 m high fish ladder penetrates the dam on the west side near the top, and has provided upstream passage for adult migrating steelhead since dam construction in 1921. The dam allows downstream passage of all life-stages over the 21 m drop from the spillway to the plunge pool below, or down the fishway when the reservoir is full. As of a retrofit in 2004, fish can also pass down the fishway when the reservoir has been drawn down, which in recent years has typically occurred in summer for safety reasons. Despite this and other retrofits, the ladder does not meet current NMFS criteria for fish-passage structures and presumably impedes movement of fish. Upstream passage by life-stages other than adults is completely blocked.

Carmel River Reroute and Dam Removal (CRRDR)

The Carmel River Reroute and Dam Removal project removes San Clemente and Old Carmel River Dams, and reroutes the river around the sediment-filled reservoir of San Clemente Dam. The reroute component makes the CRRDR strikingly different from many western dam removals, most of which have left accumulated sediment to be remobilized and transported downstream naturally by fluvial erosion. In contrast, the CRRDR is designed to stabilize nearly all sediment on site in perpetuity, while routing the river flow to one side of the stabilized sediment in a constructed river employing natural channel design elements.

Stabilization is accomplished by taking advantage of a peculiarity of the site: the roughly parallel courses of the river and a tributary, San Clemente Creek, just upstream of the dam. The river will be rerouted through a new cut in the

[1] Discharges above ~3 cms get backed up, because the dam restricts flow. At flows of about 11 cms the dam is overtopped and the effect disappears.

[2] http://www.sanclementedamremoval.org.

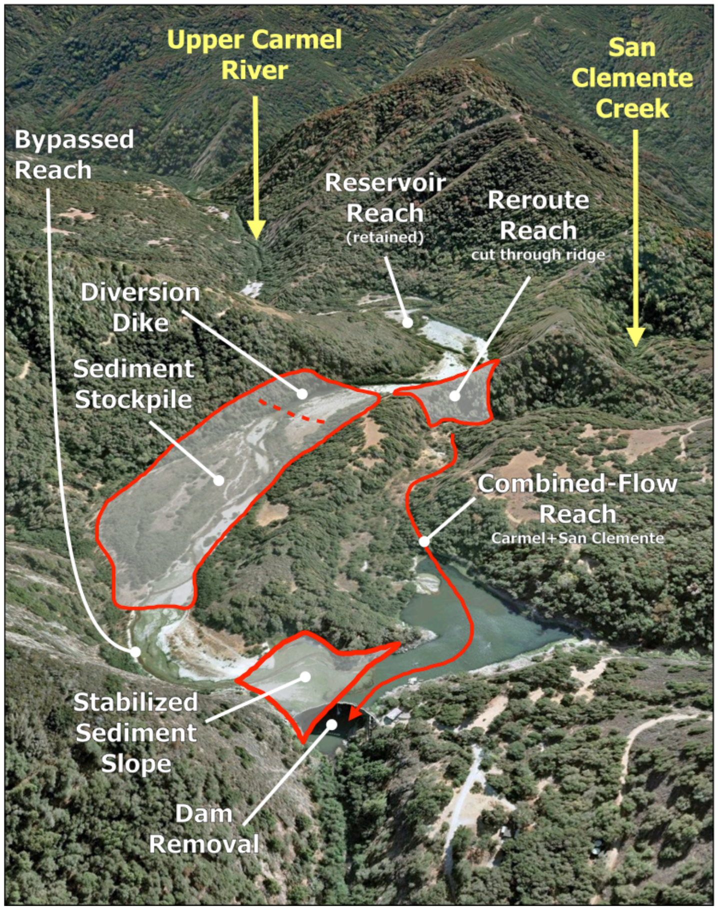

Figure 2. Main components of Carmel River Reroute and Dam Removal project (CRRDR), superimposed on the pre-removal channel configuration. (http://www.sanclementedamremoval.org). Not pictured is removal of the Old Carmel River Dam downstream of the main site. Image from AMBAG Oct 2007 and Google Earth.

ridge separating the two channels, near the upstream end of the reservoir (Figure 2). The cut is designed to be deep enough to initiate sediment transport in the retained portion of the reservoir reach just upstream of the cut. The tributary downstream of the cut will be reworked into a "combined-flow" reach that functions as a new river reach, composed of step-pools designed to exhibit natural geomorphic processes and to allow unrestricted passage of all sizes of fish in both upstream and downstream direction. Most of the accumulated reservoir sediments will be stockpiled in place, with engineered elements to protect the upper and lower ends of the stockpile from mobilization by hillslope and fluvial processes (Diversion Dike, Stabilized Sediment Slope; Figure 2).

The restored channel will add 1030 m of step pool (745 m) and riffle-pool (290 m) hydraulic habitat to the Carmel River. The step-pool section will raise the channel bed 18 m from the elevation of the lower river near the current dam site, to the elevation of the notch, where the lower-gradient riffle-pool section will continue upstream through the reservoir fill. The step-pool section will incorporate approximately 60 constructed rock steps and pools with reach-average slope of 3% (ranging from 2% to 4%). Approximately 7 pools will be larger "resting"pools for migrating steelhead, and each step of the 60 will rise no more than 0.3

m, intended to allow easy fish passage in moderate flows. The new channel is designed to transport gravel during runoff events, but the ambient gravel might also locally serve as spawning habitat, and will add considerable substrate for benthic invertebrate populations. Large wood will be incorporated as in-channel, bank-protecting rootwads and as roughness elements in the low-gradient section, where a broader floodplain will be constructed. Based upon experience elsewhere on the Carmel River, a dense riparian corridor is expected to rapidly develop along the restored channel through natural recruitment that will augment the great number of plantings that are part of the restoration project.

Due to this unique design, predicted ecological effects of CRRDR are unlike those of other dam removals. First, the project is specifically designed to avoid releasing an unnaturally large pulse of sediment into the fluvial system. Instead it is designed to allow the river to simply resume unimpaired bed-load dynamics that have been absent downstream since 1921. Flow dynamics are only weakly influenced by the dam currently, and are expected to show only weak response to the project.[3]

Second, the CRRDR will not open up new habitat to steelhead, since San Clemente Dam was equipped with a functioning fish ladder allowing upstream passage of adults and downstream passage of smolts. However, the ease of passage for migrants is expected to be improved by replacing the ladder with a step-pool river channel.

Finally, the reroute will allow unimpaired wood dynamics to resume downstream of the dam. CRRDR will allow full sized tree boles to pass downstream, predicted to generate stronger geomorphic responses than the small pieces currently passed. This in turn is expected to generate greater habitat complexity in the lower river, benefitting steelhead.

In summary, the principal ecological benefits predicted for steelhead (Figure 3) are:

1) Functioning spawning, rearing and migratory habitats at the project site (upper reservoir reach, reroute reach, combined-flow reach),
2) Partially restored bed-load dynamics (i.e., increased sediment supply) in the lower river, added to the existing episodic flow regime,
3) Restored dynamics of large wood in the lower river, with greater abundance, size, persistence, and geomorphic effectiveness,
4) Incremental improvement of existing connectivity for steelhead migrants, and fundamental improvement of connectivity for other *O. mykiss* life-stages.

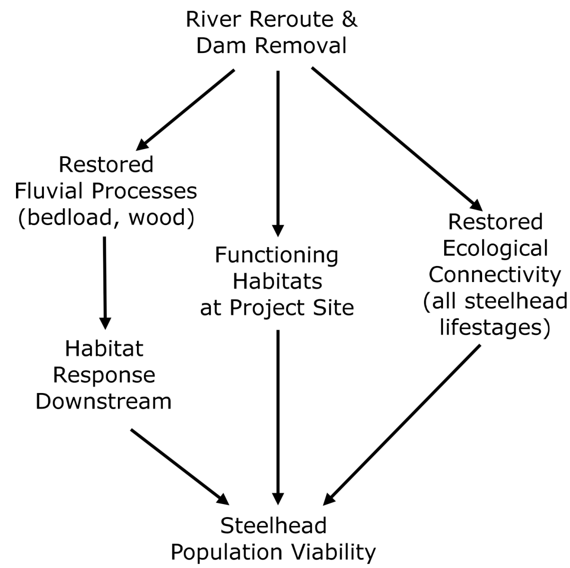

Figure 3. Conceptual model of the predicted ecological effects of the CRRDR project on steelhead population viability

[3] Flow and bed-load dynamics will still be affected by the Los Padres Reservoir upstream. Its capacity is too small to have much affect on large flow events but does play a crucial role in sustaining dry-season flows. The reservoir has some effect on bed-load by trapping sediments from a subset of tributaries upstream of the CRDRR, but given that there are sediment source areas (including an active landslide zone) between Los Padres Dam and San Clemente Reservoir, the trapping efficiency of Los Padres reservoir was not enough to prevent the lower reservoir from filling with sediment.

According to the Biological Opinion prepared by NMFS for the CRRDR, "To better understand the response of a river system post-dam removal, the Corps should sponsor the development and implementation of research projects to document the long-term changes to river dynamics over time. Studies (not all inclusive) should include:

- Habitat rebound periods – i.e., time it takes to become a mature, functional riparian canopy
- Fish passage efficiency of restored reaches
- Sediment Transport
- Species assemblages, diversity and abundance as well as recruitment and colonization of new habitat."

(National Marine Fisheries Service 2013a, p. 90). These recommendations focus on two of the five predictive elements of the conceptual model (Figure 3)—functioning habitat at the project site, and restored ecological connectivity. However, the NMFS Biological Opinion (National Marine Fisheries Service 2013a), technical reports by the local water district (MPWMD and CRWC 2004, MPWMD 2006) and the stated goals of the CRRDR itself[4] all emphasize broader ecological benefits encompassed by the three predictive elements of the conceptual model (Figure 3): Restored fluvial processes downstream of the site, beneficial habitat response downstream, and improved steelhead population viability overall. In the next two sections we develop the conceptual model by reviewing what is currently understood about habitat-forming processes and steelhead population dynamics in this coastal region of California.

Habitat-Forming Processes and Dam Removal

Regional Climate

The fundamental driver of habitat-forming processes in California coastal rivers is the region's distinctive "mediterranean" climate interacting with its tectonically active coastal mountain ranges. Distinctive features of the climate are moderate temperatures throughout the year, a dry but foggy summer, and infrequent large winter rainstorms.

Moderate temperatures arise because the high heat capacity of the nearby ocean stabilizes temperature swings, both diurnally and annually. Mean monthly temperature on the coast (Monterey) usually stays between 8° and 18° C, whereas in the eastern watershed (Hastings Reserve) it ranges more broadly between 5° and 24° C (Figure 5), which is still more moderate than continental climates further inland. The ocean's moderating effect is stronger but less consistent in the warmer months, due to spring-summer upwelling of deep cold marine water that varies in timing and strength from year to year (see curved scatter on right side of Figure 5).

In summer a subtropical high-pressure cell of dry air typically forms off the coast, capping the cool, moist marine layer. This high ensures that rain almost never falls between June and September (Figure 4), but also generates copious coastal fog. The thermal contrast of land and sea drives a daily cycle of onshore / offshore winds sensitive to local topography, moving fog inland and creating a diverse array of microclimates.

Most precipitation is rain from storm systems originating over the Pacific Ocean from October to May (Figure 4). Variable storm frequency (10 to 35 per year) accounts for most of the large annual variation in rainfall (Boughton and Pike 2013). Orographic effects produce greater rainfall at higher elevations, such that the Ventana Headwaters receives nearly twice the rainfall of the Carmel Estuary (Table 1).

[4] http://www.sanclementedamremoval.org/?page_id=60

Table 1. Mean annual rainfall 1981 – 2010 by landscape domain, from PRISM data.

Landscape Domain	Annual Rainfall (cm)	% of Total Rainfall
Ventana Headwaters	85	31.4%
Cachagua Basin	71	19.2%
Tularcitos Basin	64	21.1%
Los Padres Dam Area	61	3.5%
Santa Lucia Highlands	59	10.1%
S. Clemente Dam Area	55	2.4%
Northern Tier Tribs.	52	6.9%
Middle Carmel Valley	52	2.5%
Lower Carmel Valley	51	2.6%
Carmel Lagoon	46	0.3%

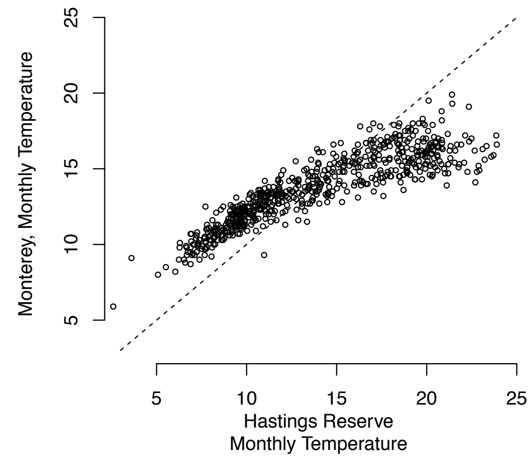

Figure 5. Mean monthly temperature from weather stations at a coastal (Monterey) and inland (Hastings Reserve) site, for the period 1959 – 2002. Dashed line shows reference condition of identical monthly temperatures inland and at the coast.

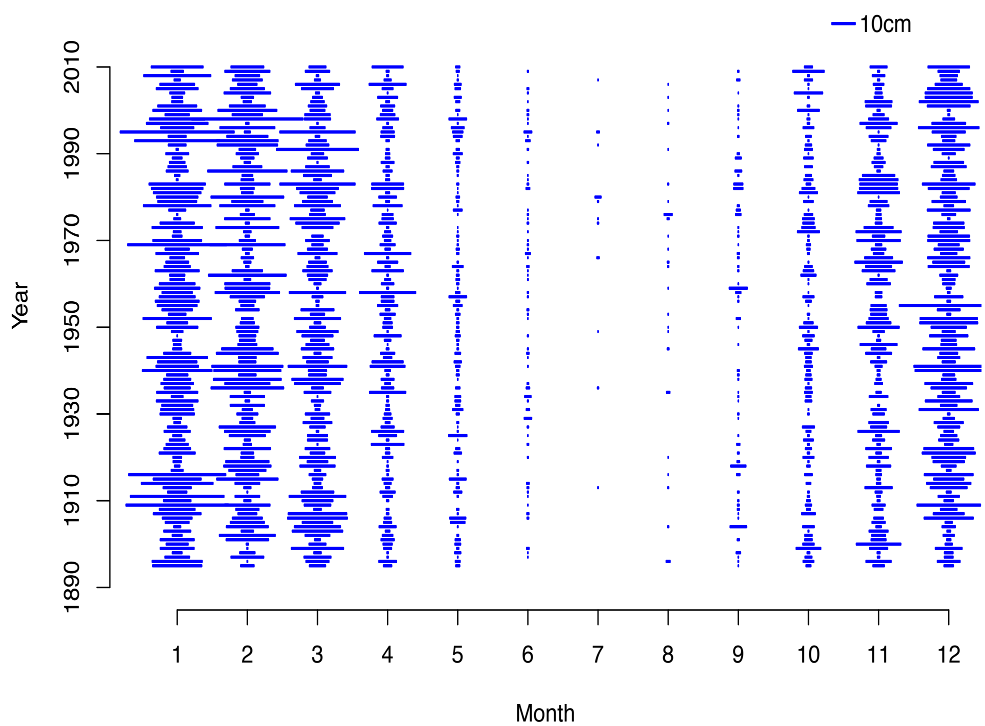

Figure 4. 116 years of seasonal and annual variation in monthly rainfall within the catchment of the Carmel River, from the PRISM dataset (Daly et al. 1994).

Models of global climate change suggest that California will retain its distinct wet and dry seasons into the future, but will warm up and perhaps develop precipitation patterns even more variable than now (Hayhoe et al. 2004, Dettinger 2005, Cayan et al. 2008, Dettinger 2011). These models do not account for regional processes, such as coastal upwelling (Stock et al. 2011), which may intensify in the future (Bakun 1990, Snyder et al. 2003). Intensification would tend to strengthen the fog regime and counteract local warming trends. Observations since the 1950s support this prediction (Schwing and Mendelssohn 1997, Mendelssohn and Schwing 2002, Lebassi et al. 2009, Iles et al. 2012), but Johnstone and Dawson (2010) show that over the longer term (100yr), fog frequency has been declining. Thus it is possible but uncertain that intensified upwelling will somewhat offset climate warming along the coast.

Wet-Season Fluvial Dynamics

Regional climate produces what has been called an episodic flow regime in coastal rivers (Kondolf et al. 2013), characterized by brief extreme peak flows after winter storms and extended periods of low flows in summer. Different physical and ecological processes dominate the wet winter and dry summer.

Streamflow

Wet-season streamflow is highly variable within and between water years. In wet years, multiple storm events produce large peak flows and streamflows remain elevated all winter, while average years tend to have lower peak flows and a shorter window of elevated discharge (Figure 6). Dry years may have virtually no baseflow between storms (Figure 6).

Los Padres and San Clemente Dams are too small to provide much flood protection—original capacity of both dams was about 0.2% of mean annual run-off at Robles del Rio gauge (USGS 11143200, near Carmel Valley Village), and would be completely filled by 7.5 days of mean February flows. Further, original reservoir capacity is currently reduced by ~65% by accumulated sediment.

Peak discharge at the Robles Del Rio gauge was measured in 1995 at over 450 cms, roughly 5 times the mean annual peak flow. Other major floods recorded at this gauge occurred in 1998, 1983, 1978 and 1958 (Figure 7). Earlier peak flows occurred in 1911, 1914 (Kondolf, 1982), 1938 and 1945. The largest appears to have been 1911, at least 480 cms (before gauge failure) and estimated at 570 cms (Kondolf, 1982).

Sediment and Channel Response

Large flows transport and rework sediment, disturb riparian vegetation, and deposit woody debris such as logs, all of which fundamentally shape channel morphology, and thus habitat structure for the river's biota. In montane streams generally, steeper channels in the upper portion of the watershed are competent to mobilize and export larger sediment particles; decreasing slope tends to decrease transport capacity and channel mobility from headwaters toward the river mouth (Montgomery and Buffington 1997). This gradient generates several important fluvial patterns:

1) A pattern of downstream fining in deposited channel sediments, from mostly boulders in the headlands to sand and silt in alluvial valleys;

2) A characteristic sequence of channel forms, from boulder cascades and step-pools in steep reaches, to cobble "plane-beds" in less-steep reaches, and pool-riffle sequences in reaches with even lower gradient; and

3) A system of sediment movement with source reaches in headwaters, transport reaches in intermediate areas, and net depositional reaches in low-gradient valleys, sometimes called "response reaches" because they respond sensitively to changes in upstream sediment supply and transport capacity.

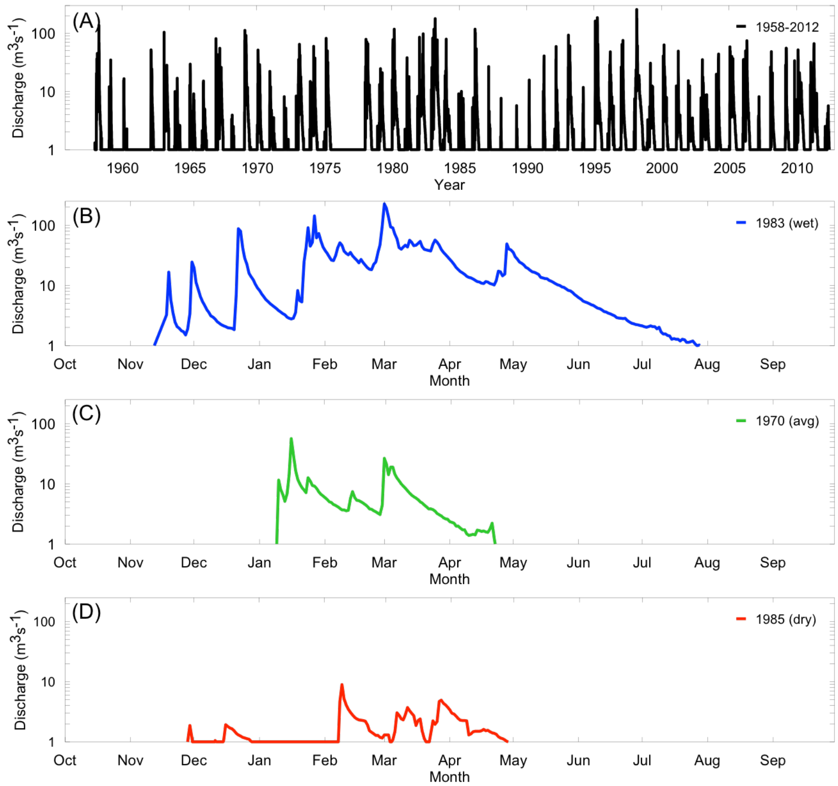

Figure 6. Mean daily discharge on the Carmel River at the Robles Del Rio stream gage (USGS 11143200). Flow data is shown for: (A) period of record (1958-2012), as well as for individual (B) wet, (C) average and (D) dry water years.

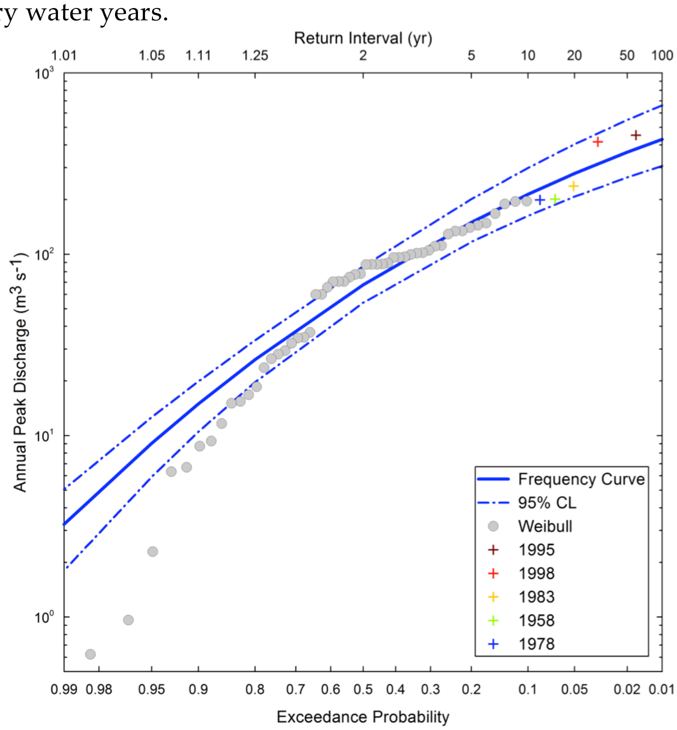

Figure 7. Carmel River flood frequency curve at the Robles Del Rio stream gage (USGS 11143200) derived from annual peak flow data for the 1956-2014 water years (three low outliers omitted from Log Pearson Type-III analysis).

