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Regional Agreements, Adaptation, and Climate Change: New Approaches to FERC Licensing in the Sierra Nevada, California

PROJECT REPORT

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Executive Summary

Hydropower generation within the Sierra Nevada, California involving more than 115 powerhouses, 421 jurisdictional dams, and 2561 diversion dams (UCD Watershed Center FERC Database), creates the most significant bioregional impact on the health of Sierran aquatic ecosystems. The periodic relicensing of hydropower facilities regulated by the Federal Energy Regulatory Commission (FERC) is the only formal opportunity to reduce these impacts through new license conditions and settlement agreements that better reflect the range of modern societal goals. However, licensing efforts typically do not recognize the broader watershed and bioregional impacts of project operations, choosing instead to focus on river and stream reaches immediately adjacent to hydropower facilities. In addition, the FERC relicensing process tends to prescribe a narrow, inflexible range of operations for facilities, even in the face of considerable uncertainty about the future impacts of operations. This issue is particularly acute in the Sierra Nevada, where significant, well-documented changes in hydrologic conditions will impact hydropower operations and, in turn, aquatic ecosystems.

To date, stakeholders, agencies and utilities lack the necessary technical, legal and policy tools to support bioregional management that reduces the ecological impacts of hydropower operations, while adapting to uncertainty and change. We are developing an integrated program to address these issues in high elevation (above 1000 ft.) dams of the west slope Sierra Nevada.

This report details the efforts of the UC Davis Center for Watershed Sciences (CWS) in the first year of a multi-year program to explore the development of new approaches to FERC licensing of hydropower facilities in the Sierra Nevada, California. With support from the Resources Legacy Fund Foundation's *Preserving Wild California* initiative, the program has focused on three broad issues:

- First, what are the legal and institutional barriers to changes to the FERC licensing process which could potentially improve the overall environmental performance of licensed facilities and allow them to adequately respond to scientific uncertainties and changes in conditions imposed by regional climate change?
- Second, how will climate change impact watershed hydrology and downstream aquatic and riparian ecosystem quality and where in the Sierran bioregion will these impacts be greatest?
- Finally, what operational tools can be used to manage FERC facilities in a truly adaptive context to mitigate the potential effects of climate change while minimizing the impacts on hydropower generation?

The resolution of these three issues occurs at the intersection of law, policy, economics, engineering and science. To meet the goals of this project, the CWS assembled a multi-disciplinary team of experts to address these issues. This team is working with federal and state agencies, members of the California Hydropower Reform Coalition, and two private utilities to develop a range of legal, policy and technical tools that can be applied to FERC licensing efforts over the next decade.

This report summarizes the work completed by the research teams during the first year to address the three broad issues described above. Proposed continued work on these issues is described in the accompanying proposal to RLFF entitled: *Phase 2, Regional Agreements, Adaptation, and Climate Change: New approaches to FERC licensing in the Sierra Nevada, California.*

Law and Policy

In this report, we consider the barriers to, and opportunities for, two types of changes to the FERC licensing process which could potentially improve the overall environmental performance of licensed facilities and allow them to adequately respond to the changes in hydrology imposed by climate change. The first is aggregated (or coordinated) licensing, that is, consideration of multiple projects together, with coordination of license conditions or mitigation requirements for improved efficiency and effectiveness. The second is flexible (or adaptive) licensing, including conditions that would facilitate modification of operations or mitigation efforts as needed to respond to environmental change over time. The results of this analysis are being used to guide the development of analytical tools to support licensing efforts.

Barriers to change

FERC has occasionally conducted aggregated licensing; however there are practical barriers to its wider use. Depending on the context, aggregated licensing could either increase or decrease the complexity of and transaction costs associated with licensing. It appears that most aggregated licensing proceedings to date have been driven not by FERC's desire to achieve certain public policy objectives, but by the licensee's perception that the projects are functionally interrelated and by the desire to develop comprehensive settlement agreements.

FERC's usual practice is to limit mitigation requirements in hydropower licenses to actions that can be carried out within the project boundaries, to the point that it has sometimes refused to impose mitigation activities extending beyond project boundaries despite their inclusion in a settlement agreement. FERC will impose mitigation requirements beyond the project boundaries only if it concludes that those requirements are necessary to address project effects.

