Linking Physical Monitoring to Coho and Chinook Salmon Populations in the Redwood Creek Watershed, California—Summary of May 3–4, 2012 Workshop

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By Mary Ann Madej, Alicia Torregrosa, and Andrea Woodward

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Introduction

On Thursday, May 3, 2012, a science workshop was held at the Redwood National and State Parks (RNSP) office in Arcata, California, with researchers and resource managers working in RNSP to share data and expert opinions concerning salmon populations and habitat in the Redwood Creek watershed. The focus of the workshop was to discuss how best to synthesize physical and biological data related to the freshwater and estuarine phases of salmon life cycles in order to increase the understanding of constraints on salmon populations.

The workshop was hosted by the U.S. Geological Survey (USGS) Status and Trends (S&T) Program National Park Monitoring Project (*http://www.fort.usgs.gov/brdscience/ParkMonitoring.htm*), which supports USGS research on priority topics (themes) identified by the National Park Service (NPS) Inventory and Monitoring Program (I&M) and S&T. The NPS has organized more than 270 parks with significant natural resources into 32 Inventory and Monitoring (I&M) Networks (*http://science.nature.nps.gov/im/networks.cfm*) that share funding and core professional staff to monitor the status and long-term trends of selected natural resources (*http://science.nature.nps.gov/im/monitor*). All 32 networks have completed vital signs monitoring plans (available at *http://science.nature.nps.gov/im/monitor/MonitoringPlans.cfm*), containing background information on the important resources of each park, conceptual models behind the selection of vital signs for monitoring the condition of natural resources, and the selection of high priority vital signs for monitoring. Vital signs are particular physical, chemical, and biological elements and processes of park ecosystems that represent the overall health or condition of the park, known or hypothesized effects of stressors, or elements that have important human values (Fancy and others, 2009). Beginning in 2009, the I&M program funded projects to analyze and synthesize the biotic and abiotic data generated by vital signs monitoring and previous in-park natural resource monitoring and inventories to provide useful information, models, and tools to park managers for addressing resource management issues. The workshop described in this report is an element of the project funded by USGS NPS-I&M program to conduct a synthesis of salmon-related datasets in the Klamath (KLMN) and San Francisco Bay Area (SFAN) networks of national parks. The synthesis focused on four park units: Redwood National Park (KLMN), Point Reyes National Seashore, Muir Woods National Monument, and Golden Gate National Recreation Area (SFAN).

KLMN and SFAN span the Pacific coast of northern California and inland Oregon. In this region, daily, seasonal, and decadal variation in abiotic drivers (for example, precipitation, fog, streamflow, and temperatures of air, ocean, and streams) regulate many ecological processes, including the distribution of vegetation and wildlife and the frequency of disturbances from fires, floods, landslides, and biotic pests. However, the exact nature of the linkages between abiotic drivers and the direct and indirect effects of these drivers on species of concern and their habitat are not well understood. Specifically, abiotic drivers commonly are analyzed as individual elements (that is, calculating mean annual precipitation) and the linkages between drivers (such as the influence of changes in streamflow on stream temperature) are poorly defined.

In addition to an understanding of the basic linkages between abiotic and biotic ecosystem elements, the question of climate change is of increasing concern to land managers in the national parks. Land managers need to understand how climate change already has affected natural resources and whether other changes may be looming. Without this understanding, it is increasingly difficult to judge the effects of management efforts (for example, stream restoration), to evaluate the resilience of existing habitats, or to plan future management actions. For example, climate change has been linked to more rain and less snow in the Sierras (Cayan and others, 2008), identifying the need for land managers to address long-term water storage. In contrast, there has been a scarcity of information depicting the effects of natural climatic cycles and anthropogenic climate change, aside from sea-level rise, in coastal California and Oregon including KLMN and SFAN (Suffling and Scott, 2002; Hayhoe and others, 2006).

Complicating a manager's ability to respond to climate change effects is the common assumption of stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability (Milly and others, 2008). The stationarity assumption is being compromised by major shifts in background environmental conditions. As a result, the timing, magnitude, and intensity of critical abiotic elements in national park units may be changing. Additionally, the common assumption that restoration planning can use historical reference conditions as a goal may not be valid if extrinsic drivers in national parks show non-stationarity. Consequently, the understanding of trends, variability, and interactions among abiotic drivers is needed to inform and prioritize restoration sites or activities and to implement scenario planning to foster strategic thinking about future conditions and management alternatives.

In central and northern California, several salmon populations have been in decline for years. In 1997, coho salmon *(Oncorhynchus kisutch)* were federally listed as threatened in the Southern Oregon-Northern California Coast (SONCC) Evolutionary Significant Unit, including Redwood National and State Parks, and as endangered in the Central California Coast Evolutionary Significant Unit, including SFAN parks. In 2012, the National Oceanic and Atmospheric Administration (NOAA) Fisheries Service is finalizing a recovery plan for the SONCC coho, and they identify Redwood Creek coho as a core population. Redwood Creek drains an area of 738 km^2 and enters an estuary at Orick, California. In the uppermost 72 km of Redwood Creek, the river flows through privately owned land primarily under timber management, and in the lower 36 km, it flows through RNSP. Prairie Creek, the largest tributary of Redwood Creek (100 km^2 in area), supports much of the coho population. Millions of dollars are being spent in coastal parks on watershed and stream restoration projects. As the NPS plans salmon restoration activities in coastal watersheds, it is critical to understand the abiotic factors and interactions that affect salmonid populations (MacCall and Wainwright, 2003; Battin and others, 2007).

Many long-term datasets are being collected by SFAN and KLMN as part of the vital signs monitoring program, and additional datasets are available from park units and other agencies. The USGS-NPS program funded the authors to conduct a synthesis of salmon-related datasets in Redwood National Park, Point Reyes National Seashore, Muir Woods National Monument, and Golden Gate National Recreation Area. The overall goals of the synthesis are to better understand (1) the linkages among abiotic drivers, (2) the direct and indirect effect of these drivers on salmon and salmon habitat; and (3) to make predictions about the effects of potential management actions on salmon habitat and populations. A step in reaching these goals was to convene a workshop for researchers and resource managers working in RNSP to share data and expert opinions concerning salmon populations and habitat in the Redwood Creek watershed.

Workshop objectives were to:

- Provide natural resource managers of RNSP with initial data compilations, analyses, and syntheses in forms relevant for decisions on issues of park concern, such as restoration of native habitats;
- Solicit expert opinions on conceptual models representing various synthesis approaches;
- Show an example of synthesis of salmonid population and habitat data developed for SFAN;
- Examine datasets from Prairie Creek, Redwood Creek, and the Redwood Creek estuary to develop conceptual models that synthesize the vital signs of Redwood National Park for park management use;
- Solicit input from the group to identify the synthesis approach that best fits the available data and the needs of park resource managers and specialists;
- Identify data gaps and action items to advance analyses; and
- Engage workshop participants in the effort to fill data gaps by contributing existing but unincorporated data or by deriving proxies for data gaps.