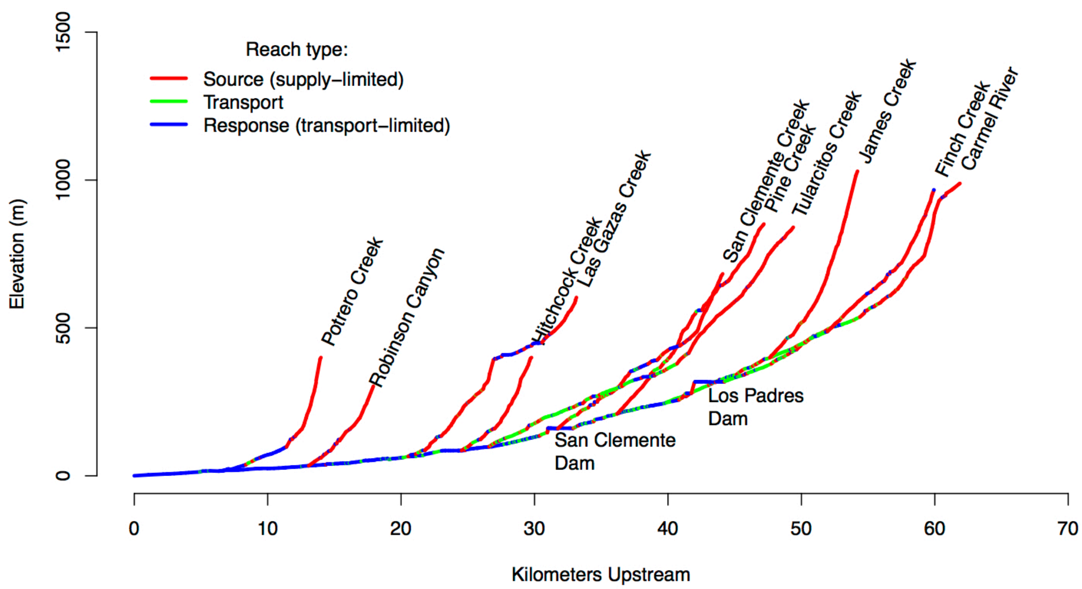

Figure 8. Longitudinal profiles of the Carmel River and principal tributaries, classified as source, transport, and response reaches according to sediment-transport scheme of Montgomery and Buffington (e.g. data summary in ENVS 660 [CSUMB Class] et al. 2012) and classifier algorithm of Flores et al. (2006).

Under this framework, the Carmel River from San Clemente Dam to the ocean is mostly a response reach (Figure 8), although the section upstream of Tularcitos Creek confluence is slightly steeper, is confined in a canyon, and functions more like a transport reach. In many coastal California landscapes, dams tend to get built on transport reaches, downstream of mountains with high rainfall and upstream of alluvial valleys with human communities. Thus their reservoirs tend to fill rapidly with sediment due to the high sediment yields off of the steep, tectonically-active mountain ranges of the region.

Most sediment in episodic rivers is moved during the largest, rare flow events, rather than annual to 2-year bank-full events, as in most hydrologic systems (Kondolf 1982, Kondolf et al. 2013). The great flood of 1911 on the Carmel River, prior to closure of San Clemente Dam (1921), generated channel movement, vegetation scouring, and extensive deposition on the alluvial floodplain (Kondolf 1982). Smaller peak flows may also generate pulses of sediment movement, especially if they follow landslides or wildfires (Florsheim et al. 1991, Hecht 1993). These types of steep, mountainous drainage basins in tectonically active areas have some of the world's highest sediment yields (Milliman and Syvitski 1992), squeezed into occasional brief windows of massive sediment movements during wet periods (Inman and Jenkins 1999).

In general, response reaches are expected to respond sensitively to changes in sediment supply from upstream and from adjacent hillslopes and floodplains (Montgomery and MacDonald 2002). The response reaches of the lower Carmel River between Tularcitos Creek confluence and the estuary have displayed such sensitivity for much of the recorded history of the valley, varying in a complex manner between primarily sandy and primarily gravel substrates and between single-threaded and multi-threaded channel morphology.

Kondolf (1982) characterized the pre-dam period as one in which the largest floods aggraded the channel and floodplain with complex layers of gravel and sand, which were then

Figure 9. Braided channel of the Carmel River, in the vicinity of deDampierre Ballfields in Carmel Valley Village.

gradually incised until the next aggradation event. The 1911 flood (before dam closure) scoured the floodplain, deposited terraces in some areas, and generated a braided channel in both the Middle and Lower Carmel Valley. In later years vegetation encroached and the river narrowed to a more incised, singled-threaded channel, first in the Lower Valley and later in the Middle Valley (Kondolf 1982). Today the only braided section is deDampierre Reach near the head of Middle Carmel Valley (Figure 9). Reaches in the lower river have incised as much as 4.3 m since dam closure (National Marine Fisheries Service 2013a). This channel evolution is attributed to a combination of no subsequent flows as large as in 1911, reduction of bed-load following closure of San Clemente Dam (Kondolf 1982), and extensive bank-hardening by local land-owners.

Various accounts from the 1950s through to 2000 indicate that in the post-dam period, the lower river was generally sand-bedded, attributed to a combination of upstream trapping of gravel behind San Clemente and Los Padres Dams, large influxes of sand (but not gravel) from Tularcitos Creek, and influxes of sand from adjacent riverbanks and floodplains due to lateral channel shifting and human disturbances.

Interestingly, since the year 2000, large sections of the lower 14 km of river have developed gravel beds for the first time in at least 50 years, significantly increasing the extent of spawning habitat for steelhead. This change appears to be driven more by a change in sand dynamics than gravel dynamics, with improved riparian and floodplain management decreasing the input of sand to the channel while flow dynamics preferentially flushed out the existing sand and reworked existing gravel into characteristic channel forms. Coring studies of sediments trapped behind San Clemente Dam suggest that even the trapped sediments there are mostly sand, with gravel comprising only 14% of total volume. Thus the episodic aggradation events referred to by Kondolf (1982) probably had a high fraction of sand, with gravel-bedded channel emerging a few years later as sand was preferentially flushed downstream to the estuary and beach.

In contrast, upstream between Tularcitos Creek confluence and the CRRDR site, the Carmel River is confined in a narrow V-shaped canyon with minimal floodplain, and lacks sand inputs from Tularcitos Creek or any other significant tributary. Thus there are no significant sources of sediment to naturally mitigate for the trapping behind San Clemente Dam. In addition, the steeper channel gradient should tend to increase the winnowing (coarsening) of the existing sediments relative to downstream areas. Consequently, the channel substrates in this section (typically cobble and boulders) are significantly coarser than substrates both downstream of Tularcitos, and upstream of the CRRDR site.

Large Wood

For most of the history of the San Clemente Dam, large wood was actively or inadvertently trapped in the reservoirs, where it eventually became water-logged and sank (MPWMD and CRWC 2004). In the largest peak flow of record in 1995, a massive deposit of wood was trapped in San Clemente Reservoir, some of which was later cut up and manipulated through the dam's arches to the river below. These smaller pieces would be less likely than whole trunks to function as geomorphic agents in the river downstream.

Currently the river appears to contain relatively little woody debris, but the degree of this apparent deprivation is uncertain. Smith and Huntington (2004) inventoried large wood in the river downstream of Tularcitos Creek confluence, and found 20.5 pieces/km. For comparison, Opperman (2005) found an average of 160 pieces/km at 32 reaches surveyed in the California Coast Ranges east and north of San Francisco Bay. These would have comparable fluvial dynamics and riparian vegetation as the Carmel River, but are much smaller streams (drainage areas of 18 ± 21 km^2, versus > 500 km^2 for the Carmel River), and would thus be expected to have greater wood frequency (Bilby and Ward 1989, Opperman 2005). ENVS 660 (2013) compared wood occurrence at 12 sites above and below San Clemente Dam and found occurrence 68% higher above the dam. This abundance was probably still unnaturally low, due to effects Los Padres Dam upstream.

CRRDR

Following the reroute, downstream patterns of sediment mobilization and deposition are expected to arise from two superimposed processes: resumption of the episodic sediment regime that occurred prior to dam construction, and mobilization of residual stored sediment in the project area—especially from the Reservoir Reach and from San Clemente Creek above its new confluence (National Marine Fisheries Service 2013a, p. 29).

Mussetter Engineering Inc. (2008) used a 1D sediment transport model (HEC-6T) to simulate patterns of erosion and deposition of the residual sediments plus an upstream sediment supply based on rating curves of the river and tributaries. Sediment transport was simulated with and without San Clemente Dam in place, spanned 41 yrs, and used historical hydrographs from wet and dry periods.

The model predicted that CRRDR would be followed by a moderate (12-14%) increase in sediment supply in the lower river, mostly of fine gravel and sand. Deposition was also modest, due to the fine texture of supply relative to the existing gravel and cobble bed. Most added sediment was predicted to move in suspension, with 74-79% stored on the floodplain during overbank floods. Between 25 and 36 acre-ft of gravel were predicted to be stored in the main channel over the 41-year simulation period. Gravel storage was greatest in the lower river where the channel gradient and transport capacity were low. Simulated mobilization and deposition did not reach equilibrium within the 41-year simulation window, and could take over a century (Mussetter Engineering Inc. 2008).

Mussetter Engineering Inc. (2008) used the best available data to project flood risks related to the dam removal. Key remaining uncertainties (acknowledged by Mussetter, 2008) include the magnitude of the residual sediment supply; inconstancy of rating curves over time, especially in the case of wildfire effects altering sediment yield (Warrick and Rubin 2007, Warrick et al. 2013); and the geomorphic response to future, pulsed sediment supply events related to extreme disturbances. Such disturbances include rainy El Niño years at the end of decadal-scale dry periods (Inman and Jenkins 1999), large atmospheric river storms (Dettinger 2011), or wildfire on upstream hillslopes followed by heavy precipitation (Florsheim et al. 1991). Such stochastic flow and sediment delivery events are characteristic of coastal California river systems and have the potential to overwhelm the relatively gradual effects expected otherwise from the CRRDR.

Channel aggradation resulting from bed-load volume (or size) that exceeds local channel bed-load transport capacity (or competence) commonly leads to sand or gravel bar growth. While river bends tend to store excess bed material on a point bar, straight river reaches can build side-attached bars or central bars. Rapid lateral point bar growth on a river bend can induce rapid retreat on the outside bank (if not currently armored with riprap), thereby undercutting shade-providing riparian trees. In straight reaches that do not currently have bank armoring, bar growth will tend to push flows against one or both banks, leading to more bank shear stress. The excess shear can then lead to stream widening, with attendant loss of riparian shade trees.

Currently, vegetation occupies a significant portion of the active channel downstream of the CRRDR site. If the outside of many of the meander bends were not hardened by local landowners, the channel would probably widen as deposits collected in the channel bottom and flow impinged on the banks. With all the hardened structure (riprap, gabions, cars, concrete rubble, etc.) that has been introduced into the banks since the 1950s, it is less clear what will happen if the sediment load increases. The channel could remain constrained and be fairly efficient at transporting sediment loads through each reach. Or streambank areas that are not currently hardened may see increased erosion potential (channel widening). Which outcome will occur after CRRDR is complete is highly uncertain.

From an ecological perspective, the most important predictions are that restoration of sediment transport out of the project site will tend to deposit gravel in channels and sand on floodplains, with the newly deposited sediment being likely coarser than the sand-dominated supply from tributaries such as Tularcitos Creek. Historical patterns and the composition of the reservoir sediments suggest, however, a transient "sand-first" model in which a mix of some gravel and mostly sand are initially laid down in extreme flow events, followed by winnowing of sand and exposure of gravel in subsequent years. In the river reach between CRRDR and Tularcitos confluence, this leads to a straightforward prediction of fining in cobble/boulder substrates; increased extent of spawning gravel over time; and increased habitat complexity beneficial to steelhead rearing (National Marine Fisheries Service 2013a, p. 72). The predictions are less straightforward downstream of Tularcitos confluence due to the confounding effects of alternate supplies of sand, and of gravel that is currently stored in the channel that is intermittently exposed by ongoing san dynamics. In addition, aggradation of the channel in this alluvial portion may drive channel widening with attendant loss of riparian shading of the water.

Dry-Season Fluvial Dynamics

Dry-season stream-flows are mainly "base-flow," discharged soil moisture and groundwater that infiltrated the ground in previous wet seasons. Base-flows generally recede through the summer at rates that vary among streams and years as a function of prior rainfall, upstream watershed conditions, and summer weather.

<u>*Intermittency*</u>

Streams are generally described as perennial if they maintain continuous surface flow and intermittent if they lose it in some places for some part of the year (Levick et al. 2008). Base-flow however is composed of both surface flow and hyporheic flow—subsurface or underflow passing through interstitial spaces in the bed substrates. Thus, many intermittent streams are simply those in which base-flow becomes completely hyporheic in some reaches for some part of the year, typically the latter part of the dry season.

Patterns of hyporheic flow are strongly linked to channel geomorphology (Wondzell and Gooseff 2013). In particular, fluvial processes that drive sediment mobilization, transport, and deposition in the wet season influence spatial patterns of intermittency in the dry season, because accumulation of sediment in the channel increases capacity for hyporheic flow, and thus increases the base-flow needed to maintain surface flow. Thus, one typically sees reliable perennial flow in headwater streams, and increasingly intermittent flow downstream where channel gradients decline and sediments accumulate (transport and response reaches; Figure 8). Examples of such "channel-based" intermittency in the Carmel River system are riffles in low-gradient pool-riffle sequences (lower Carmel Valley), alluvial fans where channels exit V-shaped canyons into alluvial valleys (confluence of Garzas Creek; deDampierre Reach; Figure 9), and the relatively featureless plane-bed morphologies that typically occur in transport-reaches (lower sections of Tularcitos and Cachagua Creeks). Such features are often the first to lose surface flow each summer. When drying is early enough to impede movement of juvenile, smolting, or adult steelhead such features are often called "critical riffles."

Aquifers

California's characteristic landscape of mountain ranges interspersed with broad alluvial valleys creates an additional "aquifer-based" type of intermittency. Mountain creeks typically flow through V-shaped valleys where surface flow and subsurface capacity are of similar order, and channel-based intermittency dominates. Alluvial valleys in contrast often have vast subsurface capacity relative to the flow of the river, and patterns of intermittency are driven mostly by the water-balance in the aquifer. This process operates at a broader spatial scale than channel-based intermittency, often drying up many kilometers of channel very quickly, killing fish and other aquatic biota.

The Carmel River corridor transitions from V-shaped canyon to alluvial valley a few kilometers downstream of San Clemente Dam and overlays aquifers in Middle and Lower Carmel Valley (Figure 1). Unusual among California valleys, an additional bedrock sill occurs near the river mouth, naturally protecting the lower aquifer from seawater intrusion. In high-rainfall years the aquifers' water tables may begin the summer higher than stream stage and contribute significantly to flow in the early part of the summer (Kondolf et al. 1987), effectively deferring intermittency to later in the summer. In low-rainfall years a dry section often appears near the estuary in late spring or early summer. Groundwater pumping by water users significantly increases the occurrence of dry channel and is one of the principal anthropogenic impacts on the river, typically drying up 8 miles of the lower river by July of each year (National Marine Fisheries Service 2013a). In Water Year 2014, the combination of two dry years plus groundwater pumping prevented surface flow from reaching the estuary at any time in both the wet and dry season.

Water table depth and channel geomorphology also have important effects on riparian plant communities. Rooting depth varies among species, so that maximum distance to the water table tends to structure riparian plant communities in the California Coast Ranges (Bendix 1999). Vegetation, especially riparian trees such as willows and alders, in turn create a feedback loop on geomorphology by hardening banks. Dropping the water table enough to kill these species leads to bank failure and rapid channel widening in subsequent wet seasons (Kondolf 1982), which in turn reduces the sediment transport capacity of the channel, tending to deposit more sand, aggrade the channel, and increase the flow needed to prevent intermittency, creating a weak positive feedback loop. Groundwater pumping combined with severe drought in the late 1970s triggered this sort of channel response near Boronda Road in Lower Carmel Valley (Kondolf 1982), but improved groundwater and vegetation management in subsequent years allowed woody vegetation to recover and the channel has since narrowed.

Dam Effects

San Clemente Dam has had three general effects on dry-season steelhead habitats downstream: as a mechanism for altering summer flows via dam releases, through its effects on downstream water quality, and through its effects on downstream geomorphology described in the previous section. Previous to the mid-1980s, Cal-Am often released no flow from San Clemente Reservoir to the downstream reaches in summer and it was only leakage through the dam that provided flow. Water quality is reduced because the unshaded alluvial channel through reservoir sediments heats up the river, and algal growth in the remnant reservoir is transported downstream.

Effects downstream occur via wet-season processes but often express themselves in distinct ways in the dry season, especially in patterns of surface flow and stream temperature, as well as the patterns of habitat complexity and food-web dynamics that are important in both wet and dry seasons. Due to the sensitivity of surface flow and water temperature to aquifer dynamics, any historic effects of San Clemente Dam or predicted effects of the CRRDR need to be interpreted within the context of ongoing changes in aquifer management in middle and lower Carmel Valley. A relatively concise summary of this complex topic can be found in National Marine Fisheries Service (2013a), p. 51.

Ecology of the Riparian-Fluvial Corridor

Generally, the biota of stream banks and stream channels are tightly integrated. Riparian vegetation influences sunlight penetration and instream primary productivity (Vannote et al. 1980); whereas baseflow and the water table affect the composition and productivity of riparian vegetation (Kondolf 1982, Bendix 1999). Movements of invertebrates link aquatic and riparian food webs (e.g. Rundio and Lindley 2008). Vegetation stabilizes banks and influences stream width, depth, and sediment transport potential (Kondolf 1982), while its composition is in turn influenced by patterns of unit stream power and sediment deposition (Bendix 1999).

Large Wood

Large woody debris in the channel typically interacts with stream flows and sediments to create complex habitats that are beneficial for many fish species: by scouring pools in shallow channels (Thompson et al. 2012), providing visual cover (protection from predators), flow complexity (high-quality feeding options), nutrients, and fine-grained heterogeneity in substrates (suitable for spawning, benthic feeding, hiding, etc. in close proximity). Redwoods and other conifers produce long-lasting, high-quality woody debris; but have restricted distribution in the Santa Lucia Mountains. Hardwoods such as oaks and alders provide more widespread but less persistent woody debris (Opperman and Merenlender 2004, Opperman 2005).

Woody debris appears to be naturally rare in arid chaparral river systems such as the Carmel. However, stream-side rock outcrops or large boulder fields may generate similar habitat elements that are used by steelhead (Boughton et al. 2009). Large, stream-side outcrops are distributed throughout the Carmel River downstream of San Clemente Dam, where they create deep bedrock-forced pools.

Biotic Diversity

Invertebrate diversity appears to partially reflect the diversity of physical habitat. A 10-year study of benthic macroinvertebrate communities at 7 sites in the Carmel River (King et al. 2010) found that the Index of Biotic Integrity (IBI, a measure of ecological integrity; Ode et al. 2005) was related both to substrate composition and reach position in the stream network. IBI was highest above Los Padres Dam, the lowest at two sites below Los Padres and San Clemente Dams respectively, with IBI gradually increasing further downstream of San Clemente Dam. This overall pattern suggests a strong negative influence of the dam beyond its effects on substrate. Near the dams mean IBI was about 40% of the reference site above Los Padres Dam and at the best sites in lower Carmel Valley, mean IBI was still only 64% of the reference (King et al. 2010, fig 2).

Riverine biota in California must contend with the physical variability and extremes characteristic of episodic rivers in mediterranean climates (Gasith and Resh 1999, Grantham et al. 2010). Such naturally dynamic flow regimes are hypothesized to benefit native fish and amphibian assemblages, where life histories are synchronized with local flow dynamics, and restrict the distribution and abundance of alien species which are largely unable to cope with hydrologic conditions that differ from those to which they are adapted (Moyle and Light 1996, Fausch et al. 2001).

This structuring of biotic communities by physical processes provides a basis for managing the capacity of the watershed to support multiple species, by managing fluvial processes to produce dynamic habitat templates that favor desired species, and disfavor undesired species (Poff and Ward 1990, Ebersole et al. 1997, Poff 1997). To develop such management strategies, Ebersole et al. (1997) suggested the following steps: 1) identify historical patterns of habitat development; 2) identify key limiting habitats and constraints on habitat-forming processes; 3) relieve those constraints; 4) classify sensitive, critical, or refuge habitats; 5) protect process diversity that remains; and 6) monitor the biotic responses to habitat development.

Aquatic vertebrates listed as resources for the Carmel River system include both native and alien species (Table 2). Most are generalist predators with indeterminate growth, eating prey of progressively larger sizes through their life cycle but otherwise specializing not on different prey but on different habitat characteristics. These characteristics include substrate, streamflow, temperature, and positions in the channel or off-channel. Habitat specialization corroborates the idea that aquatic community structure should largely reflect the wet-season and dry-season fluvial processes that organize physical and vegetative structure.

Problematic Aliens

A few alien species are both ecologically and taxonomically similar to native threatened species, and deserve more targeted management. In particular, the introduced brown trout (*Salmo trutta*) has ecological requirements similar, but not identical, to *O. mykiss*, differing mainly in an earlier breeding season (November-December) and slightly longer life span. *S. trutta* is established in the river above Los Padres Dam, where it almost certainly competes with and preys on *O. mykiss* (and vice-versa). It is occasionally observed lower in the river and it is possible that *S. trutta* will benefit from CRRDR in similar ways as *O. mykiss*, potentially expanding downstream and creating unintended impacts on *O. mykiss*. However, the river system of Arroyo Seco just south of Carmel watershed also has had *S. trutta* established in its headwaters for at least 30 yrs (Indians Campground/Memorial Park area), and they appear not to have expanded downstream despite a lack of dams.

The alien bullfrog *Lithobates catesbiana* and the native California red-legged frog *Rana draytonii* are both ranids with similar but not identical ecological requirements and life-histories. Interactions between bullfrogs and the federally-listed California red-legged frog have been cited as major contributors to the latter's decline in the Carmel River and elsewhere (Fisher and Shaffer 1996, USFWS 2002).

Bullfrogs (*L. catesbeiana*) were introduced to California in the late 1800s and early 1900s (USFWS 2002) and have been documented in pools and lentic-like habitats throughout the Carmel River watershed (Smith et al. 2004). They are opportunistic feeders known to prey on both adult and larval life-stages of native ranid frogs (Twedt 1993, Kupferberg 1995). Moreover, empirical studies have demonstrated that bullfrogs frequently outcompete red-legged frogs for limiting resources (e.g., food and/or space) because of their comparatively larger size. Using controlled experiments, Lawler et al. (1999) demonstrated that $< 5\%$ of California red-legged frog tadpoles survived to metamorphosis in habitats co-occupied by bullfrogs, and that the presence of bullfrogs significantly delayed red-legged frog growth and development (i.e., metamorphosis).

Consequently, bullfrog eradication is among the current enhancement actions for California red-legged frogs that is implemented in the Carmel River basin. Eradication, coupled with active tadpole rescue and relocation efforts (conducted annually during summer since 2003), appears to be enhancing recruitment of red-legged frogs at established monitoring sites (Froke 2007, SEIR 2012).

Table 2. Aquatic vertebrates reported in Carmel River watershed (Morley et al. 2008)

	Family	**Species**	**Origin**
Fishes			
	Centrarchidae	Green sunfish (*Lepomis cyanellus*)	Alien
		Bluegill (*Lepomis macrochirus*)	Alien
		Largemouth bass (*Micropterus salmoides*)	Alien
	Cottidae	Coastrange sculpin (*Cottus aleuticus*)	Native
		Prickly sculpin (*Cottus asper*)	Native
		Pacific staghorn sculpin (*Leptocottus armatus*)	Native
	Cyprinidae	Goldfish (*Carassius auratus*)	Alien
		Common carp (*Cyprinus carpio*)	Alien
		Hitch (*Lavinia exilicauda*)	Native
		Sacramento blackfish (*Orthodon microlepidotus*)	Native
	Embiotocidae	Shiner perch (*Cymatogaster aggregata*)	Native
	Gasterosteidae	Threespine stickleback (*Gasterosteus aculeatus*)	Native
	Ictaluridae	Black bullhead (*Ictalurus melas*)	Alien
	Moronidae	Striped bass (*Morone saxatillus*)	Alien
	Petromyzontidae	Pacific lamprey (*Entosphenus tridentatus*)	Native
		River lamprey (*Lampetra ayresi*)	Native
	Pleuronectidae	Starry flounder (*Platichthys stellatus*)	Native
	Poeciliidae	Western mosquitofish (*Gambusia affinis*)	Alien
	Salmonidae	Brown trout (*Salmo trutta*)	Alien
		Steelhead trout (*Oncorhynchus mykiss*)	Native
Amphibians			
	Bufonidae	Western toad (*Anaxyrus boreas*)	Native
	Hylidae	Pacific treefrog (*Pseudacris regilla*)	Native
	Ranidae	California red-legged frog (*Rana aurora draytonii*)	Native
		American bullfrog (*Lithobates catesbeiana*)	Alien
	Salamandridae	California newt (*Taricha torosa*)	Native
Reptiles			
	Emydidae	Pacific pond turtle (*Actinemys marmorata*)	Native

Data from rescues and monitoring has suggested a conceptual model for the co-existence of the two species (D. Reis, personal communiction). The native has a slightly earlier breeding season than the alien (Mar – Apr vs. May – July), and its tadpoles can transform by early fall while the alien typically requires 2 seasons. These life history traits allow red-legged frogs to escape impacts of bullfrogs by exploiting temporary ponds and side channels that are not suitable for bullfrogs because they dry up in the late summer or fall (D. Reis, pers. comm). This suggests a metapopulation-level mechanism for co-existence, in which *L. catesbiana* excludes *R. draytonii* from otherwise highly suitable permanent ponds, while *R. draytonii* depends on more marginal habitats less ideal for them, but completely unsuitable for the alien (Figure 10).