An opportunity to promote a greater State role

There is one potentially significant opportunity to provide additional incentives for aggregated hydropower licensing, or to improve consideration of cumulative impacts in individual licensing proceedings. Under the Federal Power Act, in order to issue a license FERC must find that the project, as conditioned, "will be best adapted to a comprehensive plan for improving or developing" the waterway for power development and other purposes. In making that determination, FERC must consider comprehensive plans developed by state and federal agencies. FERC does not require that "comprehensive plans" be very comprehensive in order to be considered. Should it choose to do so, the state, presumably through the State Water

Resources Control Board could influence the hydropower licensing process by engaging in regionally-focused waterway planning.

If California were to adopt a more consciously regional approach to water quality standards and section 401 water quality certification, FERC would be bound by that approach. California has designated the State Water Resources Control Board (SWRCB) as the agency responsible for section 401 certification under the Federal Clean Water Act. In order to certify a federal project, the SWRCB must find that it will comply with the water quality standards established by the appropriate Regional Water Quality Control Board. Under existing law the timeline for the 401 certification (one year) is not well coordinated with the FERC relicensing process, which can go on for years; but if this issue of timing could be remedied the SWRCB could play a much greater role in FERC relicensing.

Aggregated licensing

There are no substantial legal barriers to wider use of aggregated licensing. The barriers to aggregated licensing are primarily practical, chiefly the potential for increased cost, processing time, and complexity. The extent to which aggregated licensing would improve environmental performance or the efficiency of mitigation through opportunities for significant intra-project tradeoffs in operating conditions or mitigation measures is unclear. Aggregation surely would highlight the cumulative impacts of hydropower projects, and might allow the identification of useful trade-offs or combined mitigation measures. The ability to make trade-offs, however, will be limited by the Endangered Species Act and Clean Water Act. Better understanding of the environmental impacts of hydropower facilities could enhance the willingness and ability of FERC to effectively aggregate licensing proceedings, and perhaps could reduce licensee resistance. California could push FERC toward a more regional perspective by drafting formal comprehensive plans addressing the impacts of multiple projects on waterways, or by taking a more consciously regional approach to section 401 water quality certification.

Adaptive licensing

Flexible or adaptive licensing is also feasible within the boundaries of current law, but inhibited by practical barriers and institutional resistance. FERC's practice of including reopener clauses could facilitate adaptive management, as could the routine inclusion of monitoring and study requirements as license conditions. FERC, however, is committed to providing as much certainty for licensees as possible, and therefore resists the sorts of open-ended conditions that would most facilitate truly adaptive management. California could impose adaptive conditions through the section 401 certification process, but the SWRCB is reluctant to do so without strong scientific backing and confining sideboards. Improved scientific understanding of changing aquatic ecosystems and the impacts of hydropower facilities on those systems could potentially improve the ability to craft effective adaptive provisions within sideboards that are sufficiently clear and limited to satisfy FERC, licensees, and the SWRCB.

Reopener Clauses
It is now standard practice for FERC to include in the license a term that allows it to unilaterally make changes to license conditions. Reopener provisions could facilitate adaptive management, but in practice FERC has not shown a willingness to reopen licenses, nor have courts been inclined to force reopening. That seems to leave stakeholders with no way to force FERC to exercise a reopener clause if it chooses not to do so.

Hydrology and Aquatic Ecosystems

In order to address the information needs identified through the legal/policy analysis, we established a research team to assess current and future conditions of Sierran aquatic ecosystems. This unique effort seeks to develop a range of analytical tools that can evaluate current conditions of regulated and unregulated Sierran rivers in the absence of complete information. This information is vital to identifying those regions where aggregation of licenses may prove valuable and for assessing the relative impact of hydropower operations. In addition, the research group focused on developing new approaches to simulating changes in hydrologic and ecologic conditions in the Sierras under climate change. This work will allow prioritization of effort for adaptive management programs in the Sierras and help avoid stranded investments in mitigation.