Summary of Previous Fisheries Meetings

Following introductions (for a list of participants, see appendix A) and a presentation of workshop objectives, we summarized results from previous Redwood Creek fisheries meetings.

April 15, 2008, Redwood National and State Parks, Orick, California

On April 15, 2008, Redwood National and State Parks (RNSP) hosted a workshop to share information on fisheries research being conducted in the Redwood Creek watershed. More than 70 people participated in the workshop.

Presentations included:

- Monitoring of the Redwood Creek estuary and mainstem summer steelhead (David Anderson, RNSP);
- Growth of Chinook salmon in the Redwood Creek estuary (Brian Wells, NOAA);
- Research in Prairie Creek (Walter Duffy, USGS);
- Redwood Creek juvenile salmonid abundance (Michael Sparkman, California Department of Fish and Game [CDFG]);
- Fish distribution in the Redwood Creek basin (Baker Holden, RNSP);
- Freshwater mussels in Redwood Creek (Keith Bensen, RNSP);
- Long-term monitoring of channel morphology, hydrology, and stream temperature (Mary Ann Madej, USGS); and
- Summary of the Redwood Creek basin assessment (North Coast Watershed Assessment Program; Steve Cannata, CDFG).

Recommendations from the 2008 workshop were to:

1. Facilitate communication among researchers, fishery biologists, and interested people;
2. Develop a comprehensive list of relevant publications and datasets for Redwood Creek;
3. Ensure researchers send copies of field notes, data, and reports to Redwood National Park Curator, James O’Barr; and
4. Create annual synthesis reports of fisheries research in Redwood Creek.

A complete copy of the meeting notes from 2008 is available from RNSP upon request.

Since the April 15, 2008 workshop, several new observations and events have occurred:

- Four additional years of biological and streamflow monitoring data are available to add to trend analysis;
- Invasive New Zealand mudsnails have been found in the Redwood Creek estuary;
- A conference was held on environmental degradation owing to marijuana plantations, and the use of rodenticides on marijuana plots has been implicated in poisoning carnivores (Gabriel and others, 2012), leading to water-quality concerns; and
- Water-quality and algal-growth observations in upper Redwood Creek suggest possible nitrogen and phosphorus inputs from private lands.

August 30, 2011, Redwood National and State Parks, Arcata, California

On August 30, 2011, USGS scientists met with RNSP resource managers to discuss datasets available from the vital signs monitoring program and from in-park and other sources. We summarized the types of datasets used to assess time series trends, bivariate relationships, and multivariate relationships, and we discussed preliminary results from these analyses. We discussed park management concerns, especially regarding the restoration of Chinook and coho salmon populations. The management questions raised were: (1) Given current watershed characteristics, what could we be doing to improve fish survival?, (2) What is the rate of natural restoration?, (3) How do the freshwater and estuarine systems of the Redwood Creek watershed function?, and (4) How can we more effectively combine physical and biological monitoring? High-priority topics identified at the August 30, 2011 meeting included fish distribution in the Redwood Creek basin and Redwood Creek estuary dynamics. As a follow-up to the meeting, David Anderson provided data to USGS staff on fish numbers, distribution, and size, and on the dates of closing and opening of the Redwood Creek estuary berm. The USGS posted data summaries and temporal trends of abiotic and outmigrant smolt data on a website: *http://www.werc.usgs.gov/project.aspx?projectID=229*.

Summary of Existing Data and Data Gaps

In the introductory phase of the workshop, participants were encouraged to identify any data they possessed that were not previously compiled and that would be relevant to the workshop goals. As the workshop progressed, additional potential datasets were revealed, as were data and knowledge gaps. Table 1 summarizes datasets available from the National Park Service and other agencies, followed by a summary list of data needs and data challenges.

Table 1. Summary of relevant datasets for Redwood National and State Parks and Redwood Creek, California.

[RAWS, Remote Automatic Weather Stations; RNSP, Redwood National and State Parks; PRISM, Parameter-elevation Regressions on Independent Slopes Model, Oregon State University; CDFG, California Department of Fish and Game; HSU, Humboldt State University; USFWS, U.S. Fish and Wildlife Service; NOAA, National Oceanic and Atmospheric Administration]

Variable	Location	Time scale	Organization/Agency
Air temperature	Westside Access Road	Daily (2004-2012)	RAWS (Mesowest)
	Schoolhouse Peak	Daily (2001-2012)	RAWS (Mesowest)
	Orick/Prairie Creek State Park	Daily (1938-2012)	National Weather Service, RNSP
	Crescent City, CA	Daily (1897-2012, intermittent)	National Weather Service
	Park average	Monthly (extrapolated from 1895 to 2010)	PRISM (Oregon State University)
Precipitation	Westside Access Road	Daily (2004-2012)	RAWS (Mesowest)
	Schoolhouse Peak	Daily (2001-2012)	RAWS (Mesowest)
	Crescent City, CA	Daily (1897-2012, intermittent)	National Weather Service
	Orick/Prairie Creek State Park	Daily (1938-2012)	National Weather Service, RNSP
	Little Lost Man Creek	Daily	RNSP
	Park average	Monthly (extrapolated from 1895 to 2010)	PRISM (Oregon State University)
Streamflow	Redwood Creek at Orick	Daily (1954-2012)	USGS
	Redwood Creek near Blue Lake	Daily (1973-2012)	USGS
	Prairie Creek above Boyes Creek	Daily (2004-2012)	RNSP
	Prairie Creek at Wolf Creek Bridge	Daily (1991-2012)	RNSP
	Upper Prairie Creek	Daily (1990-2012)	RNSP
	Little Lost Man Creek	Daily (1975-2012)	RNSP, USGS
Turbidity	Prairie Creek stations	Daily (2003-2012)	RNSP
Water temperature, in-situ	Redwood Creek –several sites	Hourly during summers, 1997-2012	RNSP, CDFG
	Prairie Creek stations	Hourly during summers	RNSP
	Little Lost Man Creek	Hourly during summers	RNSP
	Redwood Creek estuary	Hourly during summers	RNSP
Water temperature, thermal infrared	Redwood Creek-entire length	Single day, July 29, 2003	RNSP
Channel morphology	Redwood Creek and tributaries –many sites	1975-present, intermittent	RNSP, USGS
Outmigrant smolts	Redwood Creek – River mile 4	Weekly, Spring and summer, 2004-2012	CDFG
	Redwood Creek – River mile 33	Weekly, Spring and summer, 2000-2012	CDFG
	Prairie Creek	Weekly, 1999-2008, 2011-12	CDFG, USGS, HSU
Adult escapement	Prairie Creek	1994-2012	CDFG, USGS, HSU
Water levels	Redwood Creek Estuary	Daily, 1997-2012, partial	RNSP
Bathymetric surveys	Redwood Creek Estuary	Summers, intermittent	RNSP
Dissolved oxygen	Redwood Creek Estuary	Summers, intermittent	RNSP, USFWS
Juvenile population and growth estimates (Seining)	Redwood Creek Estuary	Summers, 1980-2012, intermittent	RNSP