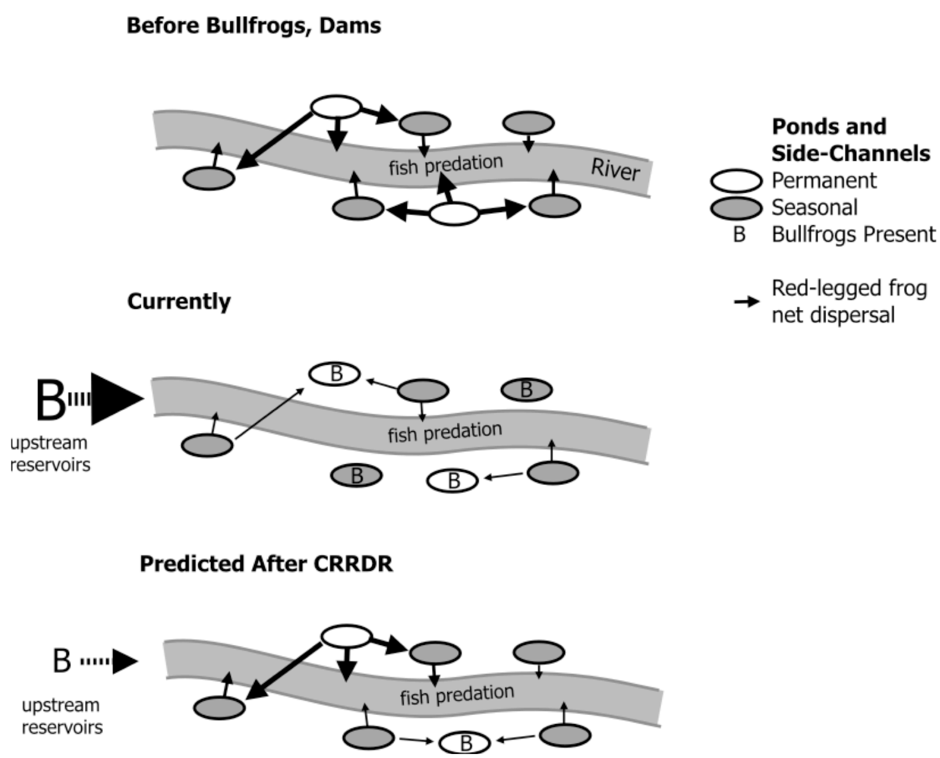

Figure 10. Conceptual model for source-sink dynamics in breeding/tadpole habitat of California red-legged frog (*R. draytonii*), along the middle and lower Carmel River.

Exceptionally large populations of bullfrogs occupy both San Clemente and Los Padres Reservoirs, as well as the deDampierre Reach of the Carmel River near Carmel Valley Village (D. Reis, personal communication). These likely function as source populations to downstream habitats, maintaining greater numbers and sizes of bullfrog populations downstream than would otherwise occur, and fewer red-legged frog populations (Figure 10, middle). CRRDR is expected to eliminate the source population in San Clemente Reservoir, which should reduce the incidence of bullfrogs downstream, allowing the incidence and abundance of red-legged frogs to expand (Figure 10, bottom). Incidence of bullfrogs is predicted to decline the most in seasonal habitats, which cannot support the 2-year tadpole stage of bullfrogs and thus functions as a true sink totally dependent on immigration. A key uncertainty is whether eliminating only the San Clemente bullfrogs, while leaving the Los Padres and deDampierre populations, will be sufficient to provide a biologically significant benefit for red-legged frogs.

Striped bass (*Morone saxatilis*) are another problematic alien, especially in the lower Carmel River and lagoon. Striped bass were originally introduced from the eastern USA to the Sacramento-San Joaquin estuary as a sport fish by the Fish and Game Commission in 1879. As an anadromous species capable of marine migration, striped bass are now regularly encountered in California's coastal waters and estuaries, though few permanent (i.e., reproducing) populations have been established outside of the Sacramento-San Joaquin drainage (Moyle 2002). Recent observations and collections in the Carmel River lagoon have confirmed the presence of significant numbers of striped bass. For example, CDFG (2011) reports that approximately 100 adults were harvested from the lagoon by anglers in just 143 hours of fishing effort in 2010.

The ecological consequences of striped bass in the lower Carmel River system are not clear.

Striped bass consume a range of invertebrate and fish species and are almost exclusively piscivorous (fish-eating) once they reach approximately 250 mm in length (~age 2; Stevens 1966, Lindley and Mohr 2003). Given that the lagoon serves as important habitat for multiple steelhead life-stages, and that a proportion of fish rescued annually from dewatered reaches are translocated to the lagoon, the presence of significant numbers of predatory striped bass could presumably adversely affect steelhead production. Unfortunately, a lack of data concerning striped bass distribution, abundance, and life-history diversity in the Carmel River watershed precludes robust assessments of predation impacts and potential reductions in steelhead viability.

Estuary Dynamics and History

Like most smaller estuaries in California, the Carmel estuary becomes a closed seasonal lagoon in the dry season, generated by the formation of a large permeable sandbar at the beach (Figure 11). The lagoon typically remains closed with a perched water table through the beginning of the wet season but usually breaches in response to winter storms or human intervention, cycling back to a true estuary.

Morphologically the estuary consists of the high flow channel of the river and three arms (Figure 11). The Odello Arm was created and South Arm deepened by restoration projects in 1997, and a dry remnant of South Arm was further excavated in 2004 as part of the Carmel River Lagoon Enhancement Project. Goals of these projects were to increase volume, and thus generate more habitat for steelhead and the California Red-legged Frog.

Estuary substrate is sand in the main body and silt and organic material in the arms. Surrounding areas support wetland species of tules (*Scirpus californicus*) and rushes (*Juncus balticus*) (National Marine Fisheries Service 2013a). Average bottom elevation is above mean sea level, and tidal range is low, creating a micro- or meso-tidal lagoon. Morphology, water depth and area, and water quality are all strongly influenced by dynamic interactions of river flows, groundwater, the Pacific Ocean, and hydraulic effects of the tidal channel over or through the sandbar.

Sandbar dynamics

Formation and breaching of the sandbar is the fundamental control on estuary condition. Sandbar dynamics stem from the interplay of four basic factors: upstream sand supply, marine sand supply, river transport capacity during high flows, and tidal transport capacity during low flows (National Marine Fisheries Service 2013a). At low flows, tidal transport capacity typically dominates, moving sand from ocean to estuary and closing the bar (National Marine Fisheries Service 2013a). However, moderate to large river flow can rapidly open the lagoon, because sediment transport is typically a power function of discharge (Chang 1997). The bar may quickly reform after storm-flows recede, especially in dry winters.

In general, sediment supply on the marine side of estuaries is strongly influenced by longshore transport (LST) and cross-shore transport (CST) of sediment due to wave action. In an embayed beach such as the Carmel River mouth, CST is usually more important (Ranasinghe et al. 1999). Wave action during storms may erode the beach and create a bar in the breaker zone, only to have the process reverse during gentler swells (Dean and Walton 1974).

Figure 11. Carmel Lagoon on 5 June 2009, showing summertime phase with sandbar barrier and elevated water level; main body, North Arm, South Arm and Odello Arm; and the Carmel Area Wastewater District plant south of a bend in the low-flow channel. Data source: NAIP imagery

Wet Season

The highest stages of the lagoon generally occur in the early wet season, when rainfall reestablishes surface flow in the lower river that gradually fills the lagoon and transforms it from brackish to freshwater. Casagrande et al. (2002) observed that during this transformation in 2001, temperatures dropped, DO increased, and salinity dropped in the top 2m of water. This reconnection also allows juvenile steelhead to once again move between the lagoon and the rest of the river.

High tides coinciding with large westerly swells may also raise the level by overtopping the sandbar. Tidal overwash can cause stratification, with bottom layers of saline and anoxic water forming in the deeper sections of the lagoon, such as the South Arm (Alley 1997).

Early in the rainy season, the County mechanically breaches the sandbar to prevent rising lagoon levels from flooding homes at the northern edge of the wetlands area (D Duffy and Associates 1998). Casagrande et al. (2002) found that within 3 days of one such breach, temperatures increased, DO dropped, and bottom salinity increased, factors that are expected to be detrimental to steelhead

After breaching, lagoon water level fluctuates with tides and ocean swells. In this condition 90% of the lagoon is 30-60 cm deep, making rearing steelhead vulnerable to avian predators.

<u>Dry Season</u>

As river and groundwater inflows decline in the early dry season, wave action builds up the beach and recloses the river mouth. James (1994) found when inflows go below 8 cfs, the water level in the lagoon gradually lowers, until the water surface elevation matches the local water table. Upstream diversions and aquifer depletion typically cause the lower river to lose surface flow around July, at which point movement of steelhead is prevented between the estuary and upper river. Thus in late summer the lagoon is isolated and its volume depends on groundwater levels in the lower aquifer, which are in turn influenced by upstream pumping (Feeney 2003).

Water surface elevation can also be influenced by the ocean, via sub-surface flow through the sandbar and waves over-topping the sandbar (Perry et al. 2007). Because seawater is denser than freshwater, it sinks and collects in the deep locations, forming stratified lenses of fresh and saline water. Due to lack of mixing and surface exposure, the saline layer typically becomes anoxic and warm, excluding steelhead and preventing benthic foraging. At high lagoon stage, the hydraulic gradient may get reversed, and lagoon water will flow into the surrounding groundwater (Watson and Casagrande 2004).

<u>CRRDR</u>

According to National Marine Fisheries Service (2013a, p. 47), the trapping of sediment behind San Clemente Dam has reduced the volume of sediment being transported to the lagoon. In combination with artificial management of the barrier sandbar, this has altered annual cycles of bar migration and reduced the amount of sand at the barrier beach. Potential effects of this reduction are lower bar height and smaller lagoon volume, prevention of bar closure, and increased number of seasonal breaches from wave overtopping or river flows. All these potential effects would be expected to negatively affect steelhead.

CRRDR is expected to increase sediment input to the lagoon, primarily sands. This may raise the crest of the sandbar, but may also aggrade the bed of the lagoon, so the net effect on lagoon volume is uncertain. A raised sandbar crest may increase resilience of the lagoon habitat by reducing inputs of saltwater from overtopping waves, and reducing the vulnerability of the lagoon to sandbar breaches that prematurely drain it, both of which would improve habitat quality for juvenile steelhead. However, a raised crest might also increase the need for breaching as a management tool to protect nearby homes from flooding. If both the bed and the crest of the lagoon are raised by the new sediment regime, necessitating increased breaching for management purposes, the net effect on lagoon volume may be negative.

Aggradation may tend to be focused in the arms rather than the main channel due to scour in the latter arising from the funneling of flow events through Highway 1 bridge. Thus CRRDR might accelerate the filling-in of these arms. Long-range plans for restoration include replacement of the southern approach to the bridge with a causeway, allowing floodwaters to naturally scour the southern and Odello arms. In summary, there are numerous uncertainties about effects of CRRDR on the bathymetry of the estuary/lagoon system, including uncertain interaction effects with current management practices and planned restoration projects.

Steelhead Population Viability and Dam Removal

Life-History

Steelhead populations in coastal California tend to be composed of fish of three fundamental life-history types: freshwater resident, fluvial-anadromous, and lagoon-anadromous (Smith 1990, Bond 2006, Bond et al. 2008, Hayes et al. 2008). Freshwater residents spend their entire life cycles in the river system and are commonly known as rainbow trout. Anadromous *O. mykiss* mature in the ocean but migrate up rivers to spawn, and are commonly known as steelhead.

The co-existence of individuals with resident and anadromous life histories in the same population is called partial migration, and is believed to have been originally widespread along the southern California coast (Boughton et al. 2006). Currently freshwater residents of native lineage are widespread and reasonably abundant on the south coast (Clemento et al. 2009), whereas the anadromous form is rare and is listed under the US Endangered Species Act. A proximate goal of recovery plans is to increase the abundance of anadromous *O. mykiss*, but the fundamental goal is to secure its long-term persistence in the ESU, which involves maintenance of partial migration (Boughton et al. 2007a).

Fluvial-anadromous *O. mykiss* hatch in late spring from eggs deposited in gravel substrata. They then spend 1 to 3 years in rivers and creeks, before physiologically and morphologically transforming into a salt-water tolerant form known as smolts. Smolts migrate to the ocean in late spring, mature for 1-4 years, and then usually migrate back to natal rivers to spawn after January-April rain storms.

Lagoon-anadromous fish are similar to fluvial-anadromous individuals, but spend their first, second, or (more rarely) third summer in an estuary (Hayes et al. 2008), where they often achieve exceptionally rapid growth that improves their subsequent survival in the ocean (Bond 2006).

What processes maintain partial migration? Partial migration in salmonids is a broad and complex topic (see recent reviews by Satterthwaite et al. 2009, Sloat et al. 2014, Kendall et al. 2015), but a fundamental concept is that steelhead are evolutionarily selected to express a conditional strategy, in which the timing of smolting and maturation (and their sequence) in individual fish is determined by physiological thresholds related to growth history, body size, and stored biochemical energy.

Additional general themes of partial migration are: 1) Anadromy is tied to the ability of females to achieve larger body sizes, and thus greater fecundity, in the ocean; yet exceptionally rapid growth in freshwater might sometimes select for freshwater maturation. 2) Partial migration is linked to the relative survival and amount of energy acquisition in different habitats, and thus conditional thresholds are likely to be locally selected, varying geographically according to selection pressures. 3) Males are under distinctly different selection pressures than females, often favoring resident life-histories for males. 4) In California the advantages of anadromy are linked to productive marine conditions associated with coastal upwelling, which varies greatly in time and space.

A focus on growth and body sizes that trigger smolting (Satterthwaite et al. 2009) is useful because it produces clear management guidance on the importance of habitats supporting rapid growth of juvenile steelhead. But this framework is clearly incomplete, not addressing partial migration in males, genetic differences between anadromous and resident forms (Pearse et al. 2014), frequency- and density-dependent growth rates, and selective factors specific to southern California, such as small asymptotic body sizes of resident rainbow trout (Satterthwaite et al. 2010), uncertainty in migration opportunities (due to drying streams, closed lagoons owing to mouth sand berms), and dynamic freshwater habitats that may select for within-stream movements of parr. These within-stream movements may involve their own set of contingent strategies (Satterthwaite et al. 2012). In general, we conclude:

- That benefits of CRRDR on the Carmel River steelhead population must be assessed in a

way that highlights effects on the anadromous component of the population;
- That these effects involve conditional-threshold strategies and are likely to be subtle and complex, involving growth rates, lipid storage, freshwater feeding, local fish density, freshwater movements prior to smolting, and genetic components;
- Therefore the effects of CRRDR on steelhead need to be assessed empirically, in terms of smolt production and anadromous run size, rather than simply as changes in the numbers or densities of *O. mykiss* in reaches affected by the dam.

Viability

Viability is "the survival of a population in a state that maintains its vigor and its potential for evolutionary adaptation" (Soulé 1987, p. 1). In the conceptual framework used by NMFS for recovering Pacific salmonids, the basis for viability is sufficient levels of abundance, productivity, spatial structure and diversity within and among populations (McElhany et al. 2000).

Greater abundance results from measures that increase the capacity of the habitat template for each life-stage (Mobrand et al. 1997, Scheuerell et al. 2006). Capacity can be increased by managing fluvial processes to release constraints on habitat-forming processes, especially for "limiting" habitats that act as bottlenecks during life-history (Ebersole et al. 1997). Capacity can also be increased by providing access to previously inaccessible habitat, for example by providing passage around migration barriers.

Productivity is the ability of a population to rapidly recover after some impact has reduced it below capacity, and is often improved by taking measures that increase survival and/or growth rate within each life stage, usually by improving habitat quality (Scheuerell et al. 2006). A key aspect of freshwater habitat productivity in coastal steelhead populations is competence to support rapid growth in juvenile *O. mykiss* (Hayes et al. 2008). Habitats with this competence tend to disproportionately contribute to anadromous production (Bond 2006).

Habitat-forming processes tend to support productivity by matching habitat conditions to species adaptations, and mismatching it to invasive species that may prey on or compete with salmonids. In episodic rivers, conditions may be naturally quite variable and frequently challenging for steelhead. Disturbances (e.g. landslides, floods) may create short-term impacts on productivity (poor water quality, scour) but longer-term benefits for productivity or abundance (extensive, high-quality gravel beds). In addition, certain habitats such as intermittent streams may be quite poor quality in dry years, and quite productive in wet years. Thus productivity and capacity must be understood within the context of habitat-forming processes over the long term, rather than under current conditions.

Spatial structure is the occurrence of suitable conditions in multiple parts of the stream network, supporting the same life-stage of the species and connected by movement corridors. Spatial structure increases viability by establishing redundant, accessible habitat patches during each life-stage.

Diversity includes inter-related concepts of genetic, habitat, and life-history diversity. A stream network supports diversity if spatial structure provides diverse habitats for particular life-stages and multiple life-history pathways through the habitat template. Genetic diversity maintains the species' capacity to exploit these diverse pathways.

The Habitat Template

The historical habitat template of a species is the long-term regime of natural environmental heterogeneity in space and time to which the species is adapted (Poff and Ward 1990). In order to apply this concept it is useful to map the four viability components described above to corresponding aspects of habitat (Table 3). From this mapping one can then use knowledge about effects of San Clemente Dam on habitat to generate predictions about the benefits of its removal for steelhead. In particular, the complex life history of *O. mykiss* confers vulnerability due to the need for a specific sequence of connected habitats—a break at any link of the sequence

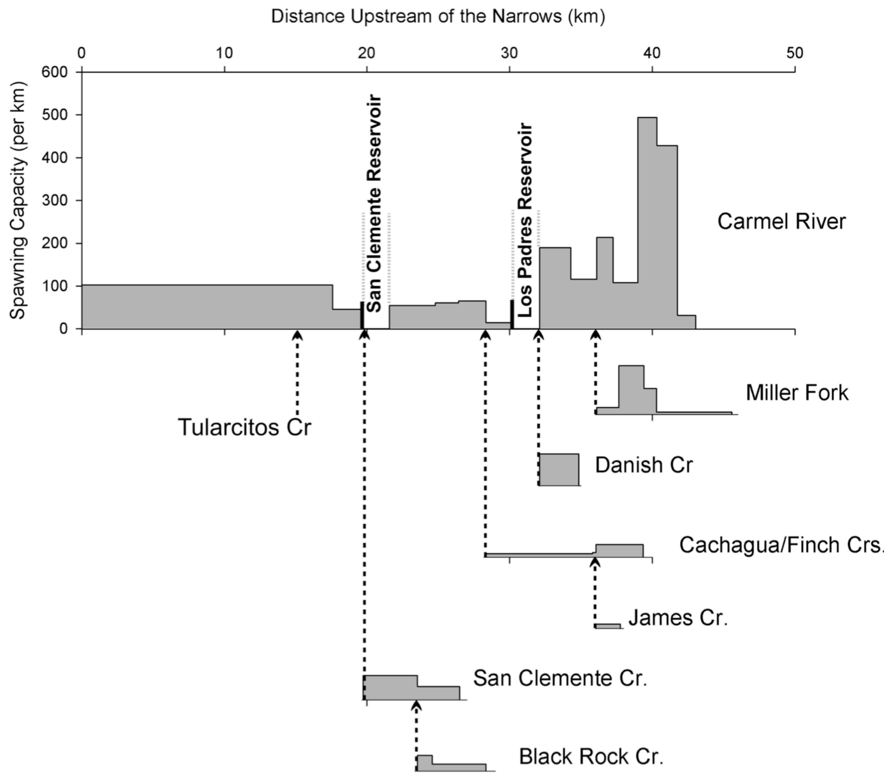

Figure 12. Distribution of spawning habitat in Carmel River and selected tributaries, from 1989 surveys by MPWMD (Daly et al. 1994). Spawning capacity estimated from area of stream channel with suitable gravel size.

prevents completion of the life-cycle. The viability concept thus implies a need for habitat templates that provide large areas of high-quality, diverse habitats for each life stage, highly connected by movement corridors (Table 3). Ecological connectivity refers to the capacity of movement corridors to allow fish to realize the benefits of spatial structure, habitat diversity, and multiple life-history pathways. This emphasis—on not just large areas of high-quality habitat, but also on diverse and ecologically connected habitats within a context of characteristic disturbances that kill fish but improve habitat—constitutes an updated view of viability that has strongly informed the rationale behind the CRRDR project.

Table 3. Components of viable salmonid populations, mapped to the habitat template

Salmonid Population	**Salmonid Habitat**
Abundance	Capacity / area
Productivity	Habitat quality
Spatial Structure	Ecological connectivity of multiple habitat patches
Diversity	Diverse selection pressures, diverse habitat-forming processes

Predicted Benefits of CRRDR

CRRDR is expected to improve the habitat template primarily by 1) creating new habitat at the project site, 2) improving upstream-downstream connectivity in ways that affect downstream habitat, namely dynamics of coarse sediment and large wood, 3) improving water quality downstream of the site in summer, and 4) improving ecological connectivity at the site. There are less predictable impacts involving the complex interplay between bed geometry (e.g. pool scour or aggradation) on the presence and intermittency of dry season base flow. Below we review the most likely ways that these predicted benefits will release constraints in the habitat template.

Spawning Capacity

Successful spawning and egg incubation in *O. mykiss* requires patches of gravel with grains 5 to 74 mm diameter (Kondolf and Wolman 1993), and sufficient porosity and bed-forms to promote through-gravel flow, which keeps eggs and fry oxygenated (Quinn 2005). Convex bed-forms, such as the tail-outs of pools, are valuable because, as regions of high bed shear stress, they promote through-gravel flow.

In general, fluvial mechanisms would tend to generate gravel-bedded channels mostly in transport and response reaches (Boughton et al. 2009). Thus, most spawning gravel should occur in the Carmel River downstream of a point about 10km upstream of Los Padres Reservoir, and in parts of Cachagua and Tularcitos Creeks (Figure 8). The lowest-gradient response reaches are susceptible to sand-rich sediment pulses that can last for several years following strong El Nino winters (or fire responses) that flush out sand stored in tributary watersheds, especially the Tularcitos. The most recent example (1998 El Nino) produced a pulse of sand from Tularicitos Creek that covered the lower Carmel River bed with sand until approximately 2006, thereby greatly limiting the local availability of spawning habitat.