Hydrology and temperature
A prominent portion of our effort involved the development of a Sierran-wide rainfall-runoff model that can simulate present and future runoff conditions. The WEAP21 (Water Evaluation and Planning) modeling platform, which consists of modules for both physical hydrology and infrastructure operations, was used to to represent hydrological processes for 15 watersheds in the Sierra Nevada. The models were developed to provide information at a spatial scale useful for studying the implications of climate change and infrastructure operations within the watershed boundaries. This is a departure from previous efforts that have only calculated runoff at the terminal reservoirs.

Analysis of 2, 4, and 6 degree centigrade increases in temperature indicate that the watersheds in the northern portion of the study area, specifically the Yuba through Stanislaus, will experience a larger shift in the timing of runoff than watersheds to the south. This impact reflects the lower overall elevation of these watersheds. This has important ramifications for analysis of hydropower operations. It is clear that projects relying on snow melt water from mid-elevation regions will experience an altered inflow hydrograph as the effects of climate change become more pronounced. The alteration of the inflow hydrograph will impact aquatic resources in several ways, including altering water temperature, a factor controlling the timing of the development of numerous species of aquatic biota.

To assess the possible impacts of a future climate change on water temperature a a numerical model was developed to represent water temperature conditions throughout the Sierra Nevada. This new model, RTEMP, is a regional, equilibrium-based temperature model that simulates

stream temperatures on weekly time steps. It is linked to the project GIS (described below) and uses the output of flows from the WEAP model.
The Mokelumne watershed was chosen to test the temperature model for a range of possible warming conditions. Results were generated for various elevational bands representing locations of FERC facilities. As an example, examining results at the 3,000 m band under existing, +2°C and +4°C warming conditions suggests that the +2°C case during winter months does not deviate considerably from existing conditions. However, during summer months there is a notable elevation in water temperatures. The +4°C case indicates considerable change in winter and summer. The sharp rise in temperature difference for the +4°C scenario during winter is attributed to more precipitation in the form of rain.

The application shows great promise in this initial representation of the Mokelumne River basin in the central Sierra Nevada. While the model is not calibrated, the results are still useful for comparative analysis. Further, results were generally considered consistent with expectations on the impacts of changes in water temperatures. The RTEMP model, in conjunction with WEAP, will provide a powerful, rapid tool for assessment of regional changes in temperatures under both climate change and operation change. In particular, this tool will be useful in assessing the relative feasibility of mitigating climate change impacts on aquatic ecosystems, both locally and regionally, through shifts in operations.

Physical habitat

Aquatic ecosystem health depends on the condition of the physical habitat, defined as zones with characteristic physical attributes where organisms perform their ecological functions. Physical habitat results from the interactions among hydrologic, hydraulic, and geomorphic processes. Changes in hydrologic patterns—whether through climate change or changes in hydropower operations -- are expected to affect physical habitat by modifying flow regime, sediment inputs, and water temperature.

The focus of the physical habitat analysis effort during the first year has been on developing a conceptual model for: 1) assembling physical habitat processes into a framework that can be used to assess overall physical integrity at any point along a river or stream; and 2) using this model to simulate changes in integrity due to climate change and/or operations changes. This conceptual model is the first step in the development of a GIS-based numerical habitat model that will be developed in year two and three of this research.

The initial step in this program involved the development of indicators of hydrologic, temperature and geomorphic conditions. Based on the nature of outputs from the WEAP and RTEMP models, hydrologic and temperature indicators were established that can be used to assess relative changes from a base condition. We have also developed a geomorphic conceptual model of physical response to hydrologic forcing that similarly defines indicators for geomorphic conditions. Metrics for assessment of the alteration of these indicators and the consequent susceptibility of the physical habitat as a whole will be used to document the impacts of climate change and identify those rivers and streams that are most susceptible. . Finally we developed: 1) a procedure to incorporate the indicators into the GIS environment; 2) a statistical model for physical and biological indicators correlations; 3) proposed additional indicators of physical habitat assessment. The physical habitat analysis scheme constitutes a tool to incorporate simple metrics within the GIS environment to visualize patterns of physical habitat alteration and susceptibility to climate change.