Adult summer steelhead abundance	Redwood Creek	Annual, 1981-2012	RNSP
Chinook life history (scale analysis)	Redwood Creek Estuary	1980-1995, intermittent	RNSP, NOAA-Fisheries
Riparian vegetation mapping	Redwood Creek levees	Single survey	Humboldt County

Little or no data are available for:

- Genetics analysis to differentiate Chinook stocks (Sparkman, CDFG, has data that still need to be analyzed),
- Analysis of circuli on fish scales collected in estuary post-1995 (NOAA) to determine growth rates of Chinook and coho salmon,
- Fish-scale collection and analysis from lower Redwood Creek smolt trap,
- Freshwater and estuarine food sources (Salamunovich, 1987),
- Large wood surveys (but assumption is that wood loading has not changed significantly during last decade),
- Vegetation change (but assumption is that vegetative cover has not changed significantly during last decade),
- Effects of commercial and sport ocean fishing on adult returns,
- Winter rearing habitat inventory in Redwood and Prairie Creeks,
- Redds in Redwood Creek (turbid conditions preclude frequent observations),
- DIDSON (dual frequency identification sonar imaging system) fish counter (pilot studies are being conducted, initial results are promising, but additional funding is needed to develop a robust data collection strategy,)
- Disease (blackspot infestation, caudal fin rot, subcutaneous nematode bumps),
- New Zealand mudsnail infestation,
- Fish use in South Slough of estuary,
- Uncertainty analysis for population estimates from estuary seining,
- Predation in Redwood Creek and estuary,
- Mortality in Redwood Creek and estuary,
- Basin-wide distribution of salmon egg-eating oligochaetes in redds,
- The relation of flow magnitude to channel bed scour depth and redd scour, and
- The relation of flow timing to spawning success.

Data challenges include:

- Different periods of record for various metrics;
- Short periods of record for several metrics;
- Different sampling frequencies (hourly to annually);
- Different sampling locations throughout the drainage basin;
- Different types of equipment for same metric (for example, tipping bucket versus storage rain gages);
- Data gaps and equipment failure;
- Changes in technology over sampling period;
- Lack of consistency or changes in sampling protocol over time;
- High observer variability with different sampling crews;
- High spatial variability of habitat units within rivers;
- Uneven distribution of fish in estuary during seining operations;
- Some older data are in uncorrected, non-electronic format; and
- Sample design does not enable inference.

Synthesis Approach Developed for Olema Creek (SFAN)

Andrea Woodward, USGS, Michael Reichmuth, NPS, and Alicia Torregrosa, USGS, presented the results of the coho-freshwater vital signs synthesis for the SFAN I&M network (Olema Creek). The synthesis tool, a dynamic systems simulation model, was developed to investigate salmon survival during the freshwater life-stages (fig. 1). Salmon survival is an important management concern and can only be explained by integrating data from many sources to describe relationships among explanatory variables and salmon outcomes. Although data describing relevant relationships may exist from vital signs monitoring and other sources, they are difficult to synthesize because they were not collected at the same time, in the same place, or over a long time series. Moreover, it may be necessary to incorporate expert opinion and hypotheses when data are not available. Finally, it is necessary to make predictions about the effects of potential management actions. To meet these needs, Woodward and Torregrosa used Stella® software to create the system-dynamics model to simulate salmon populations. System-dynamics models consist of stocks of state variables (that is, things that can be counted) at a point in time, and flows, which describe the change in stocks over time. Flows can be determined by external factors (for example, environmental conditions), or feedbacks from other stocks or flows (for example, density dependent effects). The stocks (fish) are assessed at each modeled time step depending on how flows (mortality) respond to external and internal conditions during that time step. With this modeling approach, multiple disparate data sources could be integrated to describe relationships of environmental variables with salmon mortality, including literature-based or hypothetical relationships to assess their potential influence. The Stella® software also enabled the creation of a user-friendly interface to allow park staff and others to change model parameters and to conduct sensitivity analyses, to incorporate future knowledge, or to implement future climate scenarios.

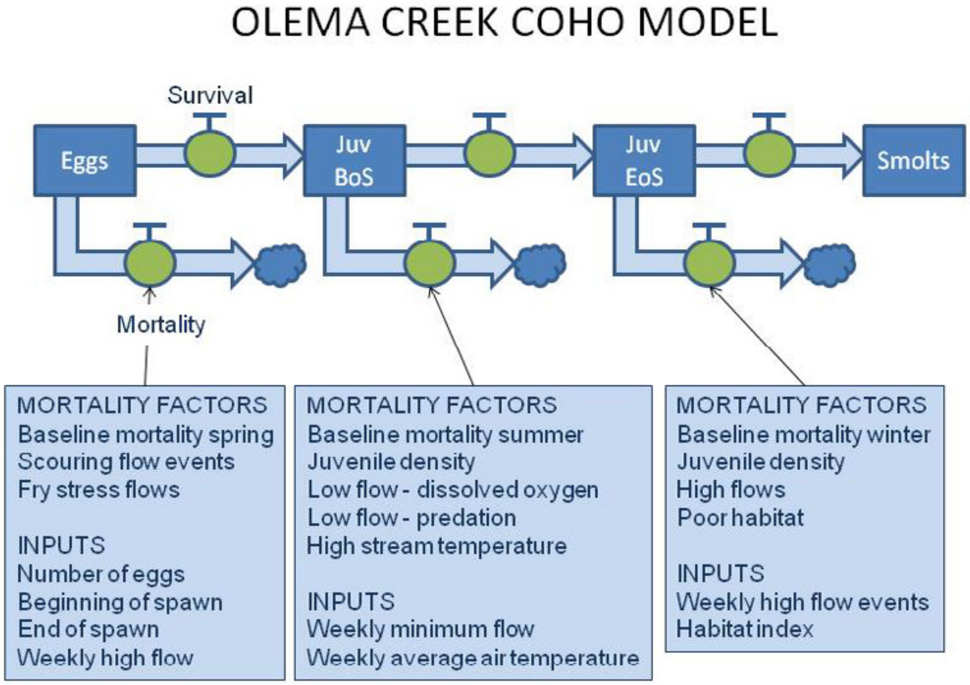


Figure 1. Schematic showing system-dynamics model built to describe the freshwater life cycle of coho salmon in Olema Creek, Point Reyes National Seashore, California. Fish cohorts progress through stocks of eggs, juveniles at the beginning of summer (Juv BoS), juveniles at the end of summer (Juv EoS), and smolts. Mortality factors and input values determine the survival of fish between each pair of stocks.