An extensive survey of spawning habitat in 1989 (Jones & Stokes Associates 1998) revealed that spawning gravel is indeed extensive for 10km upstream of Los Padres Reservoir, but is markedly less extensive downstream, with the lowest capacities just downstream of the two dams (Figure 12). This supports the idea that bed-load-trapping in the reservoirs has reduced spawning capacity downstream, where boulder lag deposits have formed. The low capacity just below Los Padres Dam ticks upward at the confluence of Cachagua Creek, suggesting that this tributary injects significant gravel that somewhat mitigates the effect of Los Padres Dam. While it might be expected that Tularcitos Creek plays a similar role downstream of San Clemente Dam, this creek drains an area with soft sedimentary rocks and contributes sand and small gravel (Smith et al. 2004).

Spawning capacities above and below San Clemente Dam appeared comparable in 1989 (Figure 12), but more recently the National Marine Fisheries Service (2013a) concluded that

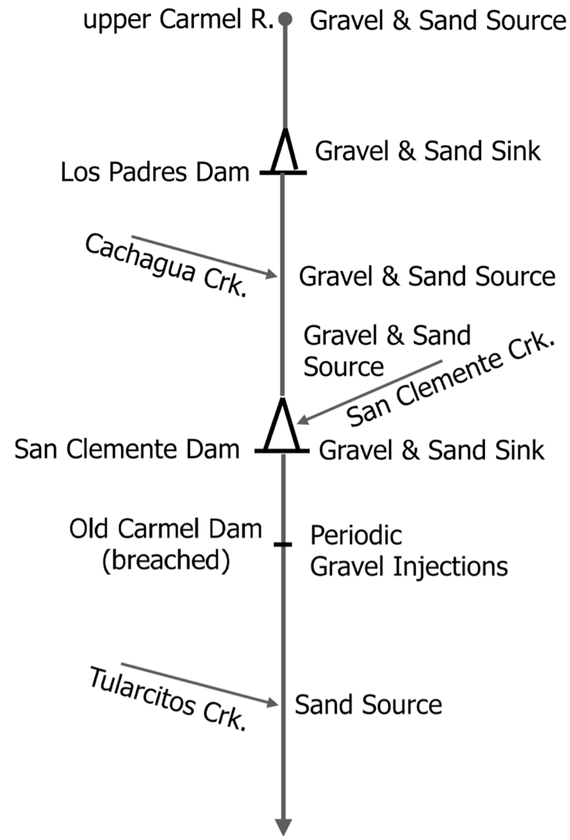

Figure 13. Schematic of gravel sources and sinks in Carmel River in vicinity of San Clemente Dam prior to the re-route.

Table 4. Predicted response of habitats to CRRDR, and designation of control and impact reaches

Reach	**Current Substrate**	**Current Habitat***	**Predicted Response**	**Predicted Habitat[1]**	**Control/ Impact[2]**
Above LPD	Diverse	Sp + R	None	Sp + R	C3
LPD to Cachagua	Cobble/Boulder	R only	None	R only	C2
Cachagua to CRRDR	Diverse	Sp + R	None	Sp + R	C
Reservoir Reach	Sand	R only	Coarser, More Diverse	Sp + R	I0
CRRDR to Tularcitos	Cobble/Boulder	R only	Finer, More diverse	Sp + R	I
Tularcitos to Robinson	Sand/Gravel	Sp + R	More gravel[4]	Sp + R	I2
Robinson to Schulte	Sand/Gravel	Sp + R[3]	More gravel[4]	Sp + R[3]	I3
Schulte to Hwy 1	Sand/Gravel	Sp + R[3]	More gravel[4]	Sp + R[3]	I4

[1] Sp = spawning habitat, R = rearing habitat.

[2] I*x* = downstream "impact" reaches expected to respond to CRRDR; C*x* = upstream "control" reaches expected to show background variation but no direct response to CRRDR.

[3] Rearing compromised - Normally dries up in summer due to aquifer depletion.

[4] More gravel on average, but highly dynamic over time and potentially confounded by other sediment sources.

spawning gravel has been completely eliminated for about 3km below San Clemente Dam. MPWMD made frequent injections of gravel from 1991-2001 at Old Carmel Dam to mitigate dam impacts, but it was apparently not sufficient to withstand the large transport capacity of the river. At the same time, the lower river was predominantly sandy for at least the half-century up to the year 2000, but has since developed extensive gravel areas due to a change in sand inputs.

CRRDR is predicted to virtually eliminate sediment-trapping at the San Clemente site, thus allowing sediment supply to reach a closer balance with transport capacity downstream of the site. This should increase the overall capacity and quality of spawning habitat downstream. But tests of this prediction must take account of the complex history of sediment sources and sinks in the Carmel River, summarized schematically in Figure 13. This complex history actually sets the stage for a powerful test of the prediction, because it implies different parts of the river will respond differently to CRRDR (Table 4), including two kinds of scientific controls above the CRRDR site representing impacted and target conditions respectively.

Response reaches of Carmel River (downstream of Tularcitos confluence) are inherently dynamic (Kondolf 1982) and their response to CRRDR must be interpreted within the context of this dynamism as well as confounding sources of sediment. The spawning capacity of alluvial reaches is expected to be highly variable over time, due to fluctuations in channel area and in sand fraction. CRRDR is predicted to superimpose a general upward trend in spawning habitat on this background "noise," though it might be difficult to discern statistically. In addition, spawning is observed in parts of the lower river that currently dry up, indicating that some benefits of CRRDR for spawning are contingent on reducing depletion of the aquifer and intermittency of surface flow.

Quality of Freshwater Rearing Habitat

Freshwater rearing habitat for juvenile steelhead is typically limited by different factors in dry-season and wet-season. A key wet-season factor is refugia from high water velocities during episodic flows. The primary limiting factor in the dry season is the availability of surface flow that is sufficiently cool and deep. Secondary factors in both seasons are food availability, other aspects of water quality, and habitat structures that provide cover from predators. These secondary factors likely affect the conditional-threshold strategy adopted by juvenile steelhead and thus are key aspects of the benefit of CRRDR.

To some degree, the incised channel produced by San Clemente Dam in the lower river tends to ease a primary limiting factor, by producing deeper summer flows for a given discharge, and robust vegetative shading that keeps stream temperature from rising. But incision—along with lost bed-load and LWD—appears to produce this benefit at the expense of the secondary limiting factors. Resumption of typical bed-load and LWD dynamics with CRRDR is expected to increase habitat complexity by creating more diverse substrates (grain sizes), more diverse water depths and velocities, larger channel area, and more extensive and diverse visual cover for hiding from predators. Also predicted are greater diversity in benthic macroinvertebrates that serve as a food base for steelhead, and closer proximity of spawning and rearing habitat, which eases the transition from eggs and fry to age 0 parr.

These predicted effects should improve survival and growth of juvenile steelhead, but how they will affect the expression of conditional strategies (smolt vs. mature in freshwater) is relatively uncertain. For example, if survival improves more than food availability, an outcome could be more juveniles that grow more slowly with fewer fish achieving smolting size at age 1 or 2; conversely, more food but poor improvement in survival could paradoxically increase the number of fish large enough to smolt. Thus the effect of CRRDR on anadromous production must be framed within the context of contingent strategies and strength of dependence of survival and growth on local population density.

In short, CRRDR should improve habitat quality, but with uncertain effects on life-history expression. Since CRRDR is also expected to locally widen the channel, decrease depths and decrease shading, it could also make rearing capacity more sensitive to weather and conditions in the underlying aquifer. Moreover, CRRDR is not expected to completely reverse channel incision, but rather to re-initiate an irregular recurrent cycle of flooding, aggradation and incision that is characteristic of episodic rivers (Kondolf 1982, 1997, Kondolf et al. 2013). Thus a key assumption of CRRDR is that over the long term, a dynamic alluvial river creates habitat quality that is more variable yet produces more smolts on average than a deeply incised channel that provides reliably mediocre habitat.

As with the case for spawning habitat, the intricate arrangement of sediment sources and sinks in the river (Figure 13) provides an opportunity for a powerful test of the "habitat complexity" prediction, because rearing habitat in different parts of the Carmel River are expected to respond in different ways to the CRRDR (Table 4).

<u>*Capacity and Quality of Lagoon Rearing Habitat*</u>

The seasonal lagoon has an important role in population viability by supporting the lagoon-anadromous life-history, characterized by juveniles with rapid spring or summer growth in the lagoon, followed by smolting the following winter. Deep water and emergent vegetation in shallower areas provide cover from avian predators.

Deep, sand-bedded areas in the main channel can provide high-quality foraging protected from avian predators, provided that a saltwater lens does not form below the freshwater due to wave overwash. Such lenses can heat up and become anoxic, excluding steelhead from benthic foraging (J. Smith, pers. comm.). Silt-bedded areas such as the arms may also become anoxic in summer, providing poor rearing habitat; but paradoxically may be the best growth habitat in spring due to high invertebrate productivity (J. Smith, pers. comm.).

Expected effects of CRRDR are less certain in the lagoon relative to the river, and include increased or decreased lagoon volume and mean depth; changed extent of open water vs. emergent vegetation as a function of depth; decreased vulnerability to wave overtopping or early natural breaching; but increased vulnerability to management interventions to protect local homes from effects of a raised sandbar crest. Changed volume presumably affects rearing capacity, while shallower depths decrease quality by making steelhead vulnerable to avian predation.

Introduced striped bass currently inhabit the lagoon and prey on steelhead; their likely response to CRRDR is unclear. Over the longer term, the planned construction of a Highway 1 causeway south of the river is expected to increase scour in the southern and Odello arms (Figure 11), and how this will interact with the increased sand supply from CRRDR is also uncertain.

Anadromous Migration

Prior to CRRDR, adult steelhead migrating upriver either spawned in the lower river or traversed the fish ladder on San Clemente Dam. The fish ladder does not meet current criteria established by NMFS for adult passage and the traverse typically took several hours (National Marine Fisheries Service 2013a). Downstream anadromous migrants (smolts and kelts) can use the fish ladder but can also end up passing over the spillway, presumably resulting in greater incidence of injury and death than would otherwise occur.

The rerouted channel is expected to require less time to traverse than the fish ladder for both upstream and downstream migrants, and to produce less injury and better survival of downstream migrants. Downstream survival has not been measured at the dam so the magnitude of potential improvement is not clear.

The benefit to viability of reducing site traversal time by a few hours is likely to be slight in most years. But it may be quite important in dry years, when there is little or no baseflow in the lower river between storms (Figure 6, bottom), and successful spawning would be dependent on getting to the upper river during a storm pulse (Boughton and Pike 2013). Dewatering due to aquifer pumping, and the expected increased frequency of low-flow years due to warming climate, exacerbates this constraint and so the incremental improvement of traverse time may have an outsized effect on long-term population resilience. This benefit would have to be assessed within the context of a life-cycle population model.

Connectivity of Spawning and Rearing Habitat

Spawning and rearing habitat are naturally vulnerable to losing connectivity, because gravel-bedded areas suitable for spawning are also prone to losing surface flow due to their large capacity for underflow (Boughton et al. 2009), and are also vulnerable to becoming too hot from solar exposure. Connectivity is highly dynamic and potentially limiting from late May through the end of June, when there is effectively a "race" for fry to develop enough to emigrate before baseflow recession and heating traps them in exposed or drying reaches. In wet years the discharge of groundwater from river banks may prolong connectivity during this critical period, but the benefit is sensitive to aquifer depletion (Kondolf et al. 1987).

Ecological connectivity in this critical period also requires a suitable destination for age 0 parr, either upstream to perennial reaches, downstream to the seasonal lagoon, to nearby perennial tributaries, or to suitable refugia (residual pools) in the spawning area (Table 5).

Reintroduction of large wood with CRRDR should scour more deep pools in gravel-bedded sections of the lower river, bringing spawning and rearing habitat into closer proximity. But these pools will provide refugia only in the narrow circumstances where aquifers are depleted enough to disconnect pools but not enough to completely dry them out. Otherwise they function as sink habitat, potentially attracting juveniles that would otherwise retreat further upstream or downstream. Currently steelhead pursuing this tactic are sustained by labor-intensive rescue and captive-rearing operations conducted by MPWMD.

Tributaries in middle and lower Carmel Valley provide relatively modest amounts of accessible perennial habitat—only about 1.8 km in Robinson Creek. Las Gazas and Tularcitos Creeks provide 10.9 km but are vulnerable to drying and thus disconnecting near their confluences in early summer (MPWMD and CRWC 2004). The lagoon is an important retreat, providing a pathway for lagoon-anadromous steelhead, but is not reliably accessible due to dewatering of the lower river. CRRDR has no

Table 5. Potential tactics for fry to retreat from alluvial spawning areas that lose surface flow.

Tactic	**Constraints**	**Predicted Effect of CRRDR**
Retreat downstream (to lagoon)	-Predation, water-quality in lagoon, dewatering in lower river.	Weak to None
Retreat to nearby tributaries	-Small capacity.	None
Retreat to nearby residual pools	-Sparse distribution. -Vulnerable (aquifer depletion, bird predation). -Tactic currently sustained by rescue operations.	Improved abundance and quality of pools, due to geomorphic effects of large wood
Retreat upstream (to perennial reaches)	-Restricted capacity below San Clemente Dam.	Improved capacity, dependent on upstream passage being realized at the CRRDR site

direct prediction for ecological connectivity of tributaries and the lagoon.

Finally, age 0 fish can also retreat upstream to perennial sections of Carmel River and tributaries, but San Clemente Dam currently blocks this up-river retreat. CRRDR could expand the capacity of the river to support this life-history tactic, by opening upstream passage at a critical spot between spawning areas in the lower basin and reliable rearing habitat in the upper basin. However, the design criterion for the reroute channel was upstream movement by juveniles of 15cm Fork Length or longer. Moreover, in dry years the 60 new pools constructed in the reroute section may become disconnected and trap juveniles attempting an upstream migration. Thus the benefit of improved connectivity for the age 0 life stage is highly uncertain but potentially large.

Implications of CRRDR for the various retreat tactics are summarized in Table 5.

<u>*Connectivity of Rearing Habitats*</u>

Upland creek habitats with either perennial or intermittent flow are widespread and of good quality in many tributaries of Carmel River. Headwater creeks in rainy areas generally have reliable, cool baseflows and complex step-pools, and seem capable of supporting robust subpopulations of both resident and anadromous *O. mykiss*. But food availability appears relatively low in the dry season and rapid juvenile growth is rare (Boughton et al. 2007b, Rundio and Lindley 2008, Sogard et al. 2009), suggesting that such habitats rarely function as steelhead nurseries. However, they may function as important refugia for steelhead to retreat to when conditions deteriorate in nursery habitats downstream (Hayes et al. 2011). Thus, *O. mykiss* appear capable of adaptively exploiting connectivity between downstream steelhead nurseries that provide good growth but unreliable survival, and upstream refugia that provide the converse. Downstream movement of numerous parr in late May and June is commonly observed in the Carmel, suggesting that this advance-and-retreat tactic could be expressed by the steelhead population if given an appropriate habitat template.

This tactic however is largely blocked by San Clemente Dam, which allows downstream movement of juveniles but not upstream. Thus it effectively enforces a source-sink structure on Carmel steelhead by allowing juveniles to enter but not leave the potentially productive yet unreliable habitat in the alluvial channel and lagoon. The annual depletion of the aquifer in the lower river and problems with water quality and predation in the lagoon would tend to magnify this source-sink structure even further.

CRRDR is expected to re-open the capacity of the river system as a whole to support the advance-and-retreat tactic. With this restored upstream-downstream connectivity, the advance-and-retreat tactic should increase in frequency in the population, contribute to greater smolt production and spawning runs, and also increasing the resilience of smolt production against problems with habitat quality in the lower river and lagoon.

An interesting question is whether or not the various retreat tactics just described have genetic components. While San Clemente Dam has been selecting against the upstream retreat, rescue and captive rearing operations in the lower river have presumably been favoring the tactic to retreat to residual pools, because such fish end up in the Sleepy Hollow Rearing Facility. CRRDR is expected to alter this selective regime.

Recommended Research Program

The preceding review suggests that predicted ecological benefits of CRRDR for steelhead fall under three broad questions:

1) How do restored bed-load and wood dynamics affect downstream habitats?
2) Does the reroute channel function as intended?
3) How does ecological connectivity affect steelhead population viability?

To address these questions, we recommend establishing a system of Indicator Reaches (IRs), selected according to design principles for Before-After/Control-Impact studies ("BACI designs;" Smith 2002). This is a general approach that can be extended to additional questions and focal species beyond the scope of what we describe here; for example by adding additional sites and/or sampling plans for additional species of interest, such as California red-legged frog, various riparian plants and animals, and problematic alien species.

Below, we outline a basic set of indicator reaches, habitat metrics, and additional data collection and integration that focus on the three steelhead-centric questions above.

Question 1: How do restored bed-load and wood dynamics affect downstream habitats?

The review suggests that the most important impacts on steelhead habitat quality in the river downstream of the San Clemente Dam are:

- Lack of LWD and habitat complexity
- Low channel substrate diversity
- Scarce riparian understory
- Channel incision and vegetation encroachment in some areas
- Scarce spawning gravel
- Decreased diversity of benthic macroinvertebrates
- Channel dewatering.

CRRDR is predicted to improve all except dewatering, by restoring characteristic LWD and sediment dynamics to the river. However, the magnitude and timescale of change is relatively uncertain and likely to be episodic. Other important uncertainties are how CRRDR will affect the downstream distribution and abundance of problematic alien species; and how the improved sediment and LWD supply will interact with existing stressors, in particular hardened banks, incised channels, and reaches vulnerable to dewatering.

A key prediction is that habitat improvement leads to a measurable response of the steelhead population. For our purposes we distinguish between a proximate response at the level of individual stream reaches, and an ultimate response at the level of the entire steelhead population (addressed in Question 3). At the reach level, habitat improvement is predicted to increase local production of *O. mykiss*, but it is less certain which aspects of habitat improvement will contribute the biggest response and how smolt production will respond.

From this reasoning we recommend performance metrics for three general processes:

1) Sediment and wood transport in the river
2) Response of habitat in Indicator Reaches to changed sediment and wood transport
3) Response of juvenile steelhead in Indicator Reaches to changed habitat

Sediment and Wood Transport

Estimating sediment transport involves rather different methods for tracking suspended sediment versus bed-load.

Suspended sediment involves sensors for continuous monitoring of turbidity, combined with periodic collection of depth-integrated estimates of sediment transport during flow events of varying sizes. The purpose of the depth-integrated estimates is to produce a rating curve for the turbidity sensor. A turbidity station thus involves collection of four data types:

1) Continuous monitoring of turbidity using electronic sensor

2) Continuous monitoring of water level using electronic sensor
3) Periodic collection of depth-integrated sediment sample to produce rating curve for turbidity data
4) Periodic collection of flow estimates to produce rating curve for water-level data

Highest priority is to track effects of CRRDR with a turbidity station downstream of CRRDR but upstream of Tularcitos Creek confluence (which also affects turbidity). We recommend a station at the weir near Sleepy Hollow where flow data are already being collected. The site can accommodate a turbidity sensor and collection of depth-integrated samples during small and moderate flow event. Depth-integrated samples of large events (unwadeable events) require a bridge crane. We recommend that the bridge that is being constructed to replace the low-water crossing at Sleepy Hollow be outfitted to collect such samples during large flow events.

We also recommend at least two additional turbidity stations:

1) Just upstream of the CRRDR project site (near the "stone cabin"), to provide an upstream control. This station would allow formal evaluation of effects of CRRDR on suspended sediment.
2) In the combined-flow reach. This station would test if turbidity is affected by runoff or ground-water inputs from the foot of the sediment stockpile.

In addition, the flow data from the three turbidity stations could be compared to assess whether significant river flow is passing through the sediment stockpile rather than through the reroute channel as intended.

The continuous collection of in-stream turbidity data during the wet season should be maintained indefinitely, and could be used to trigger event-based sampling (described later).

Bed-load is also important but much more technically difficult and costly to estimate than suspended sediment. Bed-load transport is important because it is the principle mechanism by which coarse sand and gravel get moved to the lower river, and thus plays a key role in formation of steelhead habitat, especially spawning habitat. Steel impact plates can be used to estimate bed loads but can get buried by large aggradation events, and in any case typically involve large uncertainties on the order of ±90% (Magirl et al. In press). A newer technology uses seismic sensors to estimate bed-loads, but still involves significant calibration issues (Roth et al. 2014, Barrière et al. 2015). We recommend that bed-load be monitored primarily through its effects on habitat at the Indicator Reaches (see next section). These effects include filling of pools, aggradation at monumented cross-sections, and changes in channel substrates.

Table 6. Suites of Performance Metrics.[1]

Basic
Benchmarked
Channel Geometry
Pebble Counts
LWD
BMI
Steelhead/Brown Trout (semiannual)
Complete (add to Basic)
Crayfish
Striped Bass
Bullfrogs/Calif. Red-Legged Frog
Floodplain Geometry
Floodplain Pebble Count
Riparian vegetation
Floodplain frog habitat
Focal (add to Complete)
LWD - detailed
Steelhead - detailed
Remotely Sensed
Channel Geometry – Plan-form
Riparian Vegetation
LiDAR (uncertain usefulness)
Non-Site
LWD Census
Longitudinal Profile

[1] See Appendix for additional description

Wood transport should be tracked by recurrent large wood censuses downstream of

CRRDR. These would repeat the methods and study area used by Smith et al. (2003) and Smith and Huntington (2004) to census LWD in the river between roughly Tularcitos confluence and the estuary. Ideally the recurrent iterations of the census would also extend upstream of Tularcitos confluence to the site of CRRDR.

The general schedule of wood censuses should be:

1) A census conducted as soon as practical, before completion of CRRDR, to estimate net accumulation (or loss) of wood since the first census in 2002-2003 (Smith et al. 2003, Smith and Huntington 2004). This would quantify the net accumulation (or loss) of wood in the decade prior to CRRDR.
2) Event-based censuses conducted in the summers following wet seasons predicted or observed to transport large amounts of LWD.

The event-based censuses assume that significant changes in wood recruitment to the channel are likely to be episodic, instigated by infrequent disturbance events such as extreme rainfall, wildfires or landslides that recruit large volumes of wood from hillslopes to channel. For example, such events occurred in 1995 and 1998, trapping large numbers of logs behind the dam. The census allows test of two general predictions: More abundant LWD after CRRDR, and larger pieces of LWD after CRRDR.

We recommend that the event-based censuses be used to identify new Indicator Reaches (IRs; see below) in which there is new deposition of wood. These event-based IRs would be used to test predictions about the expected ecological benefits of restoring the wood regime.

Of lower priority, but also desirable, would be to track the quantity of LWD passing through the reroute channel. This would help us ask: What proportion of downstream change (if any) in LWD characteristics could be attributed to passage of LWD through the reroute channel?

Other instrumentation should also be established to track key aspects of water quality downstream of the CRRDR sites. Parameters of interest include water temperature, dissolved oxygen, and algal content.

Test Predictions at Indicator Reaches

To learn about the downstream response of the river system to CRRDR, and to disentangle its effects from other stressors and processes, we recommend establishing a system of permanent indicator reaches with recurrent sampling of performance metrics. Conceptually, there are three main complicating factors that the research system must accommodate:

1) **Diverse Spatial Response:** Due to local factors and history, different reaches of the downstream channel are expected to respond differently to CRRDR.
2) **Mediated Delay:** Because some habitat responses are meditated by large flow events, they will likely be delayed after CRRDR until such events occur.
3) **Dewatering:** Annual dewatering in the downstream alluvial channel may obscure or prevent the response that would otherwise occur.