GIS

To house all of the data available to the project and all data generated by the project, a data repository was developed. In addition, a platform was needed to serve as a conduit for information moved between the various models used in the project. HYDRA was developed as that platform and has moved the project forward considerably. HYDRA is a geographical information system implemented using ArcGIS 9.2 (ESRI, Redlands, CA) cataloged by major watershed. A watershed-based GIS is an ideal platform for the collection and manipulation of hydrologic, geomorphic and biotic information; and is inherently organized to optimize analysis of landscapes at the watershed scale.

Our intention with the creation of HYDRA was to create a spatial and temporal base from which to manipulate, update, and extract information within a geo-referenced context. Our work for Year 1 of this project included incorporation of landscape-scale data for the 18 major watersheds of the west slope of the Sierra Nevada mountain range. In addition, in order to support initial development and testing of hydrologic, water temperature, physical habitat and biotic integrity models we developed more detailed data for the Mokelumne River watershed.

The HYDRA GIS, when completed during Year 2 and 3, will contain jurisdictional dams, diversion dams, transfer facilities, and powerhouses that will support future modeling efforts and will provide ready access to information for conservation planning. Specifically information needs that will be addressed in future work include better data on expiration of FERC licenses, storage capacities, generation capacities, throughflow capacities, and structural status (e.g. sedimentation of reservoirs, canal and aqueduct sizes, reservoir expansion potential). In addition to hydro-infrastructure data, ecological data will be incorporated into the HYDRA GIS to develop models of ecological impairment, sensitivity, and adaptability.

Indices of Biotic Integrity

In order to evaluate the impacts of changes in climate and operations on aquatic ecosystems and to identify potential mitigation strategies, we developed a simplified approach to assessing the current biotic integrity of Sierran streams. The available information on biotic integrity is limited in many parts of the Sierra, requiring approaches that can estimate integrity based on a range of watershed conditions. To meet the information needs of the project, we created a watershed index of riverine integrity (WIRI) from a composite of GIS-derived parameters depicting watershed condition. These WIRI parameters cover four broad areas: hydrologic alteration, intentional fish stocking, road impacts, and riparian impairment. Our choice of watershed parameters was guided by three complementary assumptions: 1) the metrics needed to be indicative of habitat condition and well supported by scientific literature, 2) each component needed to be largely independent of the others and readily calculated within a GIS, and 3) the resulting choices needed to be applicable to Sierran watersheds generally. We developed the WIRI indices using well-documented sites within the Mokelumne River watershed. We used two separate measures of hydropower induced alteration to hydrologic conditions for our study sites. First, we calculated the distance between each study site and the closest upstream dam, including both jurisdictional and diversional types. Second, for each site we summarized the upstream cumulative total capacity for reservoirs behind jurisdictional dams. Distance to closest upstream dam gives a relative measure of the effect of hydrologic alteration, as sites closer to dams do not have tributary inputs to dampen effects of hydropower operations. The cumulative capacity of upstream reservoirs behind jurisdictional dams gives a regional measure of impactedness, detailing the volume of flow presumably altered in its timing, duration, and magnitude.

We derived WIRI to assess the ecological condition of the Mokelumne River watershed and determine the comparability of condition indices derived at different spatial scales and with different metrics. As applied to the Mokelumne River watershed, WIRI scores were generated for 26 of 27 sites used in our instream index of biological integrity (IBI) evaluation. The results from this comparative analysis indicated that WIRI was a robust indicator of ecological condition and riverine integrity. Most prominent in this finding was that GIS-derived watershed-scale metrics of hydrologic alteration definitively indicated instream conditions at the site scale. Any discussion of site response to hydrologic alteration due to hydropower operations or climate change must emphasize that sites without dams have higher ecological integrity. Further, sites farther downstream from dams have higher integrity than those that are closer to upstream facilities, likely due in part to the influence of tributaries between sites and facilities increasing drainage area and thus flow. Our assessment of riverine integrity, conducted at different spatial scales and using independent measures of ecological condition, shows that spatial scales can be bridged. Thus, our pilot project supports future broad scale indexing to all riverine waterbodies, on a reach scale. This finding therefore allows for a wide-ranging, synoptic assessment of all rivers and streams in the Sierra Nevada. While additional field-based data, either from existing or future biophysical surveys, will be needed for validation, the use of WIRI, a GIS-derived watershed index of riverine integrity can be applied to all watersheds in the Sierra Nevada. Furthermore, our approach and findings support GIS-based scenario modeling in which watersheds can undergo any number of changes in conditions, such as changes in hydrology or land use, to depict future riverine integrity.