Michael Reichmuth, fisheries biologist, Point Reyes National Seashore, described the success of the tool, his experience contributing expert knowledge during the tool development, and its advantages. The system-dynamics model helps the NPS understand the relationship between monitoring and restoration activities. The model can accept more data as they are generated; incorporate other data in addition to the I&M network protocol-derived data, including expert opinion and knowledge; and be transferred to other systems. Available data also can be used to create testable predictions based on professional judgment.

Reichmuth described a grant proposal he had submitted to conduct sensitivity analyses to explore which monitoring data are the most important to collect. The proposal would address an insight inferred from the model results suggesting that higher frequency of data collected at specific locations for a long time period is important, yet the regional monitoring plan proposed by CDFG for interagency adoption suggests a more randomized, spatially distributed approach.

Possible Data Syntheses and Modeling Efforts for RNSP

A major objective of the workshop was to use the participants' collective knowledge to refine the conceptual model of the salmonid system at RNSP and to define the synthesis approach that best fit the model, available data, and the needs of resource managers and specialists. The presentation of the Olema coho-freshwater systems dynamic model gave participants insight into the data requirements of that synthesis approach, enabling a more informed discussion of possible options.

Three models were proposed by USGS scientists and discussed by workshop participants.

(1) Chinook Populations and Estuary Conditions Model

Background and Model Description

The Redwood Creek estuary is a bar-built system where fish, both returning adult spawners and smolts going to the ocean, can migrate between the ocean and the estuary only when streamflow and nearshore conditions are sufficient to create an opening through a coastal sand berm (fig. 2). In most years, the berm is closed from July through October (fig. 3), capturing some portion of the smolt Chinook population, which usually migrates downstream to the estuary and ocean from April through August (fig. 4). Benefits to fish from extended estuary residence include increased growth prior to entering the challenging ocean environment; costs include increased mortality because of declining water quality and increased risk of predation. Costs of estuary residence are thought to have increased since 1945, when estuary conditions changed drastically owing to agricultural development, and especially after construction of flood control levees in 1968 impaired and degraded the physical habitat and biological functioning of the Redwood Creek estuary and lower river, and their aquatic resources (fig. 2). Estuary volume decreased, circulation patterns shifted, areas of stagnant water increased, and connectivity with low velocity refugia diminished (Ricks, 1995).

USGS scientists provided a conceptual model to summarize the discussion of estuarine dynamics among USGS and RNSP staff members at the August 30, 2011 meeting (fig. 5). The model illustrates that estuary lagoon existence and size, and, therefore, habitat quality and availability, depend on weather, effects of ocean waves and human actions on berm integrity, and sediment movement from upstream and by the ocean during winter. This model was presented as the potential basis for a system-dynamics simulation model of the estuary.

A

B

Figure 2. Photographs showing changes in the configuration of the Redwood Creek estuary, California. A, Redwood Creek Estuary in 1948; B, Redwood Creek estuary in 1988. The area of estuary has decreased and the deep scour pool at the north end of the estuary (bottom left side of photograph) no longer exists.

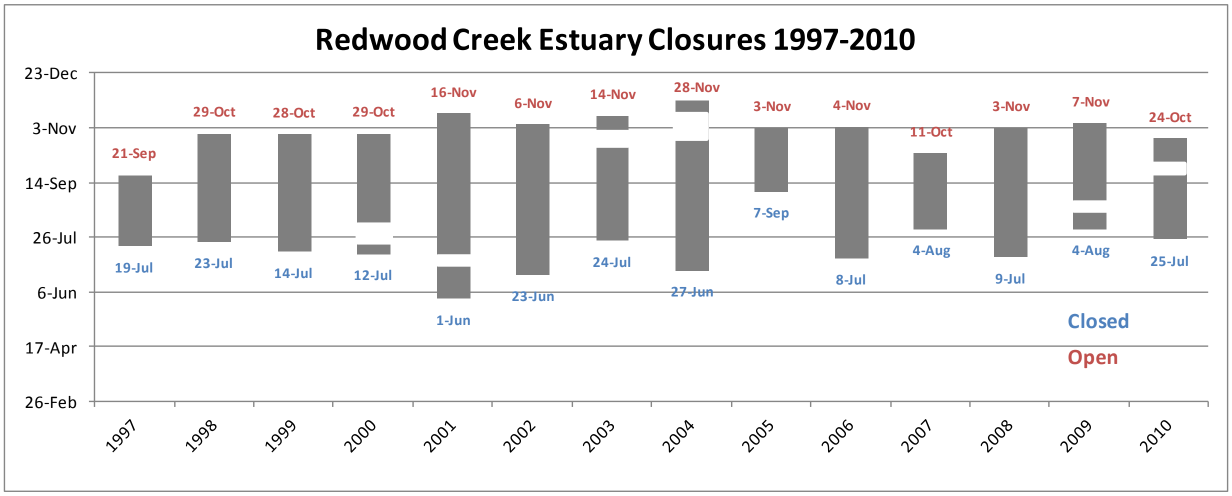


Figure 3. Graph showing the timing of estuary closures. The Redwood Creek, California, estuary is a bar-built system. Fish can only migrate into and out of the estuary when the sand berm is open.