In addition, there are standard concerns about control reaches and replication, both of which substantially reduce ambiguity in the interpretation of results (see Appendix). Finally, there is a need to identify a comprehensive suite of suitable performance metrics, which are used to quantify changes in habitat and steelhead at the site level. The Appendix characterizes Indicator Reaches (IRs) and describes selection of sites and performance metrics based on application of the BACI framework, and a review of existing datasets based on the work of ENVS 660 (2012). Here we summarize those recommendations, in order of priority:

<u>*Priority 1.*</u>

Establish a replicated, completely controlled BACI design in the confined transport reach of Carmel River. This involves establishment of at least two IRs in each section of the river between Los Padres Dam and the confluence of Tularcitos Creek (Sections C2, C and I; Table 7); with annual collection of the basic set of performance metrics (Table 6). Section C2 below Los Padres Dam serves as a standard control (dam impacts not removed) and Section C above San Clemente Dam serves as a target control (Section I predicted to become more similar to C, less similar to C2). A key assumption of this framework is that tributaries and hillslopes between Los Padres Dam and CRRDR provide enough sediment and wood inputs to the channel to differentiate the behavior of standard controls versus target controls (section C2 versus C).

As of this writing, some of the recommended IRs have been established by NOAA,[5] with substantial assistance by USGS[6]:

C2: Need to be established. Vertical precision for cross sections does not need to be as stringent as for C and I.
C: 1 reach established summer 2012, 1 reach in summer 2014; Basic performance metrics.
I: 2 reaches established summer 2013; Basic performance metrics.

Establish IRs in the reservoir and combined-flow reaches of the CRRDR. Ideally, two IRs would be established in each of the combined-flow and reservoir reaches of Section I0 (Table 7), with annual collection of Basic performance metrics (Table 6). The combined-flow reach has no clear control sites; the reservoir reach has target controls in section C, established as part of the previous item.

C: See previous item.
I0: (reservoir) 1 IR established in summer 2013; there appears to be no suitable location for second IR. See Question 2.
I0: (combined-flow) To be established immediately after CRRDR completion.

Priority 2.

Establish IRs in unconfined response reaches of the upper and lower Carmel Valley. This involves establishment of at least two IRs in each section of the river downstream of Tularcitos Creek (Sections I2, I3 and I4; Table 7); with annual collection of the Basic set of performance metrics (Table 6). These reaches have no proper controls. However, in combination with section I they can be used to test the prediction that sections of river with different impacts should converge toward a common condition of mixed substrate, greater LWD abundance, and greater habitat complexity. Vertical precision for cross sections does not need to be as stringent as for sections C and I.

Sites should be established as soon as possible, preferably before dam removal occurs; but priority is lower than for Priority 1. As of this writing, the following sites have been established by CSUMB (Leiker et al. 2014):

I2: 2 IRs established 2013, physical data only
I3: 1 IR established 2013, physical data only
I4: 2 IRs established 2013, physical data only

Establish IRs in forced-pool habitat. Basic IRs are positioned in habitat consisting of riffles and shallow pools, due to their suitability for collecting indicator data on benthic macroinvertebrates and juvenile steelhead. Bedrock forced pools (deep pools forced by streamside rock outcrops) are less tractable to sample, but comprise important habitat for juvenile steelhead, adult resident *O. mykiss* (rainbow trout), and possibly alien fish species. These pools are distributed throughout the river and are hypothesized to respond to changed sediment and wood loading in ways that may affect habitat capacity, quality, and diversity for both juveniles and adult rainbow trout. We recommend developing a set of pool-based IRs and performance metrics for testing such hypotheses.

Priority 3.

Extend the performance metrics at all IRs from Basic to Complete. The complete set of performance metrics (Table 6) allow for tests of hypotheses about responses of alien species to CRRDR, and tests of hypotheses about the response of the floodplain to altered sediment and

[5] SW Fisheries Science Center, Fisheries Ecology Division, 110 Shaffer Road, Santa Cruz, California 95060.
[6] Pacific Coastal and Marine Science Center, 400 Natural Bridges Dr., Santa Cruz CA 95060

Table 7. Recommended system of Indicator Reaches (IRs). **Basic** = Two sites with Basic performance metrics; **Complete** = Sites replicated according to power analysis, with Complete performance metrics; **LWD** = Sites selected according to new deposition of LWD, with suitable paired controls and Focal performance metrics.

Sec.	Description	Priority 1	Priority 2	Priority 3	Priority 4	Event-based
C3	Above LPD				Complete[1]	
C2	LPD to Cachagua	Basic		Complete	Pool	
C	Cachagua to CRRDR	Basic		Complete	Pool	
I0	CRRDR site	Basic		Complete		
I	CRRDR to Tularcitos	Basic		Complete	Pool	LWD
I2	Tularcitos to Robinson		Basic	Complete		LWD
I3	Robinson to Schulte		Basic	Complete		LWD
I4	Schulte to Hwy 1		Basic	Complete		LWD

[1] Potentially at sites surveyed by (1997)

LWD regimes. In addition, detailed site-level surveys of vegetation could be included as part of floodplain response, although such methods are beyond the scope of this report.

Conduct power analysis on data for existing IRs, and establish additional IRs as needed. Two sites per river section represent minimal replication for testing hypotheses. Preliminary data from such sites can be used to ask if the level of replication is sufficient for tests of key hypotheses. If additional IRs are warranted, they should if possible be established before large flow events lead to significant responses of the river downstream of CRRDR.

Priority 4.

Establish IR at Kelly site if appropriate. Kelly (2011) collected data on channel geometry and channel substrate in section C3 (above Los Padres Reservoir). Physical habitat in this area is unimpacted by dams and thus can serve as a relatively pristine target control for section I directly below CRRDR. More importantly, section C3 is the location of an established Brown Trout population and thus can serve as a target control for assessing changes in Brown Trout abundance at and around the CRRDR site.

Event-Based (High Priority after events)

Event-based data collection is conducted in the summer after wet seasons judged to produce significant reworking of the channel, transport of sediment, or deposition of wood. Priorities for event-based data collection are:

Conduct LWD Census and establish focal IRs associated with LWD. The LWD Census was described earlier; focal IRs would use the census to select reaches with significant new deposition of large wood; and identify paired control reaches matched for condition except lacking deposited wood (suitable controls might already occur among established IRs). Focal performance metrics (Table 6) would be collected annually and pairs of sites replicated enough to allow tests of hypotheses about benefits of deposited wood for steelhead production.

These event-based IRs would be used to test predictions about the expected ecological benefits of restoring the wood regime. Such predictions include:

- Larger wood will have greater hydraulic and geomorphic effects than smaller wood.
- Larger wood improves habitat complexity and quality for steelhead.

- Effects of larger wood on habitat produce greater survival, density, and size diversity of local juvenile *O. mykiss*.
- Larger pieces of wood have longer persistence times in the river

Repeat longitudinal channel profiles described by Matthews et al. (2008). Two sets of surveys were conducted between Via Mallorca and Robinson, for the years 1997, 1999, 2001, and 2007. These longitudinal surveys should be repeated after winters showing significant reworking of the channel, to test predictions about effects of CRRDR on channel incision/aggradation, and on habitat diversity (quantified as variation in depth along longitudinal profile). In 2014, NOAA/USGS completed a longitudinal profile survey from SC Dam to Old China Dam, and has also completed long profile surveys within the four study reaches currently in use. Extending this further downstream would provide additional information on the signal persistence of any sediment pulse that does develop below the CRRDR.

Track river plan-form and gross changes in riparian vegetation using aerial imagery. Monterey Peninsula Water Management District (MPWMD) has collected aerial imagery annually since the 1980s, which comprises one of the longest "before" datasets available. This imagery should continue to be collected, although it might be possible to reduce from annual flights to event-based flights or some intermediate frequency. In principal, LiDAR could be added to imagery flights to comprehensively track changes in channel geometry for the entire channel downstream of CRRDR. However, dense riparian vegetation probably limits the usefulness of this approach for obtaining fine-resolution surfaces of the channel and floodplain. ENVS 660 (2014) examined an existing LiDAR topographical dataset for the county and found its resolution insufficient to track channel geometry.

What is the Lagoon Response?

The conceptual model and review suggests a distinction between first-order and second-order predictions. First-order predictions for the lagoon result directly from aggradation of sand and accumulation of LWD, although as elsewhere the timing and magnitude of such effects is uncertain. Predictions about first-order effects can be tested by recurrent data collection on the following performance metrics:

1) **Lagoon bathymetry**
2) **Dynamics of water-surface elevation**.
3) **Sandbar shape, position, and elevation**.
4) **Beach width and position**
5) **Recurrent LWD census, possibly from aerial photos**

However, interpreting change in these metrics as a response CRRDR is difficult because 1) the first four are highly dynamic at both weekly and seasonal scales, and 2) there is no control lagoon for comparison and no replication. This inherent variability places an emphasis on sufficient repeated sampling in the "before" period to characterize the background variation prior to CRRDR. The lack of controls means that predictions can still be tested, but plausible alternative explanations for the predicted effect may not necessarily be ruled out.

Second-order predictions result in turn from the first-order predictions, especially via changes in lagoon depth, volume, frequency of breaching, frequency of overwash, and changes in circulation patterns arising from such changes. The potential second-order changes most relevant to steelhead are changes in:

1) **Aquatic vegetation**
2) **Water quality (stratification in salinity, DO, temperature, etc)**.
3) **Striped bass abundance and diet**
4) **Macroinvertebrate response**
5) **Steelhead response**

Numerous other factors, unrelated to CRRDR, have the potential to affect these metrics, so attributing change directly to CRRDR will be uncertain. Our recommendations below are prioritized based on a qualitative judgment of suitability for before-after analysis and conceptual importance for linking CRRDR to steelhead rearing in the estuary. See appendix for details.

<u>First priority</u>

- Continue annual characterizations of changes in lagoon bathymetry, using annual surveys of cross-sections at 4 existing monitoring sites maintained by MPWMD (see appendix).
- Continue collecting water-surface elevations in the south arm to produce "after" time period of similar duration as "before" time period collected by MPWMD.
- Continue the vertical-profiling program at five water-quality sites maintained by MPWMD, as well as continuous temperature monitoring at the south arm.
- Assess suitability of data from CDFW eradication program for annual estimates of striped bass abundance, size-structure and predation rates on steelhead. If appropriate, develop alternative methods for tracking these metrics through time, especially abundance and predation rates.
- Develop field studies elucidating links between lagoon structure / dynamics and striped bass ecology.
- Continue collecting data on vegetation composition in quadrats in the North Arm.
- Use PIT-tagging methods to estimate number of juvenile immigrants to the lagoon during its closed period.

<u>Second priority</u>

- Investigate suitability of aerial photos for depth-retrieval for reconstructing annual bathymetric dynamics, perhaps using existing cross-section data to calibrate the method.
- Investigate suitability of existing aerial photos for characterizing beach width prior to CRRDR.

<u>Event-driven</u>

- Conduct recurrent censuses of LWD in the lagoon on the same event-based timetable as in the river.
- Repeat the bathymetric survey (Hope 2007) at some point after CRRDR if cross-sections indicate directional change.

<u>Methods Development</u>

Water Surface Elevation.

- Develop method(s) to characterize annual frequency of breaching and stage statistics for when sandbar is in place, to characterize the "before" period.
- Develop methods to analyze step-change in dynamics associated with CRRDR.

Aquatic vegetation.

- Investigate suitability of aerial photos for estimating extent of open water and different types of aquatic vegetation. If suitable, create time-series of open-water and vegetation extents.
- If time-series of vegetation extent can be estimated, analyze relationship to water surface dynamics, also taking into account changes in bathymetry due lagoon restoration projects, etc.
- If aerial images are suitable as determined above, continue collection of aerial photos in the "after" period to create a Before-After study design.

Water Quality

- Develop methods for characterizing pre-removal variability in vertical profiles of water quality, perhaps in conjunction with water-surface elevations, wastewater outflows, tidal influences and river flows.

Macroinvertebrates

Methods development here assumes that sampling should be stratified by substrate category, based on work by CSUMB.

- Investigate use of aerial photos for mapping substrate categories that are comparable to those designated De Lay (2010).
- If aerial photos are suitable for mapping substrate extents, estimate a time-series of extents for the "before" period.
- Conduct preliminary analysis of whether invertebrate samples described by Perry et

al. (2007) are suitable for characterizing the "before" period.
- Use appropriate method (aerial photos, invertebrate samples at established sites, or both) to collect data in the "after" period of CRRDR.

Question 2: Does the reroute channel function as intended?

The re-routed section of Carmel River is intended to function similarly to a natural river channel, both in terms of geomorphologic and hydrologic processes, and in terms of comprising habitat for steelhead. At the same time it is an engineered system differing in many ways from a natural river channel, so it will be important to determine if its dynamics meet expectations.

Geomorphology

The restored CRRDR channel system will have a low-gradient section at the upstream end and a generally steeper-gradient section with step-pool geometry at the downstream end. The low-gradient section is forced to flow through the notch in the rock ridge, so at that point the channel is locally anchored in place. Upstream of the notch (the reservoir reach), the channel is expected to incise into existing reservoir sediments, steepening the channel and coarsening the bed sediments. Downstream of the notch (the combined-flow reach), the low-gradient section has bends that are expected to evolve as sediment is alternately stored and eroded in the floodplain, in keeping with natural pool-riffle systems.

The high-gradient section is in the downstream part of the combined-flow reach, and will employ approximately 1000 imported discoidal rocks with intermediate axis dimensions of approximately 1.2 m. These large rocks will be used to construct stable steps mimicking natural step-pools, controlling the gradient of the channel while passing gravel and large wood downstream. While the steps are designed to be stable, there may be large flows that gradually adjust the individual rocks. If the steps function similarly to natural self-formed step-pool systems, this adjustment process should jostle the rocks into more stable interlocking configurations that increase the resilience of the steps over time.

On a more frequent basis, logs under hydraulic stress could lever rocks out of place. As occurs in local tributaries and neighboring watersheds, large wood-debris jams can form and persist for years in step-pool settings (Casagrande and Smith 2005, Robins et al. 2014). While less likely, larger gravel might infill some of the pools.

Hydrology

A key risk for the entire combined-flow section is potential loss of surface flow during base-flow conditions. Base-flow persistence will depend upon the tendency to route alluvial groundwater through the rock gap into the restored channel. If groundwater bypasses the gap (following its original path through the sediment stockpile in the old river channel), the combined-flow reach will lose base flow and perhaps even dry up in summer or fall. The stabilized reservoir sediment may experience spring sapping and gullying, or might potentially become fluidized in an earthquake.

Steelhead

Design criteria for the reroute channel were intended to ensure passage of adults, smolts and larger juveniles, but not necessarily smaller juveniles. Our review, however, indicated that upstream passage of all sizes of juveniles could be a key ecological benefit for steelhead population viability. Thus, important questions for the reroute section are which life-stages of steelhead use it for upstream or downstream passage, and whether it comprises passage barriers for particular life-stages under particular flow conditions. The most likely impedance would be upstream passage of small juveniles in the high-gradient section.

The expected adjustment of step pool geomorphology described earlier could impair the CRRDR project by sporadically interrupting fish passage due to shifting rock structures, the filling of jumping and resting pools, and formation of barriers from debris accumulations. In addition, the potential loss of surface flow in summer or between storms in winter could impede passage of all life-stages, with particular vulnerabilities for smolts and juveniles moving downstream in late spring, or juveniles retreating upstream in summer.

Development of spawning and rearing habitat in the reroute channel is also expected, as gravel is transported into the reach from upstream, riparian vegetation develops, and benthic macroinvertebrates colonize the new channel section. Key uncertainties are the speed and degree to which problematic alien species, especially crayfish and brown trout, colonize the new habitat, and the impact they will have on successful passage, spawning, and rearing of steelhead.

Recommended Data Collection

We recommend siting an Indicator Reach in the reservoir reach prior to dam removal, to test predictions about steepening and coarsening of this channel section. This IR was established in 2013 by NOAA and USGS as described in an earlier section.

In addition we recommend detailed study of the entire combined-flow reach (from the notch to the former dam site), as this is one of the more critical and innovative elements of the CRRDR project. In particular:

- Flow monitoring sites should be established upstream of the reservoir reach, downstream of the former dam site, within the combined-flow reach (perhaps at the notch), and in the tributary (San Clemente Creek), to quantify the proportion of flow passing through the combined-flow reach, versus subsurface flow through the sediment stockpile
- Quantify the persistence of the average cross section, plan-form, and profile geometry of both the low- and high-gradient sections through time.
- Collect basic performance metrics in both the low- and high-gradient sections to quantify steelhead habitat and colonization by steelhead.
- Collect complete performance metrics to quantify colonization of alien species and establishment of riparian vegetation.

We recommend that immediately following construction, before riparian forest grows, the entire 103m of constructed channel should be mapped through low-altitude aerial photography and photogrammetry. This will require sufficient ground-control points to be surveyed so that the photographs can be used to create a very high-resolution orthophoto-draped digital elevation model. The initial channel profile and bench-marked cross-sections would be established at the same time.

Question 3: How does ecological connectivity affect steelhead viability?

Our review suggests that a key expected benefit of CRRDR for steelhead is improved ecological connectivity for all life-stages, specifically:

- Faster passage times for adult steelhead migrating upstream.
- Downstream movement of juveniles and smolts possible under greater range of flows
- Greater survival of juveniles and smolts moving downstream.
- Upstream movement of juveniles will be possible for first time in 90 years, though still potentially limited for juveniles < 15cm FL.

The last benefit (upstream movement of juveniles) is the most fundamental change in connectivity and appears to have the greatest potential to increase the capacity and resilience of the system to produce anadromous steelhead. At the same time, the first benefit (faster upstream passage of adult steelhead) appears to involve the greatest cost if the reroute fails to function as anticipated, because failure could completely block upstream passage of migrating adults. It may also have an outsized benefit during dry years, but this benefit must be evaluated within the context of a population model.

The first three of the four expected benefits above cannot be tested using a standard BACI design, due to lack of suitable "before" data. We recommend a simpler approach testing the hypotheses that passage times, range of flows suitable for passage, and survival are similar to some set of reference reaches (a "Control-Impact" study or "synchronous similarity analysis;" Kibler et al. 2011). These similarity hypotheses can be tested by implanting PIT tags in the appropriate life-stages of wild steelhead, and monitoring their subsequent movement and fate with a set of electronic monitoring stations established at various points in the river system.

The "before" condition for the fourth expected benefit (upstream movement of juveniles) is zero movement, it is safe to assume. Therefore a formal test is simply to document upstream movement. Similar to the first three predictions, this can be addressed by PIT-tagging juveniles and monitoring their movement, in this case upstream movement through one end of the CRRDR site to the other. There are some limitations to this approach, mainly that a significant proportion of newly emerged juveniles in early summer are too small to tag.

How much does each of the four expected benefits actually improve viability of the steelhead population? We emphasize that this question has fundamental importance, given the expense and complexity of dam removals such as CRRDR. To address it, the set of tagging and monitoring efforts described above should include sampling of fish from across the stream network and across key life stages, so that the resulting data can be used to fit an integrated population model.

Integrated population models (IPMs) use quantitative techniques to integrate diverse sets of data into a single, process-based model of population dynamics and trajectory (Schaub and Abadi 2011). Such models allow for population-level assessment of viability (extinction risk) and other key population traits (adult run size, anadromous fraction, etc.).

A suitably designed tagging effort and IPM would allow for formal evaluation of extinction risk under alternative scenarios. Once suitable tagging data have been collected and used to test the predictions about connectivity, such scenario analysis could then be used to ask how much the improved connectivity has improved steelhead viability in the Carmel River system. We recommend that the sampling plan include tagging juvenile steelhead during fish surveys at IR sites (previous section), so that it is possible to estimate how the population as a whole responds to changes in downstream habitats after CRRDR.

We recommend investigating possible scientific benefits of integrating the sampling and tagging framework with existing data collection efforts for steelhead, most notably the ongoing population monitoring conducted by MPWMD (summarized in MPWMD 2006), and strategies for reach-sampling and life-cycle monitoring outlined in the Coastal Monitoring Plan for California Salmonids (Adams et al. 2011). The potential benefits of such integration would be:

- A system for learning about effects of a dam removal (CRRDR) on a threatened coastal steelhead population.
- Long-term data on status and trends of the Carmel River steelhead population, suitable for Status Review Updates conducted by NMFS under the Endangered Species Act.
- A system of data collection that could potentially serve as a life-cycle monitoring station for the Coastal Monitoring Plan (CMP), with sufficient run sizes to provide robust estimates of marine survival, as required by the CMP.
- A research system that can be extended to ask other questions about response of the steelhead population to additional aspects of river restoration, such as:
    - Aquifer restoration in the lower river
    - Management of aquatic predators
    - Riparian restoration
    - Flow management

Below we outline steps in establishing this integrated sampling framework:

Establish an integrated scheme for sampling reaches and tagging steelhead with PIT tags. A potential scheme is outlined in Table 8, and is intended to reconcile varying goals and assumptions of different data-collecting schemes:

Table 8. A potential integration scheme for steelhead data collected at MPWMD reaches, IR reaches, and through the Coastal Monitoring Plan for California Salmonids (CMP). GRTS refers to the generalized random-tessellation stratified samples; see Adams et al. (2011) for additional information.

Existing	Reach Selection	Sample Type	Notes
MPWMD	Indicator	Depletion Electrofishing	- Decade+ time series
IR	Indicator	Mark-Recapture Electrofishing	- Selected for power to indicate change
CMP	GRTS rotating panel	Snorkel Surveys	- Sampled to provide unbiased estimates - Not yet initiated in South-Central Coast
CMP	Nr. confluence	DIDSON images	- Counts of migrating adults
Potential Integration			
Stratum 1	Existing Indicator (MPWMD, IR)	Existing (see above)	- Retained for continuity and focus questions - Tagging could be added for smolt production - Not used for inference to unsampled sites - May be phased out over time.
Stratum 2 (3 kinds of probability samples)	GRTS rotating panel	Mark-Recapture Electrofishing (+ Snorkel Surv.)	- CRRDR connectivity (this report) - Smolt production (Life-Cycle Monitoring CMP) - Calibrate Snorkel Surveys & Mark-Only
		Mark-Only Electrofishing	- CRRDR connectivity (this report) - Smolt production (Life-Cycle Monitoring CMP) - Calibrate from Mark-Recapture Sample Type - Can be adapted for spatial structure (CMP)
		Snorkel Surveys	- Spatial Structure (CMP) - Calibrate from Mark-Recapture Sample Type
Experimental Strata	Hypothesis-Driven	Mark-Recapture Electrofishing	- Added and removed over time to test specific hypotheses about survival, smolt production
CMP	Nr. confluence	DIDSON images	- Counts of migrating adults

Notes: Additional strata can be temporarily designated for future focus questions using BACI designs; Allocation of effort among strata can be adjusted depending on focus questions.

Hypotheses linking connectivity, smolt production, and population viability, emphasized in this section, are addressed by stratified-random sampling of reaches in which to tag juvenile fish (Stratum 2, experimental strata, in Table 8). Compatibility with the Coastal Monitoring Plan could potentially be achieved by using its sampling method to provide spatially-balanced set of reaches for tagging (Adams et al. 2011), and calibrating electrofishing against snorkel surveys by collecting both types of data in some samples.

Movements of tagged juveniles can be tracked by a system of electronic detection stations throughout the river system. Detection stations positioned at either end of the CRRDR site would allow estimating how many juveniles move through the site, in which direction, with what survival, at what time of year. Detection stations positioned at either end of reference reaches would provide the same kind of data to make the comparisons as recommended earlier. Finally, a detection station near the mouth of the river[7] would be used to identify tagged fish whose fate was ultimately to smolt and migrate out of the system. These outmigration data can be used to test hypotheses that smolt production differs for juveniles using and not using the CRRDR as a movement corridor.