Optimizing Hydropower Operations

Using the legal/policy assessments and the new methods for assessing hydrologic and biologic conditions in watersheds, we initiated the development of new tools to model strategies and outcomes, which optimize mitigation effectiveness while reducing the impact on hydropower production. Optimization and simulation modeling helps regulators, utilities and stakeholders better understand and define trade-offs between hydropower and ecosystem objectives and to estimate their societal, economical, and ecological value.

High Elevation Hydropower and Operations: Adaptation to Change

Climate warming is expected to shift the runoff peak from spring to winter in California as a result of the reduction in snowpack. The Sierra's high-elevation hydropower system supplies roughly 74 percent of California's in-state hydropower supply and is composed of more than 150 power plants with relatively small reservoirs associated with them. Such low capacity reservoir systems have been designed to take advantage of snowpack, the natural reservoir. With climate warming, adaptability of the high-elevation hydropower system is in question as a shift in runoff peak can have important effects on power generation and its economic value. In order to address this issue we simulated changes in hydroelectricity generation under three different climate warming scenarios (dry warming, wet warming, and warming only). These were then compared to historic generation to investigate the adaptability of Sierra's high-elevation hydropower system to climate warming.

We found that, overall, climate warming results in average revenue reduction. Energy spill increases dramatically under all types of climate warming, whether dry or wet. However, the available storage and generation capacities can compensate for snowpack losses to some extent. Expected revenue reductions of 16, 2 and 5 percent are estimated for dry, wet and warming only scenarios, respectively. Storage capacity expansion, and to some extent generation capacity expansion, result in increased revenues. However, these expansions may not be economically justified.

Adaptation. In absence of detailed information about the available energy storage capacity at high-elevation in California, this study explored a simple approach for estimating the adaptability of Sierra's high-elevation hydropower generation to climate warming encompassing virtually all of California's high-elevation hydropower facilities. By substituting the estimated energy content of runoff water inflows for these relatively high-head hydropower units and determining seasonal inflow distribution patterns by elevation band, the study developed a methodology to allow preliminary optimization-driven monthly system operations modeling of one hundred thirty-seven hydropower plants with and without climate change.

With climate warming, the Sierra loses snowpack which has functioned historically as a natural reservoir; but existing hydropower energy storage and generation capacities at high-elevation provide some flexibility to the system to adapt to hydrologic changes. Lower-elevation reservoirs, constructed primarily for water supply, already have substantial re-regulation capacity for seasonal flow adjustments. However, operating rules would need to change under different climate warming scenarios to adapt the system to different changes in hydrology.

Impact on Revenues. Our work indicates that climate warming can cause reductions in high-elevation hydropower generation and revenue which are not only the result of less precipitation, but also the result of changes in seasonal runoff timing. Energy spills increase dramatically under climate warming under existing storage and generation capacities. More storage capacity would increase revenues but may not be cost effective. Storing water in reservoirs helps to shift natural energy runoff reductions to months with lower energy prices to reduce total economic losses. More generation capacity also results in higher revenues by reducing energy spill from the system. However, annual marginal benefits of capacity expansion are higher for storage than for generation, showing the greater gains in revenue from storage over generation capacity expansion to the system.

Nevertheless, current storage and generation capacities give the system some flexibility to adapt to different climate warming scenarios. Although the Dry scenario examined in this study has 20 percent less runoff than the base historical hydrology, system-wide revenues decrease by less than 16 percent through optimally re-operating storage and generation facilities within existing capacity limits. Thus, the current storage and generation capacities are able to compensate for snowpack loss to some extent, and to a greater degree in the Wet and Warming-Only scenarios where revenues decrease very little.

Limited current capacities are unable take advantage of greatly increased energy runoff under the Wet scenario to increase system revenues. Although average annual generation increases by more than 2 percent under Wet climate warming, average annual revenues drop by about 2 percent as a result of a mismatch between monthly generation and monthly energy price patterns and insufficient storage and generation capacities to resolve the mismatch. In a Warming-Only scenario with unchanged historical precipitation, generation and revenues are expected to decrease by 3.5 and almost 4 percent, respectively.