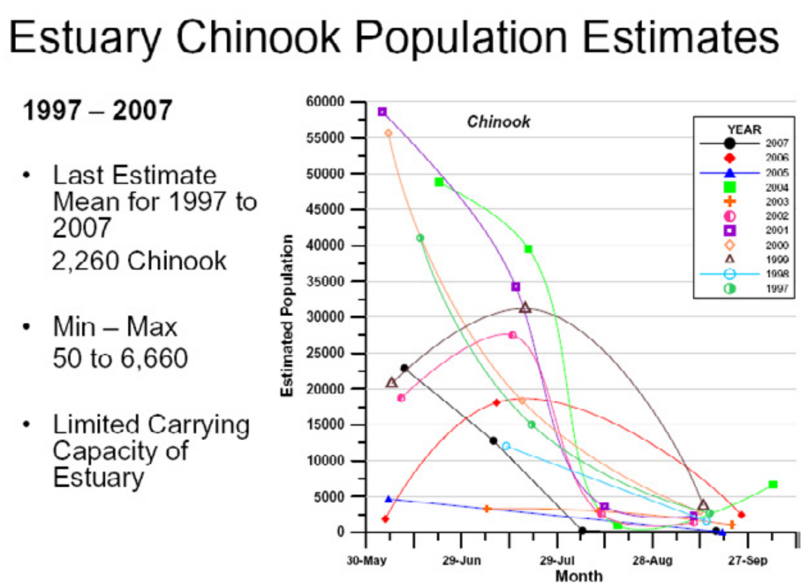
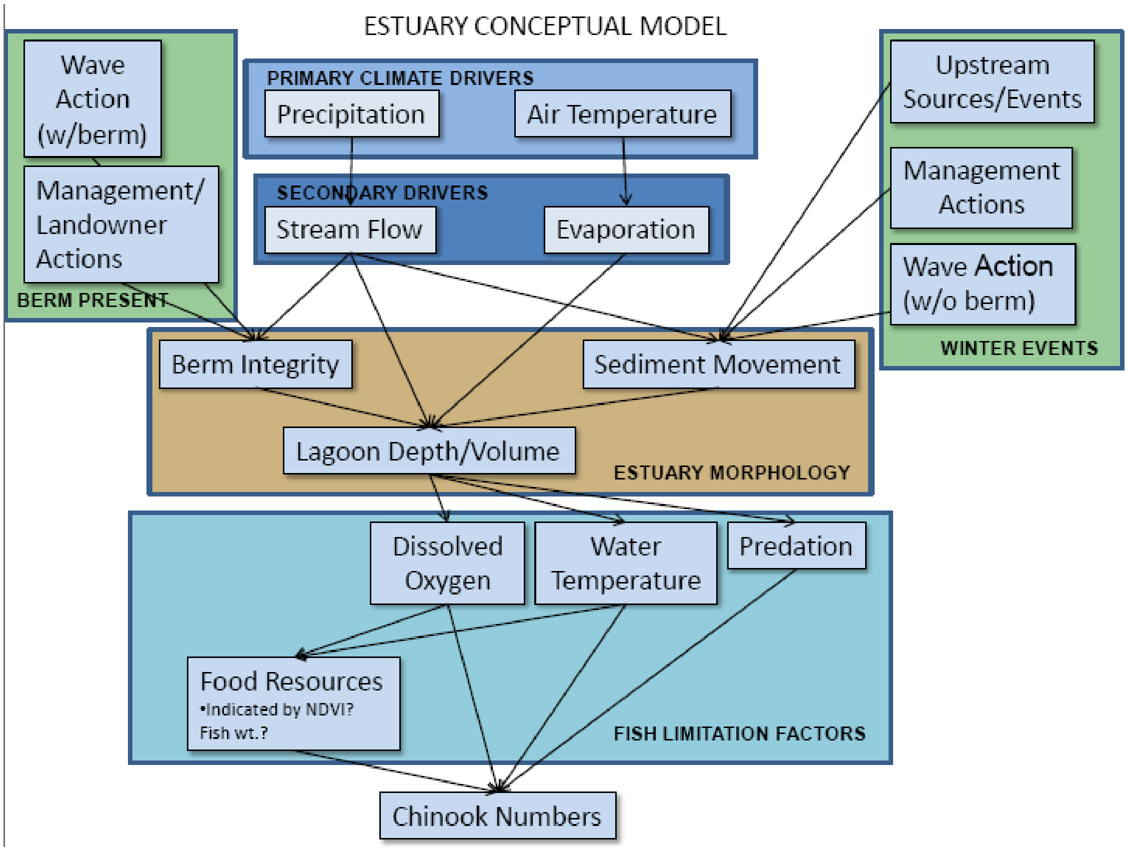


Figure 4. Graph showing estimates of Chinook populations in the Redwood Creek estuary, California, 1997–2007 (from David Anderson, Redwood National and State Parks).



*NDVI: Normalized Difference Vegetation Index

Figure 5. Diagram showing proposed conceptual model showing linkages of estuarine conditions and Chinook populations in the Redwood Creek estuary, California.

Discussion of Model Merit

Feedback from workshop participants was that the model generally reflected estuary dynamics but that a few elements were missing. Future restoration activities, including planned work in 2013 for Strawberry Creek (a tributary of the estuary), could feasibly improve off-channel habitat, provide refuge from high-velocity flows, and improve canopy cover for the estuary. If restoration elements were included in the model, they could be manipulated to predict effects of restoration. Additionally, the model does not express the connection between the amphipod *Corophium*, which is a high-oil food source for fish, and the requirement of berm closure for *Corophium* growth. Although the population dynamics of *Corophium* are not well known, it seems that the tube-dwelling organism cannot colonize a moving sand substrate. The model may be more accurate if a connection between food resources and berm integrity were added. The model also should be able to accommodate temperature-related stress, not just a threshold. Additionally, the relationship between the diurnal fluctuations in dissolved oxygen and algae growing on the bottom of the estuary when the berm closes could be a water quality-factor affecting fish.

Finally, the model does not include New Zealand mudsnails (*Potamopyrgus antipodarum*) (NZms), which have recently been observed in the lower estuary. The NZms were first found in the U.S. in the Snake River drainage in 1987, and have been detected in lagoons and estuaries in the western United States since 2008 and in the Redwood Creek estuary beginning in 2010 (Benson, 2011). Although the potential impacts largely are unknown, in some places NZms have reordered food webs completely and harmed water quality (*http://www.dfg.ca.gov/invasives/mudsnail/*). Adam Sepulveda (USGS) is addressing these issues for Redwood Creek. The potential for NZms spreading throughout lower Redwood Creek and the estuary, with their highly mobile channel bed and saltwater intrusion, is still unknown, however.

Potential Value of an Estuary Simulation Model

The estuary is of critical importance to the salmon populations in Redwood and Prairie Creeks. Quiñones and Mulligan (2005), Bond and others (2008), and Hayes and others (2008) show that juvenile fish residing longer in the estuarine setting have increased survival in the marine setting, resulting in increased potential to return as spawning adults. Moreover, the estuary is important to Chinook and steelhead, and with improvement in off-channel habitat, would benefit coho as well. Unlike the upper watershed where regulations regarding timber harvest, road decommissioning, and other restoration activities have been implemented, there are no immediate plans to improve the estuary, which was affected severely 40 years ago. The complex situation involving public and private lands and a mix of objectives (flood control, agricultural use, and aquatic habitat improvement) have hampered efforts to modify levee configuration. Nevertheless, poor estuary habitat is one of the greatest impediments to salmon production, and there are many potential restoration activities that would benefit the estuary and that would likely result in a measurable response in salmon populations. A simulation model could be a useful tool for prioritizing potential restoration efforts. Finally, a simulation model could describe baseline estuarine dynamics for comparison with the potential effects of NZms.