Hypotheses linking changes in downstream habitat and smolt production, emphasized in the previous section, are addressed by tagging fish at selected IR sites (Stratum 1 in Table 8). Subsequent within-stream movements and smolt production are assessed using the same system of detection stations as the previous item. Hypotheses can be tested using the BACI framework outlined in the appendix, combined with mark-recapture analytical methods.

Continuity of status monitoring can be maintained by continuing the sampling of the MPWMD reaches (Stratum 1 in Table 8). Smolt production from these indicator sites can be estimated by tagging the fish captured as part of depletion sampling. However, neither these reaches nor the IRs were randomly sampled. The MPWMD reaches likely comprise better-than-average habitat and thus cannot be used to make unbiased inferences about smolt production from other parts of the river system. Such inference must be based on Stratum 2.

If sampling from MPWMD sites overlaps for a number of years with sampling of stratum 2, it may be possible to bias-correct the MPWMD data, including the historical time series. If so, the MPWMD sites could gradually be phased out if desired, without destroying continuity of status monitoring.

Life-cycling monitoring consistent with CMP needs could be achieved as a byproduct of the above activities (Table 8). These activities can be used alone or in combination with DIDSON monitoring of adult steelhead recently initiated by MPWMD, as described below.

Life-cycle monitoring is proposed by the Coastal Monitoring Plan (CMP) for a series of salmonid populations distributed across the entire California coast. The primary purpose of a life-cycle station is to concurrently estimate annual smolt production and annual spawner returns for an entire steelhead population over a long period of time. From this, ocean survival is estimated and used to interpret run-size data from systems that have no life-cycle monitoring.

The stratified learning system outlined in Table 8 produces data suitable for estimating smolt production, spawner returns, and ocean survival (Boughton 2010), and thus by itself can support life-cycle monitoring as envisioned by Adams et al. (2011). The chief limitation of the approach is that large numbers of tagged juveniles may be required to estimate spawner returns and ocean survival (Boughton 2010). However, reasonable estimates of smolt production can be made with a much more modest tagging effort.

The DIDSON acoustic camera deployed by MPWMD can provide data on spawner returns but is much less useful for estimating smolt production, due to ambiguity in resolving images of small fish (K. Pipal, pers. comm.).

The existing DIDSON monitoring, in combination with the tag-based learning system outlined here, would produce a dataset suitable for life-cycle monitoring (i.e. suitable for annual estimates of smolt production, spawner returns, and marine survival). The estimates of spawner returns and marine survival would likely have greater precision than a tag-based system alone.

Establish a system of electronic detection stations to track movements and survival of tagged fish. Migrating PIT-tagged fish can be identified using simple detection stations that involve wire-loop antennae in the river channel and associated electronics and batteries on the banks (*e.g.* www.oregonrfid.com). Typically a

[7] A trial run of such a tagging station has been conducted by NMFS in 2014 and 2015 at the plant of the Carmel Area Wastewater District

detection station involves two or more redundant antennae positioned in series, to detect direction of movement and to estimate detection rates (from proportion of fish detected by one antenna but not both). The cost of materials per station is moderate ($5K-$10K) and power requirements are low. The principle limitations of this technology are: 1) the modest size of antenna loops (c.20m wide x 1m tall) makes them vulnerable to high-flow events or floating debris; and 2) the small PIT tags used on small juvenile steelhead (<100mm FL) tend to have very short detection distances (distance from antennae < 15 cm) and thus low detection rates. Very small juveniles (< 70mm) cannot be tagged at all according to NMFS guidelines. These represent practical problems that need to be worked through as part of implementation.

To compare smolt production from different parts of the system or at different times, a detection station is needed near the mouth of the river. This station can detect both out-migrating smolts and returning adults, and so can also form the basis for collecting data consistent with needs of the CMP Life-Cycle Monitoring as described previously. In fall 2013, NMFS established and began testing such a station on the grounds of the Carmel Area Wastewater District's treatment plant, just upstream from the estuary. Testing of the station has been hampered by the 2013-2014 drought, which kept the lower river dewatered for the entire 2014 water year. The principal limitations of this system are that it may be vulnerable to floating debris, especially during high-flow events; and that it does not distinguish between downstream migrants heading for the ocean and migrants heading for the estuary.

To determine smolting rates of juveniles that move through the CRRDR, two additional stations need to be established, at the top and bottom of the CRRDR site respectively. These stations have not yet been established but would be located on Cal American or BLM land near the CRRDR site.

To ask if juveniles, smolts, or adult steelhead moving through the CRRDR site survive and move at rates similar to other parts of the river, it will be necessary to establish one or more reference reaches with detection stations at either end.

Integrated Population Model.

An integrated data-collection scheme such as the one in Table 8 can be used to parameterize a steelhead life-cycle model, using the general quantitative techniques of Schaub and Abadi (2011) for combining different datasets into an integrated population model. Other relevant references include Boughton (2010), who shows how mark-recapture at sampled sites can be assembled into a hierarchical model to estimate smolt production, marine survival and spawner abundance. Boughton et al. (2009) shows how electrofishing can be used to calibrate snorkel counts, also in the context of a hierarchical model. Buoro et al. (2012a) and also Buoro et al. (2012b) show how the parameters of a contingent strategy model can be estimated using mark-recapture data. Finally, Easterling et al. (2000) and Ellner and Rees (2006) show how to construct population models structured by growth and body size; and Schaub and Abadi (2011) describe how various modeling components, such as the ones just described, can be combined into an integrated population model using a Bayesian quantitative framework.

It is straightforward to use these established techniques to construct an integrated population model, which can then be used to assess how CRRDR has affected viability of the Carmel River steelhead population. In particular, it could be used to ask how strongly CRRDR has affected mean run size, year-to-year variation in run size, spatial structure of the population, and life-history diversity. It could also be used to conduct various scenario analyses, or be augmented with additional, hypothesis-driven tagging ("Experimental Strata" in Table 8) to ask how CRRDR interacts with other management activities to affect steelhead viability.

Acknowledgements

We would like to thank the participants in the Nov. 2012 CRRDR workshop in Santa Cruz, California: Matt Collins of the NOAA Restoration Center, Marcin Whitman of California Department of Fish and Wildlife, Andy Collison of ESSA, Leonard Sklar of San Francisco State University, Yantao Cui of Stillwater Sciences, Mike Burke of Inter-Fluve, Rich Svindland of California American Water, Desiree Tullos of Oregon State University, George Pess of NMFS NW Fisheries Science Center, Steve Rothert of American Rivers, Brian Cluer of NMFS West Coast Regional Office, Noah Finnegan of UC Santa Cruz, Matt Kondolf of UC Berkeley, Mark LaChevallier of California American Water, Pat Shafroth of USGS – Ft. Collins, Brian Spence of NMFS SW Fisheries Science Center, Gabby Alberola of the Planning and Conservation League Foundation, Jon Major of USGS Cascades Volcano Observatory, Gary Greene of the Tombolo Institute, Jon Warrick of USGS – Santa Cruz, and Marc Los Huertos of Cal. State University Monterey Bay.

Tetra Tech and Granite Construction kindly allowed us to review preliminary design drawings of the new channel design.

We would also like to express our great regard for Joyce Ambrosius (NMFS West Cost Regional Office, Santa Rosa) and Trish Chapman (California Coastal Conservancy, Central Coast Region), for spearheading the workshop and especially for sustained leadership and vision for the CRRDR project over many years of planning.

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Appendix

Framework for Learning from Indicator Sites

To test hypotheses about the downstream response of river habitats to CRRDR, we recommend establishing a set of indicator sites. Indicator sites should comprise a series of short (c. 300 m) reaches downstream of CRRDR suitable for testing hypotheses about habitat response, and comparable sites upstream of CRRDR that function as scientific controls. Care must be taken in selecting sites to provide as much clarity as feasible for interpreting CRRDR and river response in terms of cause and effect. Although CRRDR and Los Padres Dam can be viewed as an experiment and a control, they lack two key elements of classical experimental tests: Random assignment of experimental treatments (dam removal) to experimental sites (dams); and replication (Beyers 1998, Kibler et al. 2011).

Replication allows one to reduce the probability that an experimental treatment and predicted response are associated purely by chance, leaving cause-effect as the most compelling explanation for the association. Random assignment resolves ambiguity in cause and effect: A given association could arise either because the treatment caused the response, or because the treatment was somehow applied mostly to units predisposed to the response. Randomization reduces the probability of the latter, again leaving direct cause and effect as the most compelling explanation.

Replication and randomization are almost always impractical for large-scale environmental impacts such as dam removal (Underwood 1992, Michener 1997). In addition, a key difficulty in ruling out alternative explanations of causality is that ecosystems themselves tend to be highly variable and heterogeneous and so restoration or disturbance effects must somehow be distinguished from this background variation (Underwood 1991, 1992, Michener 1997). Ecosystem impacts in this context are commonly assessed using statistical models known as "Before-After/Control-Impact" designs, abbreviated BACI (Smith 2002).

In BACI designs, different restrictions on the number and kind of controls place different limits on the number of simplifying assumptions necessary for a cause-effect interpretation (Table 9). Causal interpretation is less robust than classic experimentation, because it is contingent on the assumptions, which must be validated by external arguments of plausibility, background information and so forth (Beyers 1998).

Underwood (1991, 1992) discuss BACI designs within the context of linear mixed models, where the fixed effects describe differences between controls and impact sites, before and after periods, and their interaction. The random effects describe stochastic variation among sites and times of observation, modeled as:

$$x_i + y_t + z_{i,t} + \epsilon_{i,t}$$

where x_i is a random effect of site i, y_t is a random effect of time t, and $z_{i,t}$ is additional random variation of individual site/time combinations. The final term $\epsilon_{i,t}$ is observation error (difference between observed and true state of the site). Note that x_i is the mean effect of site i averaged over all times; and likewise y_t is the mean effect of time t averaged over all sites. These two effects capture the common situation of spatial and temporal heterogeneity in ecosystems. Note that the third term $z_{i,t}$ is only non-zero if there is an additional second-order heterogeneity, interpreted as some sites being more stable over time than others or some times exhibiting greater spatial uniformity than others. Table 9 summarizes the assumptions that different BACI designs must make about these sources of heterogeneity to support a cause-effect interpretation.

Table 9. A taxonomy of BACI designs.

Name	Controls	Description	Key Limitations
BA (Before-After)	None	Data collected repeatedly at impact site before and after the impact. Tested for change coincident with impact	Cause-effect interpretation only valid if background temporal variation is small relative to impact. Not applicable to mediated delay.
BACI (Before-After/ Control-Impact)	One (paired)	Data collected repeatedly at an impact site and a similar control site before and after the impact. Tested for 2-way interaction	Cause-effect interpretation not robust to second-order heterogeneity.
Asymmetric BACI	Multiple	Data collected repeatedly at an impact site and multiple control sites. Testing uses linear mixed models.	Robust, but identifies response only if it is an outlier from 2nd-order heterogeneity. Inefficient if 2nd-order heterogeneity is negligible.
Reverse BA	None	Data collected repeatedly at diverse impact sites, tested for convergence after impact	Relies on sites with distinct starting conditions, but modest ecological heterogeneity after impact.
Reverse BACI	One (target)	Data collected at impact site and site with target condition, tested for convergence via 2-way interaction	Not robust for 2nd-order heterogeneity.

Applying the general BACI framework to the question of downstream effects of CRRDR, we can identify some key constraints and opportunities:

Los Padres Dam can serve as a control, allowing for a true "BACI" design. Removal of small dams can sometimes use nearby retained dams as controls (e.g. Ahearn and Dahlgren 2005), but this is rarely possible for large dams. Interpretation of dam removal effects without a control is problematic because of the great temporal variability of river habitats and because in episodic rivers there is an expected delay of years or decades between the impact (dam removal) and the response (downstream channel change). Thus the CRRDR/Los Padres combination offers a unique opportunity to do a controlled study of how episodic rivers respond to dam removal.

The experiment and control are NOT replicated. A fundamental limitation is that the response of sediment regime and wood regime to CRRDR is not replicated. This means that one must anticipate possible alternative explanations for changes in regimes, then select sites and/or collect ancillary data accordingly. Here the alternative explanation would be that the changes had resulted from delivery of sediment and wood from hillslopes and tributaries downstream of CRDRR. In particular Tularcitos Creek is a significant episodic contributor of sediment from a large tributary watershed (Smith et al. 2004), so the most robust assessment of how CRDRR alters sediment delivery would focus upstream of its confluence.

The responses of individual reaches to altered sediment and wood regimes IS replicated. Indicator sites should therefore be selected and replicated so as to avoid confounding of CRRDR effects and ecological heterogeneity. It is safe to assume substantial spatial and temporal heterogeneity, but what about second-order heterogeneity? We can make a rough estimate of the magnitude of second-order heterogeneity using juvenile steelhead density (MPWMD 2006) as a performance metric. The variance components for recent densities in the Carmel River are presented in Table 10.

Table 10. Variance components for 10 years of steelhead densities at 9 sites (fish / ft).

	Variance Component	As % of Total Var.	Coef. Var.
Year	0.18	33%	52%
Site	0.09	16%	36%
Residual[1]	0.28	51%	65%

[1] Observation error + second-order variation

Observation error and second-order heterogeneity are confounded in this dataset, and together they account for half the variance of fish density. The coefficient of variation for observation error alone in such datasets is typically about 30%, which is less than half of the confounded residual error here. This suggests substantial second-order heterogeneity, and that indicator sites will need to be replicated.

Dam-impacted and unimpacted reaches are expected to converge after CRRDR, providing a second type of "reverse" BACI experiment. Classic BACI designs start with a set of similar sites, one of which diverges in condition from others due to an impact. However, when ecological restoration is the impact, the site should not only diverge away from other similar degraded sites, but also converge toward sites that are already in good condition. For simplicity we call this a "reverse" BACI, although the statistical approach is identical; it is only the direction of change that differs. The cleanest comparison for CRRDR is between reaches directly above and below the reservoir site. Slightly more broadly, reaches downstream of Cachagua confluence and upstream of Tularcitos confluence should all be generally comparable in terms of hydrologic, geomorphic, and biotic processes, so that those upstream of CRRDR represent target conditions for those downstream of CRRDR.

Due to heterogeneity in governing processes, some reaches do not have suitable controls. In particular, the unconfined alluvial channel downstream of Tularcitos confluence should behave differently than the steeper, confined river upstream of Tularcitos confluence, which means the alluvial channels have no sites suitable for paired controls. It is possible that sections of the nearby Arroyo Seco River, which is undammed and relatively pristine, might serve as a target control for physical processes in alluvial response reaches. However, its biota and climate are somewhat different.

Downstream reaches are heterogeneous in the direction of expected response, providing additional degrees of freedom. For channel sediments, National Marine Fisheries Service (2013a) identified 3 spatial domains expected to have distinct responses to CRRDR (Table 4). Because the two alluvial domains (downstream of Tularcitos) have no controls, they are limited to "Before-After" type designs, but they should show a distinctly different response than the impact reaches upstream of Tularcitos confluence.

Mediated delay in response creates two classes of predictions. The first is immediate response to CRRDR itself, for example the modest sediment wave expected by mobilization of sand from the reservoir reach and ongoing transport of LWD. The second is a response to a large episodic flow event that moves much larger amounts of sediment and wood past the former dam site, but which may not occur for years or possibly even decades after completion of CRRDR. Since this episodic channel change is expected to be the major engine of channel recovery after the reroute, one of the most salient tests of the success of CRRDR will be comparison between reaches downstream of Los Padres and downstream of CRRDR, before and after such an event.

Table 11 and Table 12. summarize a prediction-testing framework based on these constraints and opportunities.

Table 11. Prediction-Testing Framework for Response of Downstream Habitats to CRRDR.

A. Predictors (Fixed Effects in Linear Mixed Model)

Control Sites – above CRRDR		**Impact from Upstream Dam**	**Process Domain**
C3	Above LPD	No	Transport reaches
C2	LPD to Cachagua	Yes	Transport
C	Cachagua to CRRDR	Yes, tempered by trib sand & gravel	Transport
Impact Sites – below CRRDR			
I0	Reservoir reach (CRRDR)	Yes	Response reaches
I	CRRDR to Tularcitos	Yes	Transport
I2	Tularcitos to Robinson	Yes, tempered by tribs (sand)	Response, Restored aquifer
I3	Robinson to Schulte	Yes, tempered by tribs, aquifer	Response, Depleted aquifer
I4	Schulte to Hwy 1	Yes, tempered by tribs, aquifer	Response, Depleted aquifer
Time Periods			
B	Before CRRDR	Impact of San Clemente Dam	
A	After CRRDR, until large episodic flow	Direct impact of CRRDR itself	
A2	After episodic flow(s)	Impact of restored fluvial processes	

B. Testable Predictions

Prediction	**Sites**	**Periods**	**Caveats**
i. Before reroute, SCD degraded the river	I vs C	B	Causal interpretation assumes no systematic pre-dam differences between I and C.
ii. CRRDR causes change in dam-degraded reaches	I vs C2	B vs A	Robust causal inference (standard BACI).
	I2 vs C2 I3 vs C2 I4 vs C2	B vs A	**Not Recommended**: Standard BACI, but difficult to interpret (confounds process domains & treatments)
iii. CRRDR causes convergence of degraded and control reaches	I vs C I vs C3?	B vs A	"Reverse" BACI, causal inference for transport reaches only (no controls for I2, I3, I4)
iv. CRRDR produces little response in some traits	I2, I3, I4	B vs A	Equivalence testing. No control sites, but not as important when testing for equivalence.
v. CRRDR + episodic flow causes stronger response in degraded reaches	I vs C2	A vs A2	Robust causal inference (standard BACI), but no controls for I2, I3, I4
vi. CRRDR + episodic flow causes convergence of degraded & control reaches	I vs C	A vs A2	"Reverse" BACI, robust causal inference for transport reaches (no controls for I2, I3, I4)
vii. CRRDR + episodic flow causes convergence of degraded reaches in different process domains	I, I2, I3, I4	A vs A2	"Reverse" BACI, robust inference relies on assumption of different directional responses rather than on use of controls

Table 12. Prediction testing framework for indicator sites in the reroute section of Carmel River.

Testable Prediction	Sites	Periods	Caveats
i. CRRDR causes reservoir reach to converges toward transport reach	I0 vs C	B vs A	"Reverse" BACI design, robust causal inference.
ii. CRRDR causes geomorphic change in reservoir reach	I0 vs. ?	B vs A	True BACI design, if appropriate control sites located (upper end of Los Padres Reservoir?)
iii. CRRDR + episodic flow causes reservoir reach to converge on transport reach	I0 vs C	A vs A2	"Reverse" BACI design, robust causal inference.
iv. CRRDR + episodic flow causes natural geomorphic behavior (step pool formation)			

Performance Metrics for Indicator Sites

The review in the main text suggests that key predictions to be tested at individual sites are:

- Increased deposition of sand and gravel, detectable through pebble counts.
- Greater diversity and temporal variation in sediment sizes, detectable through sustained pebble counts over time.
- Reversal of incision and channel-narrowing, perhaps episodically. Detectable by repeated topographic/benthic surveys of channel geometry.
- Increased deposition of sand on floodplain, increased variability of deposition over time, detectable by repeated facies mapping or pebble counts in the floodplain.
- Increased occurrence of spawnable gravel, increased variability of spawnable gravel over time, detectable by repeated facies mapping or pebble counts.
- Increased diversity of benthic macroinvertebrates, detectable by standardized sampling techniques.
- Increased variability of benthic macroinvertabate community over time, detected by standardize sampling techniques, sustained over time.
- Increased density of YOY steelhead (associated with spawning gravel), increased variability over time (also associated with spawning gravel). Detectable using closed-population mark-recapture methods or depletion sampling.
- Increased occurrence and size of LWD, detectable by quantification of LWD.
- Increased geomorphic effect of LWD, detectable by repeated pebble counts and surveys of channel geometry at sites with accumulated wood vs those not accumulating it.
- Increased density of age 1+ steelhead (associated with BMI diversity, LWD, channel complexity), and increased variability over time. Detectable using closed-population mark recapture methods.
- Decreased pool depth, increased variability in pool depth.
- Uncertain response of exotic species to CRRDR: especially crayfish, bullfrogs, brown trout.

Most of these predictions can be tested by recurrent data collection on the following performance metrics:

1) **Channel Geometry**.
2) **Sediment Characteristics:** of both bed and floodplain.
3) **Large Woody Debris**: density, size composition and geomorphic effect.
4) **Benthic Macroinvertebrate community**. Composition and density if practical.
5) **Juvenile Steelhead**: density, site distribution, possibly genetics
6) **Alien Species**, particularly crayfish, brown trout, bullfrogs.
7) **Riparian vegetation**

This section reviews existing data that could potentially be used to describe the river conditions before the dam removal. Each metric is considered in terms of the components of steelhead viability (Table 3): habitat capacity, habitat quality, habitat diversity, and ecological connectivity.

The review is based on metadata compiled for the Carmel River by ENVS 660 (2012). In addition, we also consider a collaborative initiative began in 2013 by NOAA, USGS, and CSUMB to establish high-priority sites for collecting additional "before" data for the CRRDR. The initial set of collaborative Indicator Reaches (IRs) were designed by NOAA and USGS to implement a reverse BACI design for the river directly downstream of CRRDR (Table 11B, iii and vi), as well as for the reservoir reach within the CRRDR project area (Table 12, i and iii). An additional set of IRs were established by CSUMB (Leiker et al. 2014) in the response reaches of middle and lower Carmel Valley (Table 11B, iv and vii).

The IRs were selected according to criteria necessary for suitable sampling of key indicator data. In particular, sites needed to be shallow enough to allow for pebble counts, BMI kick-sampling, and back-pack electroshocking using standard methods. In addition, sites were designated to consist of at least 3 riffles with intervening (shallow) pool habitat, to permit additional replication at the channel unit (sub-reach) level.

Generally we recommend that for new sites established as part of the prediction-testing framework of Table 11, the approaches used should follow or extend the template established for the collaborative IRs. However, there will be tension with existing datasets that use other approaches but that provide valuable "before" data. Because of this, we expect there to be some heterogeneity of methods for both site-selection and protocols.

Table 13. Existing datasets for channel geometry

Source	Year	Area	Description
Ground Surveys			
IRs[1] (NOAA-led)	2013-present	2 reaches below SCD, 1 in upper SCD reservoir 2 above SCD reservoir influence	7 benchmarked, ground-surveyed cross sections per reach.
IRs[1] (CSUMB-led)	2013	5 reaches in lower river, from deDampierre to Hwy 1	More cross sections below NOAA BACI cross-sections Leiker et al. (2014).s. Sheldon's.
(Jones & Stokes Associates 1998)	2008-2011	Six cross sections above Los Padres Reservoir, near Bluff Camp and Carmel Camp	Designed to study channel response to fire impacts
Matthews et al. (2008)	1978-2007	2 reaches, Via Mallorca to San Carlos Road and	Repeat longitudinal profiles in 1997, 1999, 2001, and 2007. Some historic surveys from 1978 and 1984.
Remote Sensing			
LiDAR	2010	Entire watershed	LiDAR collected at 1 point per meter with a 3 m DEM product
Photogrammetry from Aerial Photos	Annually since 1980s	SCD to Estuary	Suitable for plan-form changes

[1] Collaborative Indicator Reaches (NOAA/USGS/CSUMB)

Channel Geometry

Channel geometry can indicate all four components of the VSP framework: habitat area (capacity), quality, connectivity, and diversity. Channel geometry can dictate total available habitat area and habitat quality by creating conditions that are suitable for fish production. Channel geometry can create hydraulic conditions that present a velocity or depth barrier, which would restrict both connectivity and habitat area. Varied channel geometries can also create a diversity of channel types that can be related to a diversity of habitat types.