Coordinated Operations. Although, revenues decrease under all climate warming scenarios, the change may be economically insufficient to justify expanding storage or generation capacity, especially given future uncertainty about the type of climate change likely to occur.Adaptability of Sierra's high-elevation hydropower system to climate change can be improved by joint operation of hydropower plants. Hydropower system adaptability in California can be improved and overall energy generation quantities, seasonal patterns, and revenues could be better preserved when facility operations are optimized jointly across the region and across elevation bands rather than independently and separately for each system. This insight supports the broader notion that a more regional approach to FERC re-licensing could help minimize negative impacts on Sierra hydropower generation caused by runoff shifts to, or reductions in streamflow, as well as by mitigation option implementation. By integrating operations of individual hydropower systems that span different watersheds and elevation bands, greater operational flexibility to respond to changes in climate, streamflow, and runoff is created.

Hourly operations of hydropower reservoirs often involve sudden changes in releases associated with the hourly fluctuations in energy prices. This release pattern, known as hydropeaking, affects stream ecosystems by changing flow conditions on short time scales. Within the FERC licensing process, operations are often restricted by limiting rates of change of reservoir releases and by setting minimum releases to the stream. These restrictions limit the ability of the system to follow the pattern of energy prices and potentially reduce the economic value of daily generation.

Afterbays. An alternative to direct constraints on hydropower operations is to re-regulate the release pattern with a water storage facility downstream of the power house. Such an alternative typically exists in cascade hydropower systems, where the most downstream reservoir can be used for this purpose. In some systems, afterbays have been created for this purpose.

As part of our optimization analyses, we explored tradeoffs between economic benefits and instream flow requirements. Constraints on releases to the stream have an economic impact on hydropower revenues. However, a re-regulation reservoir, such as an afterbay, can mitigate this effect significantly by dampening the connection between hydropower generation flows and releases to the stream. Stringent minimum instream flow (MIF) requirements alone can reduce revenues by 15% when no re-regulation capacity is in place. If a re-regulation reservoir is introduced, the revenue reduction is decreased to 9% and 6% for afterbay capacities equivalent to one and two hours of operation at turbine capacity, respectively. Similar effects where observed for restricted ramping rates alone. However, it was observed that, for the cases with an afterbay, only very stringent ramping rates, below 15% of turbine capacity, affect hydropower revenues. When higher hourly fluctuations of instream flows are allowed, revenues reach the unconstrained levels. The effect of combined minimum flow and ramping constraints was studied for a MIF of 10% turbine capacity and varying levels of minimum required releases to the stream. The results are very similar to those obtained for MIF alone. Therefore, limiting ramping rates to 10% of the turbine capacity per hour has no additional effect on revenues to that attributed to minimum required releases to the stream.

The magnitude and timing of hydropower generation flow releases were also studied. In general, releases tend to follow the price pattern characterized by high prices during the afternoon and evening hours and lower prices during the rest of the day. These two periods can be considered peak and off-peak, respectively. Constraints on releases to the stream restrict the ability of the system to follow the daily pattern of energy prices. Minimum required releases to the stream force the system to generate electricity during less valuable hours, when no afterbay is available. With an afterbay, operations are not affected for MIFs up to 10% and 20% of turbine capacity, for the smaller and larger storage capacity, respectively. Constraints on ramping rates tend to equalize hourly releases. As larger ramping rates are allowed, more generation is observed during peak hours. When re-regulation is possible, only very severe constraints on ramping (less than 20% of turbine capacity) have an impact on hydropower release decisions.

Releases to the stream match the minimum required during off-peak hours and are higher and fluctuate more during peak hours, even twice turbine capacity when re-regulation is available. These fluctuations can be attributed to the lesser peaks in energy prices during the peak period, requiring the afterbay to be empty before a new peak hour. However, this can also be due to the fact that releases to the stream do not affect the revenues, and therefore several alternative instream flow patterns can yield the same revenue. An extension to this work, which is currently in progress, explores this aspect by introducing penalties to the revenues associated with potentially undesirable instream flow patterns. The most desirable instream flow pattern among those can be identified for the particular needs of the ecosystem of interest.