Limitations to Model Construction and Usefulness

A major limitation to building a system-dynamics model is the lack of basic understanding of what is driving the observations. For example, although early-season estuary Chinook population numbers vary greatly, by the time the estuary berm breaks in autumn, there are never more than 5,000 juvenile Chinook remaining and experiencing an extended estuary rearing (fig. 4), suggesting a carrying capacity for the estuary. Participants raised several questions regarding this observation: (1) Is the high variance earlier in the season driven by sampling or environmental factors?, (2) How much feeding and rearing occur between the CDFG smolt trap on lower Redwood Creek and the estuary?, and (3) Could we crosswalk between the lower trap and the estuary population numbers? The fundamental problem with formulating a system-dynamics model based on stocks of fish at different traps is that presently (2012) there is no way to resolve the temporal movement of fish. After fish migrate past the smolt trap, we do not know when they enter the estuary or how long they stay in the estuary. One possibility is that they are changing their life history to respond to poor estuary conditions by leaving the estuary before the berm closes at the mouth of Redwood Creek. It seems that answering some of these basic questions is a precursor to building a model. A limitation to the usefulness of the model is the need to understand the estuary in the context of the entire system, including the upper watershed, the channelized levee reach, the north and south sloughs, and access to tributary habitat.

Ideas for Future Work

The group made several suggestions for future work. One idea was to use the data from periods when the berm is closed to compare numbers of fish passing the lower smolt trap with numbers estimated in the estuary. This would indicate something about how fish use the lower river and residence time in the estuary. However, the limitation of narrowing the focus to a short time period is the loss of the population context. For example, if the fish that remain when the berm closes do not contribute significantly to the whole population, are they important? Moreover, if only a small percentage of the population is experiencing the high mortality rates in the closed lagoon, it does not mean that more fish would choose to stay if conditions were more favorable. We also do not have a historic perspective on berm behavior. Because of the deep (10–15–meter) scour hole that historically was present at the north end of the estuary, Redwood Creek, with a larger tidal prism, may not have had a closed summer berm as frequently in the past as it does now. Another suggestion was to use the available data, such as the opening and closing of the estuary (fig. 3), and bathymetric surveys and water levels throughout the summer, to compute changes in the volume of the estuary. These data then could be used to determine what percentage of the population had migrated prior to berm closure and how the growth rate of fish in the estuary relates to water temperature, estuary volume, dissolved oxygen, fish density, and other factors.

A key need is to determine whether there is differential smolt-to-adult survival between fish that reside for some time and grow in the estuary versus fish that move directly to the ocean from the river at a small size. In other words, which life history is more successful—fewer, bigger fish or many small ones? Residence time of the fish in the estuary is currently (2012) unknown, but eventually may be a good metric to measure the success of estuary restoration actions. We need a dataset containing the full expression of fish number and habitat diversity to evaluate the r-to-K ecological selection relationship, where “r” is the maximum growth rate of the population and “K” is the carrying capacity of its local environmental setting (MacArthur and Wilson, 1967). Fish scale samples have been collected from returning adults to begin addressing this question. However, the samples have not been processed completely by the NOAA laboratory where they are being analyzed. Several participants have made a commitment to investigate the status of the sample analysis.

Finally, planned monitoring with a DIDSON (dual frequency identification sonar imaging system) fish counter in lower Redwood Creek and Prairie Creek will help put adult fish migration patterns into perspective. From November 2009 to March 2010, a pilot study by Dr. Walter Duffy (USGS) and Matthew Metheny (Humboldt State University) using a DIDSON monitored escapement of adult salmon and steelhead in Redwood Creek. Initial results are promising, and such monitoring also can be used to validate redd counts in the creeks.

(2) Comparison of Trends in Coho in Prairie Creek and Redwood Creek

Background and Model Description

Coho salmon spawn and rear in Redwood Creek and its tributary, Prairie Creek. The Redwood Creek basin was logged heavily until the national park was established in 1968 and expanded in 1978, and logging continues on private lands in the drainage basin. Consequences of logging include high water temperatures because of lack of riparian shade, high sediment loads owing to slope erosion, and generally harsh summer conditions. In contrast, Prairie Creek has been protected since the 1920s, is relatively intact, and hosts most of the coho population.

The contrast between these basins is the basis for a second approach to integrative modeling proposed by USGS scientists and illustrated in another conceptual model (fig. 6). The conceptual model describes different levels of impairment that are expected to result in contrasting responses to climatic drivers. These responses are expected to produce different survival rates of coho eggs to smolts. Because we do not have long-term, detailed climatic data throughout the basins, the distribution of precipitation from any given storm will have to be inferred from storm characteristics such as precipitation at a given station, air temperature, and topography to determine snow line, storm direction, and other factors. These relationships must be developed from the existing time series of data.

Discussion of Model Merit

The most fundamental problem with the model is that the differences between the basins extend to many dimensions besides level of impairment. Prairie Creek is a low-gradient system with different bedrock types than most of the Redwood Creek basin, whereas other Redwood Creek tributaries generally are steep and the Redwood Creek basin is about six times larger than the Prairie Creek basin. Habitat complexity generally is much greater in Prairie Creek than Redwood Creek. One approach to address these contrasts would be to normalize fish use by habitat abundance (that is, spawning, over-wintering, and summer rearing). However, the driver for juvenile-to-smolt survival in Prairie Creek probably is overwinter survival rather than summer conditions, as it is in Redwood Creek.

The potential for developing the model is limited by data availability. Although the proposed model has most of the important parameters, data have not been collected for all the parameters (for example, large wood as a habitat element). Turbidity has been measured at the “Wolf Creek” gaging station in Prairie Creek, but those turbidity levels may be lower than the turbidity levels at the Prairie Creek trap site located downstream on private lands. Turbidity probably is more of an issue in Redwood Creek, where suspended sediment concentrations are higher, but no turbidity measurements are available there. When turbidity is high, the fish may wait out the high flows before migrating. Wright (2011) showed a low probability of movement of coho salmon in Prairie Creek on days with higher turbidity.

In other cases, some of the parameters that had to be estimated for the Olema Creek model are collected in RNSP, enabling empirically based values. Specifically, for the Prairie Creek–Redwood Creek model, the fecundity of the female salmonids is known, redd counts index the adults, summer field work estimates juvenile abundance, and the smolt trap catches some juvenile coho. Currently (2012), there is a proposal for funding to look at juvenile overwinter survival.