Channel geometry datasets have been collected by MPWMD, CSUMB, USGS and NOAA. In 2013, NOAA and USGS established a series of collaborative Indicator Reaches (IRs) in anticipation of dam removal. Within each of the four IRs there are 6 benchmarked cross-sections, although one cross-section in the reservoir reach was lost in 2014 due to construction activities. In 2014 the remaining cross sections in the reservoir reach and six in the reach just below SCD were surveyed. NOAA/USGS surveys also collected detailed bathymetric data in two large pools in the two IRs below SC Dam, as baseline information that will allow detection of new sediment filling these pools after dam removal. MPWMD has surveyed repeat longitudinal profiles in the lower mainstem of the river between Via Mallorca and Robinson (Matthews et al. 2008).

CSUMB also established a series of IRs using similar methods as NOAA/USGS, focusing on the alluvial river between Rosie's Bridge and Hwy 1. Above LPD there are six cross sections near Bluff Camp and Carmel Camp. These sites were first serially surveyed to quantify stream response to the marble Cone Fire (Hecht 1981). New benchmarks were established in 2008, following the Basin Complex fire (Richmond 2009). Kelly (2011) resurveyed the sites established by

Richmond (2009) and summarized the existing data sets from 2008 to 2011.

In addition to ground surveys, remote sensing data may be used to track some aspects of channel geometry. Aerial photos for the Carmel dating back to the 1980s can be used to monitor plan-form changes in the river. Of particular interest is the lower mainstem downstream of the Narrows, where the river was braided in the early 1900s, but is now an incised single thread channel (Kondolf 1982). Surface modeling methods such as photogrammetry or LiDAR may be used to map 3-dimensional changes in the river (e.g. incision or aggradation). However, as the Carmel has dense riparian vegetation along the most of the river, the vertical accuracy of these remote sensing methods is highly variable (ENVS 660 [CSUMB Class] 2014).

Recommendations

- Establish cross-sections in IRs suitable for tracking changes in channel geometry.
- Use similar method of bench-marked cross-sections in any additional IRs that are established
- Aerial photos useful for indicating plan-form channel changes.
- Variability of thalweg depth from long profiles can be interpreted as habitat variability (Tullos et al. 2014, East et al. 2015). Long-profiles could thus provide meaningful Before/After comparison, distinct from the IR system.
- LiDAR-derived DEMs not currently useful for inferring channel geometry, though reanalysis of point clouds at finer resolution may prove useful.

Sediment Characteristics

Sediment characteristics are physical metrics that can indicate habitat quality and habitat diversity. Sediment characteristics indicate the quantity and quality of spawning habitat. This is particularly important in reaches below dams, which often lack gravel-sized substrate needed for spawning. Sediment characteristics can also indicate habitat diversity through varied sediment size, which can facilitate steelhead production at a variety of life stages.

Datasets on the size distribution of sediment before the dam removal have been collected at the IRs. At each of the NOAA IRs, pebble counts were collected in 2013 using a modified Wolman pebble count. CSUMB also has collected pebble count data at its IRs.

Above LPD, at each of the cross sections pebble counts were conducted annually between 2008-2011 (Kelly 2011).

Between 1992 and 1997, suspended sediment and bed-load data were collected at the USGS gaging station *Carmel River near Carmel (station number 11143250).* These data are relevant for the total historic sediment load in the Carmel River, but the relative effect of CRRDR would be difficult to detect through continued monitoring at this site. This is because the effect of CRRDR on overall sediment load is expected to be small, and the USGS monitoring site is downstream of several high sediment yield tributaries (i.e. Tularcitos, Robinson Canyon). Therefore the relative contribution of CRRDR to the total sediment yield would be difficult to detect through monitoring at this USGS gaging site

In November 2014, the USGS installed a continuous in-stream turbidity sensor (DTS-12) just upstream of the weir above the MPWMD rearing facility, which is tracking turbidity (cf: suspended sediment) temporal trends with a 15-minute sampling interval. If funding permits, it would be advantageous to install additional DTS-12 sensors at other places on the river, including above the CRRDR in the mainstem Carmel River and at another location on the mainstem river downstream from the confluence with Tularcitos Creek. CSUMB is collecting suspended sediment samples during flow events of varying magnitudes to construct a rating curve for the turbidity sensor.

Table 14 Existing datasets for sediment characteristics

Source	Year	Area	Description
IRs (NOAA/CSUMB)	2013	Sediment data were collected at 2013 cross section survey sites	Pebble counts were collected doing using a grid laid on the substrate to sample random particles
USGS/CSUMB	2014-present	Continuous monitoring of turbidity below dam	In addition to turbidimeter, CSUMB is collecting suspended sediment samples for rating curves
Kelly (2011)	2008-2011	Sediment data were collected at each of the six survey cross sections	Pebble counts were collected using a modified Wolman pebble count method
USGS	1992-1997	At the USGS gage *Carmel R nr Carmel* (11143250)	Bed-load and suspended sediment data were collected at the gage site
Jones and Stokes 1998			Survey of location of spawning gravel?

<u>*Recommendations*</u>

- Recurrent collection of pebble counts at NOAA and CSUMB IRs, and any additional IRs that are established.
- Continuous monitoring of turbidity at turbidity stations above and below CRRDR, combined with periodic collection of suspended sediment samples to rate the turbidity stations.
- Additional turbidity stations as funding allows, including in the combined-flow reach and downstream of Tularcitos Creek confluence.
- If sites above LPD (Kelly 2011) are incorporated into the IR system, careful attention to reconciling pebble count methodologies might be needed.
- Special focus on seeing if spawning gravel size substrate appears in IR directly below dam.
- Well-conducted pebble counts can be used for a variety of substrate-related habitat metrics. However, methods for estimating area of spawning habitat are not clear.

Table 15. Existing datasets for large woody debris (LWD)

Source	Year	Area	Description
Kelly (2011)Smith et al. (2003)	2002	7 reaches from RM 0.5 - 15.8	Representative (non-random) sample of sites. Evaluation of physical function, GPS locations.
Smith and Huntington (2004) Matthews et al. (2008)	2003	RM 3.2 – 15.8	Comprehensive inventory, evaluation of physical function, GPS locations in GIS, 29 pieces tagged
ENVS 660 [CSUMB Class] Smith et al. (2003)	2013	Six 500m reaches between SCD and LPD, and six 500m reaches between SCD and Lagoon	Reaches selected based on Smith and Huntington (2003) data, then subsampled as 100m reaches. Occurrence of LWD, GPS coordinates, bed and bank scour

<u>*Large Woody Debris*</u>

Large woody debris is an important indicator of habitat quality and diversity. Large wood can be used for cover and feeding opportunities, which increases habitat quality. Addition of large woody debris into a system can also create habitat diversity through hydraulic complexity and scour.

In 2002 and 2003 CSUMB completed a census of LWD on the mainstem of the Carmel between the upstream end of the lagoon and the Stonepine Bridge (RM 15.8, downstream of SCD) (Smith and Huntington 2004). Due to lack of time the section upstream of Stonepine to Sleepy Hollow was omitted. Following the work of Smith and Huntington (2004), a 2013 study subsampled 3 km of river downstream and compared results to the 2004 work (ENVS 660 [CSUMB Class] 2013); and also surveyed 3 km of river upstream of SCD (six 500 m reaches), beginning in the reservoir deposits and reaching to RM 25.75.

<u>*Recommendations*</u>

- Re-surveying reaches defined by ENVS 660 [CSUMB Class] et al. (2013)(3 km DS, and 3 km US)
- Full LWD censuses downstream of Stonepine, repeating methods of Smith and Huntington (2004). Timing of census could be contingent on flow events moving large quantities of wood.
- Subsequent establishment of IRs at sites with newly-deposited LWD, to evaluate response of habitat and fish populations to wood deposition.

Table 16 Benthic macroinvertebrate (BMI) datasets

Source	Year	Area	Description
Smith and Huntington (2004)	2000-2010	8 sampling sites along main-stem from approx. Robinson Canyon to Los Padres Reservoir	Used the California Stream Bio-assessment Procedure. Some sites co-located with MPWMD steelhead sites
Kiernan (2013, unpublished)	2013	NOAA IRs	Collected 3 drift samples at 3 riffles within each of the 4 NMFS IRs (36 samples)

Benthic Macroinvertebrate Community

As the food source for salmonids, the benthic macroinvertebrate (BMI) are an important indicator of habitat capacity, quality and diversity. BMI communities relate to capacity by providing a suitable food, which can influence densities of salmonids in a reach. Similarly, BMIs indicate habitat quality by influencing the growth potential and production of individuals. Diversity of the BMI community provides resilience to the steelhead food source.

There are two datasets for benthic macroinvertebrates from the Carmel. The first covers 8 sampling sites between Robinson Canyon and the Los Padres reservoir (King et al. 2010). There was repeat sampling at each site between 2000 and 2010. This report used Index of Biotic Intergrity (IBI) metrics, which were designed for water quality monitoring and have a variable relationship to fish viability. Although the reported metrics may have unclear applicability to fish population viability, the raw data collected can be reexamined using a more appropriate analysis. These data showed that the highest diversity of BMI was upstream of Los Padres Reservoir; and the lowest diversities were at sites just downstream of each of the two dams. The existing pattern thus suggests negative impacts of dams, attenuating (but not abating) with distance downstream from the dam. This dataset therefore allows for meaningful tests of several BACI designs in Table 11.

BMI samples have also been collected at the 4 of the NOAA IRs. These comprise 36 samples between the 4 IRs, three samples at three separate riffles in each of the 4 reaches.

Recommendations

- Continued collection of samples at NOAA IRs, using IR protocols
- Continued collection of samples at sites of King et al. (2010), keeping consistent sampling protocol
- Analysis protocol of King et al. (2010) should be reconsidered, as IBI metrics may not be appropriate.
- Add BMI sampling to CSUMB IRs and any newly established IRs, using IR protocols.

Table 17. Alien Species

Source	Year	Area	Description
Ecological Studies	Ongoing	Bullfrog occurrence in in lower river below SCD, in reservoir of SCD	A bull frog removal program is in place in sensitive CRLF habitat portions of the river
NOAA	2013, 2014	BACI electrofishing sites	Occurrence of brown trout were noted during juvenile steelhead sampling

Table 18**.** Riparian Vegetation

Source	Year	Area	Description
MPWMD		Restoration sites	
Aerial photography		Entire watershed	
LiDAR		Entire watershed	Use LiDAR to get a sense of riparian density/vertical structure

<u>*Alien Species*</u>

Alien species can have a negative impact on population viability by negatively affecting abundance, productivity and diversity. Direct predation can impact both abundance and diversity, while competition can impact a population's productivity. Although there are many alien species in the Carmel River, we recommend focusing on 4 problematic species likely to have strong effects on steelhead viability: crayfish, bullfrog, striped bass and brown trout.

Brown trout would be sampled through the same methods as juvenile salmonids, so many of the juvenile steelhead datasets also contain valuable information about brown trout. Brown trout are currently well-established in the section of river upstream of Los Padres Dam and occasional in the vicinity of the CRRDR project site. Thus it would be useful to establish IRs upstream of Los Padres as target controls for the hypothesis that CRRDR may inadvertently increase the abundance and distribution of brown trout.

<u>*Recommendations*</u>

- Brown trout: Continued monitoring at the Indicator Reaches
- Identify and review existing datasets for crayfish, bullfrog, striped bass.
- Develop methods and sampling scheme for quantifying abundance and distribution of crayfish, bullfrogs, striped bass.

<u>*Riparian Vegetation*</u>

Riparian vegetation can be an indicator of population viability though its effects on habitat quality and diversity. Riparian vegetation can create shaded, cool waters that have a positive effect on a population's productivity. Riparian vegetation can also contribute LWD, both of which can lead to a diversity of habitat types.

Existing riparian vegetation datasets are both field-based surveys and remote sensing. Remote sensing data sets include aerial photography and LiDAR, both of which cover the entire length of the river downstream of the CRRDR site.

MPWMD riparian vegetation surveys are focused on restoration sites, including those actively managed through watering. They might prove useful for tracking effects of CRRRDR on restoration projects, but are less appropriate for testing predictions about the response of the river overall.

Table 19. Juvenile steelhead datasets

Source	Year	Area	Description
MPWMD (2013)	1993-present	9 sites (2 above SCD, 7 below)	Depletion-sampling each October. Some co-located with BMI sites of King et al. (2010)
NOAA IRs	2013-present	2 reaches below SCD, 1 reach in the upper reservoir and 1 reach above the reservoir influence	Each of the 4 sites divided into 4 sampling units. Single pass electrofishing.

Aerial photography can be used in image classification to estimate the total area covered by riparian vegetation. It can also be used to parse out specific types or classes of vegetation. LiDAR can be used to assess the vertical structure of vegetation, although this method is also susceptible to low data quality in the extremely dense riparian zone of the Carmel River.

Recommendations

- Continue collection of aerial imagery after removal of dam.
- Conduct analyses of existing imagery to determine what frequency of flights is necessary. Less than annual may be sufficient.
- Conduct land cover classification from aerial images, to track change in riparian vegetation
- Use existing LiDAR point cloud data to determine if feasible source of data on vertical density of riparian vegetation.

<u>*Juvenile Steelhead*</u>

Repeated sampling of juvenile steelhead gives direct performance data for all four aspects of viability: abundance, productivity, spatial structure and diversity. If juvenile sampling is co-located with the sampling of habitat-related performance metrics, it can offer insight into how the population is responding to changes in habitat, including changes attributable to CRRDR as well as other restoration activities or human impacts.

Data on juvenile steelhead have been collected by MPWMD for nearly 20 years at 2 sites above the CRRDR location and 7 sites widely distributed below it. (Monterey Peninsula Water Management District 2009). In addition, each summer the MPWMD conducts rescues of juveniles in sections of the lower mainstem where the river dries into isolated pools in the summer, trapping individuals. The rescued fish are counted and either relocated to the Sleepy Hollow Rearing Facility and then re-released in the Fall, or released immediately to wet parts of the river when the Rearing Facility is either full or non-operable. MPWMD has a variety of other fish data as well, including lagoon seining, counts of adults at the two dam sites, and redd surveys.

Since 2013, the NOAA South West Fisheries Science Center has been sampling juvenile steelhead twice annually at the NOAA CSRs, using subsite-replicated mark-recapture design. Mark-recapture was chosen over the more established depletion approach for two reasons: lower-intensity electrofishing creates a smaller impact on fish and habitat; and mark-recapture estimates are more robust statistically than depletion estimates, particularly if fish vary in their catchability. IRs are divided up into 3 subsampling units and single pass electrofishing is used to collect and mark (fin clip) fish in each subunit; then the procedure is repeated a week later to recapture marked fish.

For detecting response of steelhead to changes in habitat, it is important that data on all the various performance metrics be co-located, i.e. collected from the same set of sites. The IRs were designed with this in mind, but lack a long time-series for the "before" period of dam removal. The MPWMD sites have a much richer history and some are co-located with the

BMI sites tracked by MPWMD, but in general lack the full suite of performance metrics. For this reason the two datasets are complementary.

Recommendations

- Continue sampling at both the MPWMD depletion sites and Collaborative Monitoring Sites
- New sites should use IR protocol
- Consider calibrating IR and MPWMD protocols by conducting both concurrently at a subset of sampling occasions.
- Other fish data collected by MPWMD (rescues, redd counts, adult counts at dams, lagoon seining) are useful for parameterizing the integrated population model described in the next section.

Power analysis

The four NMFS sites established in summer 2013 have enough preliminary data to conduct a simple power analysis for the reverse-BACI design. A power analysis determines whether the existing data and sampling methods provide sufficient statistical power to detect a response to CRRDR.

Interpretation of the preliminary data is potentially affected by unique steelhead management events related to the great drought of 2013-2014. Extremely low flow in the Carmel River in September 2013 interfered with operation of the Sleepy Hollow Rearing Facility, requiring release of 10,000 large juvenile *O. mykiss* into the river in section I in October 2013, and another 1,000 in February 2014. However, size distributions and wear patterns of fish sampled at the IRs over this same time period suggested that the influence of these releases on the data were negligible.

For simplicity we limit our power analysis to the summer 2013 sampling occasion. At that time there was substantial heterogeneity among sites in density of fish (Figure 14) and sizes of fish (Figure 15). Interestingly, the reaches with the greatest population density and the largest *O. mykiss* are the two sites most impacted by San Clemente Dam: the reservoir reach (RES) and the reach just below San Clemente Dam (SCD),

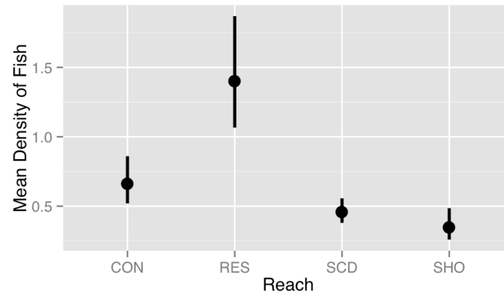

Figure 14. Estimated density (m^{-2}) of juvenile *O. mykiss* from first sampling occasion at Priority 1 sites (bars = 50% CI). CON=Control site in section C; RES=Reservoir site in section I0; SCD=I site directly below San Clemente Dam site; SHO=I site near Sleepy Hollow. Estimates are from mark-recapture.

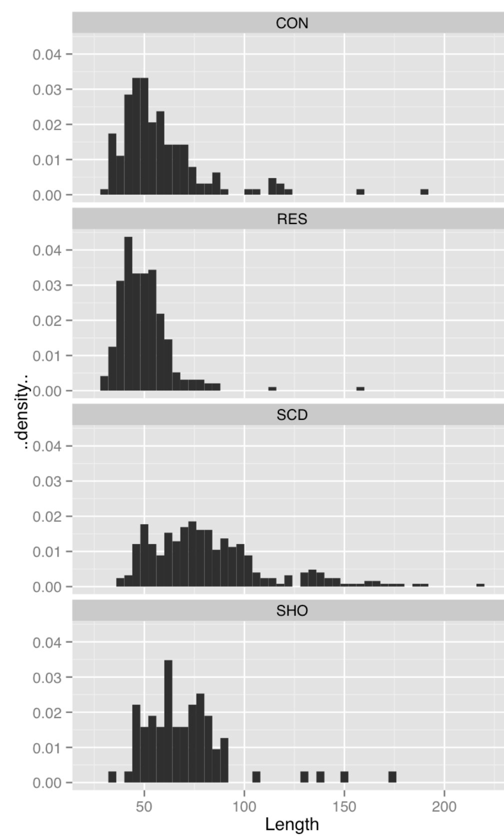

Figure 15. Fork Lengths of juvenile *O. mykiss* from first sampling occasion at Priority 1 sites. 3-letter site codes as in Figure 14.

respectively. However, although the reservoir reach has the greatest density, it also appears to have the slowest-growing fish (Figure 15); whereas the SCD reach appears to retain more age 1+ fish (c. >100mm), even mature rainbow trout (c. >200mm). These preliminary findings reinforce the point made in the review that benefits of CRRDR for steelhead must be interpreted within the context of the conditional-strategy model of steelhead life-history-expression.

To conduct a power analysis we used information-theoretic methods, in which the explanatory power of two competing models are compared using Akaike's Information Criterion (AIC; see Burnham and Anderson 2002). The model with the lowest AIC score is considered to have the greatest explanatory power, and competing models whose AIC is 10 or more units higher are considered to have essentially no support relative to the best model (Burnham and Anderson 2002).

First we simply ask if there is significant heterogeneity in fish sizes among reaches during the first sampling occasion. For the fish data, each IR is composed of 3 or 4 sampling units, so we compare a model in which fish size (log-weight) varies randomly among units to a model where it also varies systematically among reaches (Table 20A). The Reach + Unit model is clearly the superior model, with an AIC score 20.3 units lower than the Unit-only model. This demonstrates great reach-level heterogeneity in the distribution of fish sizes, indicating the potential for convergence of impact and control reaches to be detected statistically.

We used these first-occasion data to simulate a second sampling occasion in which fish weights in the SCD reach converged to the same mean and sd as the control reach, while the other sites retained the same mean and sd as the first occasion (Table 20B). The Reach:Time interaction in Table 20B represents a test of the "reverse BACI" hypothesis in which an impacted site is restored to the same condition as the control site, and Table 20B shows that the dataset provides sufficient power to distinguish models with and without this effect. In fact, the dataset was also sufficient to detect partial convergence of the SCD reach to the control reach (Table 20C).

Table 20. Power analyses for reverse BACI designs at Priority 1 sites, based on log-weight of juvenile *O. mykiss*.

A. First sampling occasion only

Model	**df**	**AIC**	**ΔAIC**
Unit	3	2218.5	20.3
Reach + Unit	6	2198.2	0

B. Reverse BACI scenario with full convergence of SCD to CON

Model	**df**	**AIC**	**ΔAIC**
Reach + Time + Unit	7	4490.6	199.5
Reach + Time + Unit + Reach:Time interaction	10	4391.1	0

C. ANOVA for reverse BACI scenario with partial* convergence of SCD to CON

Model	**df**	**AIC**	**ΔAIC**
Reach + Time + Unit	7	4501.3	88.8
Reach + Time + Unit + Reach:Time interaction	10	4412.5	0

* Partial = half the change of full convergence

Notes: Mixed-effects models with sampling units within reaches treated as random effects. Model with lowest AIC score has greater explanatory power. ΔAIC greater than 10 indicate models clearly inferior to the best model (ΔAIC=0).

Table 21. Datasets for each performance metric in relation to the proposed BACI design reaches

River Section	Channel Geometry	Sediment	Large Woody Debris	BMIs	Juvenile Steelhead	Alien Species	Riparian Vegetation
C3	Kelly (2012); Remote sensing	Kelly (2012)		King et al. (2010)	None		Remote sensing
C2	Remote sensing		ENVS 660 (2013)	King et al. (2010)	MPWMD (1990-2014)		Remote sensing
C	IRs (2013-14); Remote sensing	IRs (2013-14)	ENVS 660 (2013)	King et al. (2010); IRs (2013-14)	MPWMD (1990-2014); IRs (2013-14)	IRs (2013-14; brown trout)	Remote sensing
I0	IRs (2013-14); Remote sensing	Reservoir deposits; IRs (2013-14)	ENVS 660 (2013); Data from 'log catcher' at reservoir?	King et al. (2010); IRs (2013-14)	MPWMD (1990-2014); IRs (2013-14)	IRs (2013-14; brown trout)	Remote sensing
I	IRs (2013-14); Remote sensing	IRs (2013-14)	Smith and Huntington (2004); ENVS 660 (2013)	King et al. (2010); IRs (2013-14)	MPWMD (1990-2014); IRs (2013-14)	IRs (2013-14; brown trout)	Remote sensing
I2	Leiker et al. (2014); Remote sensing		Smith and Huntington (2004); ENVS 660 (2013)	King et al. (2010)	MPWMD (1990-2014)		Remote sensing
I3	Leiker et al. (2014); GMA (2007); Remote sensing		Smith and Huntington (2004); ENVS 660 (2013)	King et al. (2010)	MPWMD (1990-2014)		Remote sensing
I4	Leiker et al (2014); GMA (2007); Remote sensing		Smith and Huntington (2004); ENVS 660 (2013)	King et al. (2010)	MPWMD (1990-2014)		Remote sensing

Relating Performance Metrics to Testable Predictions

In order to be useful to the testable predictions (Table 11B), existing or future datasets must match the temporal and spatial requirements of a specific prediction. Each of the performance metrics have some datasets from before the dam removal process began, although some metrics have very limited data.

Relating the existing (before dam removal) performance metrics datasets to specific BACI design reaches (Table 21), it can be seen that not all performance metrics have enough data to be evaluated within each testable prediction. For example, to evaluate the prediction that *CRRDR causes change in dam-degraded sites* there would need to be existing data in both *C2* (LPD to Cachagua) and *I* (CRRDR to Tularcitios). Several of the Performance Metrics, including Channel Geometry and Sediment Characteristics, have no data in C2 making testing that particular prediction impossible.