There also are many important influences on and questions regarding fish populations that were not addressed in the Olema model. In Prairie Creek, years with poor sport fishery catches had higher numbers of returning Chinook. How do exploitation rates affect wild stocks of salmon? We also need to learn more about distribution of coho in the tributaries of Redwood Creek, and we may see more coho in Redwood Creek as streams recover. Based on fish scale work, the ratio of 1-year to 2-year steelhead smolts in upper Redwood Creek is 14 to 1, and 8 to 1 in lower Redwood Creek, which may reflect the harsh conditions in Redwood Creek (in contrast, the nearby Mad River, which also has a long history of timber harvest and grazing, has a ratio of about 1 to 5). As conditions in Redwood Creek improve, will we see a shift in the smolt age ratios? A new (2013) study that is starting will look at the distribution of juveniles in the drainage basin (basin-wide randomized approach). In terms of model structure, the model needs to account for a continuum of effects, such as stress levels, in addition to specific thresholds.

Finally, the relevance of the model to management decisions was questioned. It was observed that, of all the parameters in the model, the only one that is amenable to management activities is habitat. But even if habitat were to improve (for example, by adding wood to the upper watershed), we would not know whether fish merely were redistributed or whether production actually increased. This concern is supported by the observation that, to date (2012), the road restoration work in the Redwood Creek basin has not resulted in higher fish population numbers. Additionally, some factors (for example, stream temperature mortality threshold), are not amenable to management action. On the other hand, a Redwood Creek watershed model might be useful, especially in the context of management activities, current and planned, such as addressing Sudden Oak Death and the effect of lost shading on increasing water temperature.

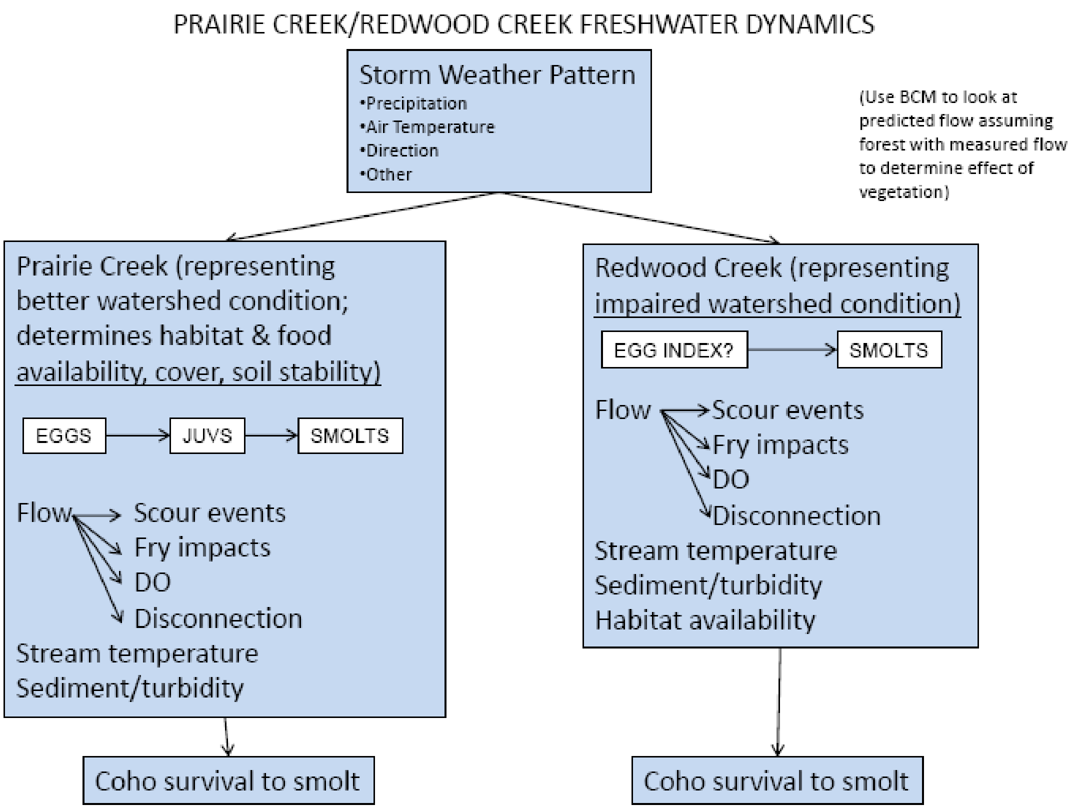


Figure 6. Diagram showing conceptual model comparing good coho habitat (Prairie Creek, California) with an impaired watershed (Redwood Creek, California).

(3) Basin Characterization Model

Water-balance modeling can be used to determine the flow of water into and out of a watershed. A Basin Characterization Model (BCM) calculates water-balance components by using spatially distributed climatic data (precipitation and air temperature) and information on soil, geology, and topography (fig. 7). Flint and Flint (2012) developed a BCM to reconstruct historical conditions and to simulate future conditions for climatic scenarios in the San Francisco Bay area (Russian River Valley and Santa Cruz Mountains). The model considers potential evapotranspiration, snow accumulation, and snowmelt across a watershed, and combines that information with soil and bedrock properties. The potential water available for recharge and runoff is calculated using monthly time steps using a grid scale of 866 ft (270 m). The data necessary to run the model for the Redwood Creek basin are available, so the model could be applied to this area in the future if park staff thinks it might be useful.

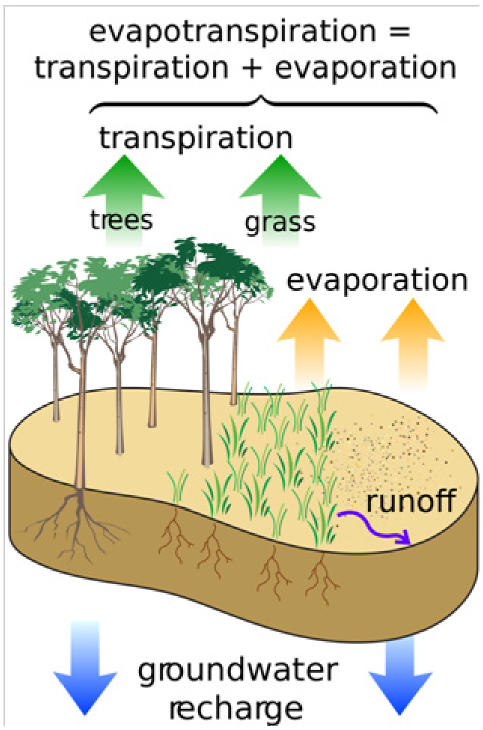


Figure 7. Diagram showing the relationship of three Basin Characterization Model outputs, transpiration, runoff, and groundwater recharge. Of the many inputs required to run the model—such as precipitation, solar radiation, air temperature, potential evapotranspiration—only transpiration is shown in the diagram. [Diagram from Surface Water Cycle from Wikimedia Commons, accessed April 10, 2012, at http://en.wikipedia.org/wiki/File:Surface_water_cycle.svg].