Indicator Reaches within CRRDR

Reservoir Reach

The new notch will be deep enough that it is predicted to allow fluvial processes to begin steepening and coarsening the "reservoir reach" directly upstream (Figure 2); (National Marine Fisheries Service 2013a). Currently the reservoir reach has a high proportion of sand due to the low-gradient channel established behind San Clemente Dam. As the channel incises into the accumulated reservoir sediments and steepens, it should increase transport capacity. This in turn should drive a net loss of channel area covered by sand, and a net gain of channel area covered by gravel and cobble (National Marine Fisheries Service 2013a, p. 72).

We recommend that indicator sites be established in the reservoir reach, using the same methods as outlined in the previous section. Two types of controls can be used to ask slightly different questions: A standard control would be a reach similar to the reservoir reach, but in which no downstream notching is occurring. It is not clear if the Carmel system has such a control site; the only likely site would be the upper end of Los Padres Reservoir. A target control would be a site that is currently similar to the expected target condition of the reservoir reach, and not effected by CRRDR. The section of Carmel River upstream of the reservoir reach could provide this sort of control site.

Key questions to be addressed with these data are outlined below:

Steepening and Coarsening: Does the reservoir reach steepen, coarsen, and develop a channel composed primarily of gravel and cobble? If so, how quickly and is it episodic or gradual?

Channel and Floodplain Morphology: How does the channel and floodplain morphology evolve in response to channel steepening?

Riparian Vegetation: How does riparian vegetation respond to channel steepening and morphological evolution?

Losing Reach: Does the channel function as a losing reach in summer? Under what conditions (climatic, channel evolution) does it lose all surface flow? Does the losing function change as coarsening and steepening occurs?

BMI response: Does composition and abundance of benthic macroinvertebrate community improve (more diverse, more abundant, more stable) as the channel steepens and coarsens? Does composition and abundance converge toward the target control?

Steelhead response: Do fry, age 0 parr, age 1+ parr, and/or resident O. mykiss develop greater abundances and/or growth rates in the reach as the channel coarsens?

Combined-Flow (CF) Reach

Plans for the 425m long Combined-Flow Reach specify boulder step-pool sequences interspersed with low velocity areas (typically pools) which would provide holding areas for migrating adults and juveniles (National Marine Fisheries Service 2013a, p. 73). This area is also intended to serve as new habitat for steelhead fry and age 0 juveniles, and improved habitat for age 1+ juveniles. Specific criteria for success are improvement in cover from predators (due to boulders and LWD), lower water temperatures (due to more vegetative cover), greater inputs of terrestrial insects and nutrients from riparian vegetation, and rapid colonization by a greater diversity and higher abundance of freshwater macroinvertebrates than occur in the present reservoir reach (National Marine Fisheries Service 2013a, p. 73, 75). Some existing riparian vegetation will be removed during the CRRDR and may cause habitat features dependent on vegetation (temperature, terrestrial insect inputs, etc.) to become degraded for several years, but the overall prediction is that such degradation will only last until new plantings develop enough to provide a net improvement in habitat quality.

Key uncertainties not covered in the Biological Opinion are how quickly *O. mykiss* will colonize the new, vacant habitat, and whether introduced species with similar habitat requirements might colonize the habitat and produce negative impacts on *O. mykiss*. Three introduced species that especially pose this risk are bullfrogs (*L. catesbiana*), crayfish (spp). and brown trout (*S. trutta*)

Monitoring required in the NMFS Biological Opinion (National Marine Fisheries Service 2013a, p. 29) focuses on establishing that suitable habitat conditions are directly produced by the project. Criteria for success are instream areas providing unobstructed fish passage, forage, cover, step-pools, and resting pools. Monitoring of restored habitats, fish passage, and instream flow in the project area is specified for years 1-3 and 5, and possibly year 10 if success criteria have not been met by year 5. The BO indicates that corrective actions may be necessary in the first 5 years to ensure fish passage structures and instream habitat components "are functioning as intended" (National Marine Fisheries Service 2013a, p. 29).

We recommend that the CF-reach become an indicator site after CRRDR, with similar data-collection as elsewhere. Emphasizing intended function as the criterion for success suggests that data-collection efforts should not be limited to those of other sites, but augmented as noted below. Key questions about the improvement of habitat and colonization by *O. mykiss* are:

Cover: Does the Combined-Flow Reach develop cover (from boulders and LWD) similar in structure and function to natural channels with similar morphology (step-pools, plane-beds, bedrock pools)?

Water Temperature: Does the rise in water temperature between the top and bottom of the project site, observed prior to the reroute, significantly decrease after CRDRR and especially, after development of riparian vegetation in the Combined Flow Reach?

Predictions from the NMFS BO (National Marine Fisheries Service 2013a, p. 79) are that the mechanisms for cooling in the combined flow reach are 1) greater flow velocities creating more evaporative cooling than would occur in the bypassed reach; 2) more topographic shading due to narrow, north-aligned canyon, 3) better riparian shading; and 4) removal of heating in large, shallow reservoir.

To test these predicted mechanisms, a detailed study of thermal fluxes would need to be made. This would involve a variety of sensor types positioned throughout the CF-reach.

Terrestrial Inputs: As riparian vegetation develops, do inputs of terrestrial insects and nutrients to the channel converge with those observed in natural channels with similar morphology and riparian vegetation? Methods would be similar to those used by Rundio and Lindley (2008).

Benthic Macroinvertebrates: Do benthic macroinvertebrates rapidly colonize the Combined-Flow Reach, and do their abundance and community composition converge on those observed in natural channels with similar morphology or to nearby unimpaired channels? Methods as at other indicator sites.

Steelhead Colonization: Do fry, age 0 parr, age 1+ parr, and/or resident O. mykiss develop similar abundances, growth rates, and survival as unimpaired channels with similar morphology? The BO specifies data collection in years 1,2,3,5 and every 5 year thereafter until success criteria are met. A question is what sites could serve as target controls? Methods as at other sites.

Brown Trout Colonization: Do fry, age 0 parr, age 1+ parr, and/or resident *S. trutta* colonize the Combined-Flow Reach and use it at similar abundances as similar habitat upstream of Los Padres Reservoir? Are there negative consequences for *O. mykiss*?

In addition to the mark-recapture methods used at other sites, additional removal experiments could be conducted to unambiguously determine impacts on *O. mykiss*.

Crayfish, Bullfrog Colonization: Do exotic crayfish and/or bullfrogs colonize the Combined-Flow Reach, and if so how quickly relative to *O. mykiss*, and are there negative consequences for *O. mykiss*? Here again, removal experiments could be conducted to unambiguously determine impacts on *O. mykiss*.

Table 22. Lagoon datasets

Metric	Source	Year	Description
Water surface elevation	MPWMD (2006) & subsequent annual reports	1991 to present	15-minute water surface elevation from south arm
Bathymetric Cross sections	MPWMD annual reports	1994 - present	4 cross sections on the central arm, surveyed annually in September
Bathymetric	King et al. (2010)	2006	Complete bathymetry from ground-surveys, photogrammetry, and LiDAR
Beach width, beach grain sizes	MPWMD (2005)		
Wetland Vegetation (species composition)	MPWMD annual reports	annually 1995-2005, then semi-annually	Quadrats along transects in wetlands of north arm
Beach width, Emergent Vegetation (extent)	Aerial photos		Image analysis methods and time-series need to be developed.
Water quality	Hope (2007)	2009	
Steelhead	MPWMD (2013)	2012	Schnabel-type mark-recapture.

Performance Metrics for the Lagoon

The conceptual model and review suggests four important first-order predictions for the lagoon, stemming largely from the expected increase in sand supply after the CRRDR:

- Aggradation of sand in the estuary/lagoon, especially in the main arm.
- Increased deposition of sand on the beach, with possibility of higher sandbar crests and a wider beach.
- Displacement seaward of the sandbar crest.
- Lagoon less vulnerable to wave-driven breaching due to higher sandbar crest, but more vulnerable to management-driven interventions.
- Changes in extent of fine-sediment substrate relative to sandy substrate.
- Net accumulation of LWD in the estuary.

The possibility of either or both the estuary bed and the beach/sandbar aggrading means that volume and depth of the lagoon could respond in either direction of change: increase if bar building is greater than bed aggradation, but decrease if aggradation dominates. This is one of the key uncertainties in the predicted response of the lagoon to CRRDR.

The first-order predictions in turn lead to a number of important second-order predictions:

- Decrease or increase in lagoon volume, leading to altered rearing capacity for steelhead.
- Decrease or increase in lagoon depths, leading to altered extent of emergent vegetation vs. open water, and altered vulnerability of steelhead to avian predators.
- Uncertain implications for water quality, distribution of predatory striped bass, composi-

tion of macroinvertebrates and response of steelhead using the lagoon.

The first-order predictions can be tested by recurrent data collection on the following performance metrics:

1) **Lagoon bathymetry**
2) **Dynamics of water-surface elevation.**
3) **Sandbar shape, position, and elevation.**
4) **Beach width and position**
5) **Recurrent LWD census, possibly from aerial photos**

Interpreting the response of these metrics to the CRRDR is difficult because 1) the first four are highly dynamic at both weekly and seasonal scales, and 2) there is no control lagoon for comparison and no replication. This places an emphasis on sufficient repeated sampling in the "before" period to characterize the background variation prior to CRRDR. The lack of controls means that predictions can still be tested, but plausible alternative explanations for the predicted effect may not necessarily be ruled out. Some of the second-order predictions follow directly from first-order predictions (depth, volume), but for others alternative explanations may be much more difficult to rule out (e.g. water quality, distribution of striped bass).

Below we review existing data that could be used to characterize the "before" period.

Bathymetry

Lagoon bathymetry relative to water elevation or sandbar crest is an important indicator of habitat capacity and quality, through effects on water volume and extent of different water depths in the lagoon. Water depth has many ramifications for steelhead, including vulnerability to avian predators, thermal fluctuations, and extent of different vegetation types used for cover and feeding.

Since 1994 the MPWMD has annually surveyed four cross-sections in the main arm of the lagoon; all show inter-annual variation, but no long-term trends except for the most upstream cross section, which is incising (similar to the river channel immediately upstream).

Aerial photos have been collected annually in the summer time since the 1980s, and depending on image quality and water clarity, it might be possible to conduct depth-retrieval, an image-processing technique by which tone or color intensity of the image is converted to water depths. Depth-retrieval requires calibration by ground-based measurements of water depth at the time the imagery was collected.

Complete bathymetry was measured in 2006/2007 by Hope (2007). The dataset is useful for estimating lagoon volume and distribution of water depths at different stages. However, it provides no estimate of temporal variability in bathymetry. Given the modest variability and lack of trends in the cross sections (see above) it may still be reasonable to view this dataset as representative of the pre-CRRDR period.

Recommendations

- Continue annual surveys of 4 cross sections to detect change after CRRDR
- Investigate suitability of aerial photos for depth-retrieval for reconstructing annual bathymetric dynamics, perhaps using the cross-section data to calibrate the method.
- Repeat the bathymetric survey (Hope 2007) at some point after CRRDR if cross-sections indicate directional change.

Water Surface Dynamics

Water surface dynamics, measured as changes in surface elevation over time, show the pattern of breaching and the elevation (stage) of the water surface when the sandbar is in place. Thus it can be used as in indicator for a number of predictions: 1) raising of the mean water level due to higher sandbar crest; 2) increased resilience of the sandbar to breaching in summer and early fall; 3) in combination with bathymetry, estimates of mean depth, variation in depth, and volume of the lagoon, both after breaching and when the sandbar is in place.

MPWMD has collected water-surface elevations in the south arm, at 15-minute intervals nearly continuously since 1991. This is a very valuable dataset for testing some first-order predictions for CRRDR. As with other aspects of lagoon response to CRRDR, the predictions can be tested but alternative explanations for them cannot necessarily be ruled out due to lack of controls and replication. However, the particularly long and detailed record of water surface elevation should provide an unusually powerful "Before-After" test for effects even without controls, since it can be used to assess background variation at all relevant scales (diurnal, weather-related, seasonal, annual, etc.). If CRRDR alters sandbar behavior it should produce a qualitative change in one or more components of water-level variation soon after removal.

Recommendations

- Continue collecting water-surface elevations in the south arm to produce "after" time period of similar duration as "before" time period.
- Develop method(s) to characterize annual frequency of breaching and stage statistics for when sandbar is in place, to characterize the "before" period
- Develop methods to analyze step-change in dynamics associated with CRRDR.

Sandbar shape and position, beach width

Some predictions for the sandbar can be tested using water surface elevation (see above), but others—such as increased beach width and movement of the crest seaward—can only be tested using data about sandbar morphology itself. One would expect sandbar morphology and beach width to be highly dynamic at multiple scales: inter-annual, seasonal, tidal, and according to storm patterns. Currently there appears to be no "before" dataset for beach width and position that is collected at a suitable frequency to capture this variation.

Storlazzi and Field (2000) used aerial photos to characterize beach width at three points near the river mouth, for each of three times. While this is inadequate for characterizing temporal variability in beach width, consideration of additional aerial photos might produce a useful dataset. MPWMD has contracted for the annual collection of aerial photos in summertime from the lagoon to San Clemente Dam since the 1980s. Using these photos to estimate annual beach width might prove useful, but would confound annual and short-term variation. It would, however, presumably control for seasonal variation by focusing on beach width in the summertime.

It appears that morphology and position of the sandbar itself have been ground-surveyed occasionally, but not frequently enough to adequately characterize variation in the "before" period (e.g. see data summary in ENVS 660 [CSUMB Class] et al. 2012).

While it would be useful to test predictions about beach width and crest position, it is more important to test predictions about water-surface dynamics and lagoon volume and depth, because the latter are expected to have stronger implications for steelhead habitat capacity and quality.

Recommendations

- Investigate suitability of existing aerial photos for characterizing beach width prior to CRRDR, if resources permit.

Large Wood Accumulation

One possible benefit of CRRDR in the estuary is comparable to in the river: an increased rate in the accumulation of LWD. The estuary was not included in past censuses of LWD in the river mainstem, but should be included in future censuses.

Recommendations

- Conduct recurrent censuses of LWD in the lagoon on the same event-based timetable as in the river (see previous section).

Second-order predictions

Second-order predictions stem from changes in lagoon depth, volume, frequency of breaching, frequency of overwash, and changes in circulation patterns arising from such changes. The potential second-order changes most relevant to steelhead are changes in:

1) **Water quality (stratification in salinity, DO, temperature, etc.)**.
2) **Striped bass abundance and diet**
3) **Macroinvertebrate response**
4) **Steelhead response**

Numerous other factors, unrelated to CRRDR, have the potential to affect these metrics, so attributing change directly to CRRDR will be uncertain. The strongest case will be when second-order predictions can be linked strongly, both conceptually and statistically, to first-order changes such as aggradation of the lagoon bed.

Aquatic vegetation

Changes in lagoon depth due to aggradation of the lagoon bottom or build-up of the sandbar crest are predicted to alter the composition and extent of emergent aquatic vegetation, due to its sensitivity to water depth. This has implications for various species of wildlife, including steelhead.

MPWMD has collected data on aquatic vegetation composition and cover from quadrats in the North Arm since 1995. Data were collected annually until 2005 and biennially since then. Summaries and interpretation are given in annual MPWMD mitigation reports, especially the 2005 report (MPWMD 2006). Data gathered so far show that changes are subtle, but that unidentified factors may be favoring a shift from salt-tolerant to freshwater species (MPWMD 2013). Aquatic vegetation would be expected to respond to a marked change in water level dynamics or aggradation and so would be a useful indicator for change after CRRDR.

Spatial extent of emergent vegetation and of open water has not been monitored, but the annual aerial photos collected for the river since the 1980s could potentially be used to estimate a long annual-time-series of these metrics. Depending on the resolution of the photos it may also be possible to resolve plant communities into simple types, such as emergent vs. submerged. A useful analysis of the "before" period would be to use this long time-series to relate variation in vegetation, if any, to the similarly long time-series in water-surface dynamics.

Recommendations

- Continue collecting data on vegetation composition in quadrats in the North Arm.
- Investigate suitability of aerial photos for estimating extent of open water and different types of aquatic vegetation. If suitable, create time-series of open-water and vegetation extents.
- If time-series of vegetation extent can be estimated, analyze relationship to water surface dynamics, also taking into account changes in bathymetry due lagoon restoration projects, etc.
- If aerial images are suitable as determined above, continue collection of aerial photos in the "after" period to create a Before-After study design.

Water quality

Water quality in the lagoon can affect steelhead in a variety of ways, especially during the closed phase, which we focus on here. Warm temperatures (>17C) can intensify metabolic respiration and energy consumption, slowing down growth; and hot temperatures (>21C) can stress steelhead or even lead to death. Low dissolved oxygen (DO) impedes respiration, so low DO in combination with warm temperatures can suffocate steelhead. Salinity provides an osmotic challenge to respiration for juvenile steelhead not yet physiologically prepared for the marine environment. In addition, denser salt water may not mix with fresh, instead sinking below the fresh to "stratify," i.e. form a layer in the benthos. Stratified salt water lenses in coastal lagoons are sometimes observed to exhibit hotter temperatures and plunging DO relative to the layer of freshwater above, effectively excluding steelhead from feeding in the benthos.

Aggradation may change bathymetry in a way that effects water circulation and mixing, encouraging or discouraging stratification and/or replenishment of dissolved oxygen from the surface. Decreases in mean depth of the lagoon increase the surface-area-to-volume ratio of the lagoon, making it vulnerable to excessive heating during the day.

Perry et al. (2007) and also MPWMD annual mitigation reports describe water-quality monitoring at 5 sites in the lagoon. Data includes vertical profiles of water temperature, salinity and dissolved oxygen, collected roughly at monthly to biweekly intervals back to 2001. One of the sites, on the South Arm, is near a treated wastewater outfall and also in one of the deepest parts of the lagoon, and thus most prone to stratification. This site also includes a continuously operating temperature logger.

Recommendations

- Continue the vertical-profiling program at the five sites, as well as continuous temperature monitoring at the south arm.
- Develop methods for characterizing pre-removal variability in vertical profiles of water quality, perhaps in conjunction with water-surface elevations, wastewater outflows, tidal influences and river flows.

Striped Bass

Very little is known about how striped bass use the lagoon currently and this limits understanding of how they might be affected by the CRRDR. Because striped bass are piscivores known to have large impacts on juvenile salmonids in other parts of California (Lindley and Mohr 2003), their response to CRRDR could easily have a bigger impact on steelhead survival and growth in the lagoon than effects of CRRDR on steelhead via other causal pathways.

We are not aware of any population assessments of striped bass in the Carmel system. CDFW maintains an eradication program, and the data associated with this program might be suitable for estimating changes in abundance, using depletion-estimators or catch-per-unit-effort approaches. Unfortunately these sorts of approaches are more biased and less robust than mark-recapture or visual survey methods. CDFW catch data may also be suitable for detecting change in the size-structure of the striped bass population, which also probably affects predation risk for steelhead.

The CDFW program also includes diet studies using captured striped bass, which may be useful for detecting changes in per-bass predation rates on steelhead. However, without also knowing about changes in abundance of striped bass, this is not a strong indicator of net effect of striped bass on steelhead nor of striped bass response to CRRDR.

Recommendations

- Assess suitability of data from CDFW eradication program for annual estimates of striped bass abundance, size-structure and predation rates on steelhead. If appropriate, develop alternative methods for tracking these metrics through time, especially abundance and predation rates.
- Develop field studies elucidating links between lagoon structure / dynamics and striped bass ecology (especially depth, water quality, substrate and cover)

Macroinvertebrates

Benthic macroinvertebrates, as well as marine invertebrates brought into the estuary-lagoon system by tidal, wave, or overwash dynamics, comprise important feeding resources for steelhead. The composition and especially abundance of the invertebrate community is expected to be highly dynamic, especially as a function of sandbar breaching and closing. Thus, to detect response to CRRDR it is necessary to have long time series of data for both the "before" and "after" period.

Fields (1984) sampled invertebrates from stomachs of juvenile steelhead rearing in the lagoon and from the lagoon bed, on one day in late summer 1982. He found that food was extremely abundant in the bed but not in fish stomachs, and that the most numerous food eaten was of the species *Corophium spinicorne*.

Larson et al. (2005), Larson et al. (2006), and Perry et al. (2007) sampled seven sites on nine occasions over 2.5 years. Sampling in the first year was event-driven, whereas sampling in the other two years was at 3-month intervals. Sites, detailed methods, and summarized results are described in the reports. Co-location of invertebrate and water-quality sampling allowed for analysis of inter-relationships.

Watson (2007) collected weekly samples for 15 weeks in summer 2007 from 1 site with 4 subsamples in the Odello arm. She focused on *C. spinicorne* and found a strong association between their abundance and sandy bottom, no relationship with water quality, and synchronous, iteroparous reproduction. From this she concluded that most variation in abundance of *C. spinicorne* would tend to be associated with spatial and temporal variation in habitat, rather than in endogenous population dynamics.

De Lay (2010) examined spatial patterns of invertebrate abundance, by conducting a stratified random sample of 6 samples from each of 6 substrate types in the lagoon, in March 2010. Four key invertebrate taxa, *C. spinicorne*, *Eogrammarus*, *Neomysis* and *Gnorimosphaeroma* were each found to be strongly associated with different substrate types. This corroborated the idea that spatial variation in abundance of invertebrates is mainly due to habitat associations.

Thus, changes in invertebrate abundance and taxonomic composition are expected to be closely associated with changes in substrate extents.

Recommendations

- Investigate use of aerial photos for mapping substrate categories that are comparable to those designated De Lay (2010).
- If aerial photos are suitable for mapping substrate extents, estimate a time-series of extents for the "before" period.
- Conduct preliminary analysis of whether invertebrate samples described by Perry et al. (2007) are suitable for characterizing the "before" period.
- Use appropriate method (aerial photos, invertebrate samples at established sites, or both) to collect data in the "after" period of CRRDR.

Steelhead response

Capacity, survival and growth of juvenile steelhead inhabiting the lagoon are fundamental indicators of steelhead population viability, because they are related to abundance and persistence of the lagoon-anadromous life-history. Unfortunately, it is difficult to estimate these metrics, and even more difficult to confidently link their dynamics to first-order and second-order effects predicted for CRRDR.

A variety of steelhead abundance estimates have been made for the lagoon, none very satisfactory nor repeated in more than a few years. Student and faculty at CSUMB have tried a number of methods based on boat-mounted underwater cameras and sonar devices (ESSP 660 [CSUMB Class] et al. 2007, Perry et al. 2007). The methods can be useful for identifying habitat-associations but have inherent limitations due to water turbidity (camera) and species identification (sonar). They have not been used to produce an abundance estimate. It is possible that additional experimentation, combined with technological advances (especially in sonar and robotics) may lead to improvements in the general approach.

MPWMD (2013) conducted the first mark-recapture study of steelhead abundance in the lagoon during its closed phase, sampling juveniles via seine on three occasions in early summer 2013. They only captured 31 fish and only one recapture, which does not provide sufficient data for reliable estimates using standard analysis methods. This estimation method is also constrained by when it can be deployed: only at times when water levels are sufficiently low that vegetated areas are not inundated (vegetated areas cannot be sampled).

Methods using PIT-tagging to estimate smolt production, recommended in the main text for assessing ecological connectivity, may also be useful here. What was recommended was stratified-random sampling of freshwater reaches in which to PIT tag fish, combined with a series of electronic detection stations to track movement. The lowermost such station, at the sewage treatment plan, is used to estimate out-migration of steelhead during the time estuary is open, but it can also estimate movement of juvenile into the lagoon at the time it is closed.

Recommendations

- Use PIT-tagging methods to estimate number of juvenile immigrants to the lagoon during its closed period.