Field Visit to Monitoring Sites

The May 3, 2012, science workshop concluded on May 4, 2012, with field visits to (1) examine estuary configuration and monitoring sites, and (2) observe outmigrant smolt trapping in lower Redwood Creek upstream of Prairie Creek. Discussion continued on the topics raised the previous day , with an emphasis on filling in the details of the analyses identified through the group process.

Questions to Answer and Next Steps

The discussion of models and options for synthesizing data raised many science questions, some that could be answered with existing data. There were many opinions about the relative advantage and disadvantage of empirical analytic approaches versus simulation modeling approaches. One advantage of empirical analytic approaches is the defensibility of an analysis that can define unambiguously the confidence level of a reported statistical relationship. In contrast, an advantage of the system dynamics simulation modeling approach includes the capacity to include expert opinion and hypothesized relationships to gain insight into the system. Many science questions discussed by the group were fundamental questions about the functioning of the system best investigated with traditional statistical analysis.

Table 2 groups the questions by ecosystem component and lists the datasets needed to address the question. The relative importance value assigned to each question in table 2 reflects the authors' sense of the group consensus and is not a result of a structured priority process. Previous experience with vital signs data compilation highlighted for the group the value of knowing how much work still might be required for data to be ready to be used in a statistical analysis; hence, the discussion also focused on data readiness. The following codes describe levels of data completeness for questions in table 2.

1 – Data have been collected, quality assured, and are available digitally.

2 – Data are available, but need additional level of review, calibration, or manipulation.

3 – Data are not known to be available.

Table 2. Questions identified by workshop participants, May 3–4, 2012.

Ecosystem Component	Resource Question	Relative Importance	Datasets
Estuary	Is Chinook abundance correlated with water volume?	1	Summer fish seine data (1) Water levels 1997-2011 (2) Bathymetric surveys 1998-2011 (1) Pre-1997 calibrated water levels (2)
Estuary	Is Chinook growth correlated with water volume?	1	Fork length-weight data 2001-2011 (1) Water levels 1997-2011 (2) Pre-1997 calibrated water levels (2) Bathymetric surveys 1998-2011 (1) Scale analysis 1980-1995 (1) Updated scale analysis, including adult scales (NOAA) (3)
Estuary	Is dissolved oxygen correlated with water volume?	2	Dissolved oxygen data (2) Water levels 1997-2011 (1) Bathymetric surveys 1998-2011 (1)
Estuary	Is water temperature correlated with water volume and algal growth in the estuary?	2	Water temperature data (1) Water levels 1997-2011 (2) Bathymetric surveys 1998-2011 (1) Distribution and abundance of algae (3)
Estuary	Is the distribution of New Zealand mud snails expanding and affecting the food web?	1	Visual inventories of snail aggregations in lower estuary 2010-2011 (1) Quantitative surveys in full estuary (3) Effects on food web (3)
Freshwater-estuary transition	How do ratios of smolts at RM4 to estuary seine catches relate to the closing of the berm?	1	Estuary berm closure dates 1997-2011 (1) CDFG smolt data-Lower Redwood Creek 2004-2012 (1) Summer estuary seine data (1)
Freshwater-estuary transition	Does smolt-to-adult survival differ between riverine and estuarine-rearing fish?	1	CDFG smolt data-Lower Redwood Creek 2004-2012 (1) Summer estuary seine data (1) Updated scale analysis, ,including adult scales (NOAA) (3)
Freshwater	How do Chinook and coho populations and migration patterns relate to flow regimes?	2	Daily stream discharge 1953-2012 (1) CDFG smolt data-Lower Redwood Creek 2004-2012 (1) Updated fry/smolt ratio data for Redwood Creek (2)
Freshwater	How do Prairie Creek populations relate to those in Redwood Creek	2	Escapement- Prairie Creek 1999-2011 (1) Smolt data-Prairie Creek, 1999-2008, 2011 (2) Smolt data-lower Redwood Creek 2004-2012 (1)
Freshwater	How does turbidity in Prairie Creek affect coho growth?	3	Daily turbidity in Prairie Creek (1) Fork lengths and weights of smolts 2009-2011 (1)

Freshwater	Does fish condition in Redwood Creek relate to flow or temperature?	2	Fork lengths and weights of smolts, (1) Daily flow and water temperature, 2004-2011 (1)
Freshwater	What is the effect of water temperature on fish disease?	2	Daily water temperature (1) Disease recorded in field notes, but not in database (2)
Freshwater	What is the effect of Sudden Oak Death on water temperature?	3	Coarse scale vegetation surveys (2) Hourly water temperature (1) Detailed mapping of dead trees in riparian zone of Redwood Creek (3)
All	How will climate change affect flow and temperature regimes?	1	Daily air temperature, precipitation, stream flow, water temperature (1) More accurate summer low flow measurements, winter water temperatures (2)
All	What biotic and abiotic variables are valuable to continue monitoring?	1	All datasets

Concluding Remarks

This meeting was one step in the process of synthesizing vital signs data and, as a byproduct, may help coordinate salmonid habitat research among various disciplines and agencies. Draft copies of the meeting notes were sent to all workshop participants, requesting comments and feedback. Many actions identified during the meeting will require follow up, such as completing the datasets listed in table 2.

The workshop reinforced the opinion of the authors that a collaborative process can help guide analyses of complex systems, such as physical and biological interactions of the coastal ecosystems of northern California. Although developing simulation models to relate science to resource management decisions eventually may be desirable, this workshop's collaborative process determined that developing fundamental relationships among ecosystem components in RNSP is needed first. Once the system is better understood, data synthesis can progress to include multiple connections among the interacting system elements, possibly to the stage of a simulation model. Meanwhile, this workshop provided a starting point for future research and analysis, which can lead to a better understanding of how the freshwater and estuarine life phases of salmon are influenced by interacting abiotic factors in the watershed.

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Appendix A. List of Participants

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Parkinson	Doug	Consultant
Reichmuth	Michael	Point Reyes National Seashore
Roemer	David	Redwood National and State Parks
Seney	Joe	Redwood National and State Parks
Short	Darci	Redwood National and State Parks
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