Conclusion: Next Steps

The initial results of our research indicate although there are strong strong policy barriers to aggregation and adaptive management at the Federal level, there is potential for the State of California to exert considerable influence on the relicensing process and to promote regionalization and adaptive management. In addition significant influence resides in stakeholder groups and licensees, who often lack the technical tools to evaluate or promote alternative strategies or efficiencies in relicensing efforts. Based on our Year 1 work, we will continue to focus our research on two promising areas that will inform FERC relicensing in the future. The first area of research will complete our Sierran-wide rainfall-runoff and temperature model and the GIS-based physical habitat and biotic integrity models. These models will be used to evaluate current levels of impairment, simulate future conditions due to changes in operations or climate, and help prioritize investments in mitigation. An added benefit of this work will be a comprehensive GIS data base for hydropower facilities and related biological information for the Sierra. The area of emphasis will be on the development of multiple new optimization tools that can be used to evaluate trade-offs between hydropower generation and environmental flow requirements. This work is essential for developing and testing adaptation strategies to climate change and uncertainty, as well as approaches to regional licensing.

Hydropower Relicensing in a Changing Environment: Barriers to and Opportunities for Improved Coordination and Flexibility

PROJECT REPORT

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Abstract

Private hydropower projects above a threshold size require a license from the Federal Energy Regulatory Commission. Many private hydropower projects in California are currently undergoing or about to begin the relicensing process. Relicensing presents an opportunity to reduce or mitigate the environmental impacts of hydropower generation. Because renewed licenses run for thirty to fifty years, relicensing also presents substantial challenges given the likelihood of significant changes both in the environment and in our understanding of it over that time. Two types of changes to the FERC licensing process could potentially improve the overall environmental performance of licensed facilities over time. The first is aggregated or coordinated licensing, that is, consideration of multiple projects together, with coordination of license conditions or mitigation requirements for improved efficiency and effectiveness. The second is flexible or adaptive licensing, that is, including in the license or in negotiated side agreements conditions that would facilitate modification of operations or mitigation efforts as needed to respond to change over time. Both face serious practical and legal barriers, but there are also opportunities that have not yet been explored to improve coordination and adaptability. Most notably, the Clean Water Act section 401 certification process could allow the state to push FERC toward more regionally conscious and adaptive licensing.

Keywords: California, climate change, climate warming, global warming, hydropower, energy, licensing, Federal Power Act, Endangered Species Act, Clean Water Act, Federal Energy Regulatory Commission

Introduction

About 1000 private hydropower facilities in the United States, accounting for roughly half the nation's hydropower generating capacity, operate under licenses issued by the Federal Energy Regulatory Commission. Many licenses were issued in the 1950s and 1960s, an era of rapid water power development, for terms of 40 to 50 years. Little attention was paid to the environmental impacts of hydropower facilities at the time. The National Environmental Policy Act, Endangered Species Act, and modern Clean Water Act did not yet exist, and until the 1980s the Federal Power Act gave scant credence to environmental values. Together with other water projects, hydropower facilities constructed in the mid-20th century bear substantial responsibility for the highly degraded state of the west's aquatic ecosystems.

Today, many hydropower projects are in or nearing the relicensing process. In California alone, nearly one-third of the FERC-licensed hydropower facilities are due for relicensing by 2025. The current wave of relicensing provides a unique opportunity to address the impacts of hydropower production for the next several decades. That opportunity is made more important by global warming. On one hand, hydropower is currently the most economically practical technology for producing electricity without carbon emissions. On the other, global warming may significantly affect both hydropower production and its environmental effects. Like the global climate, both scientific understanding of aquatic ecosystems and societal goals with respect to power generation and environmental protection are likely to change over the decades the second wave of licenses will last.

In this report, we consider the barriers to and opportunities for two types of changes to the FERC licensing process which could potentially improve the overall environmental performance of licensed facilities over time. The first is aggregated (or coordinated) licensing, that is, consideration of multiple projects together, with coordination of license conditions or mitigation requirements for improved efficiency and effectiveness. The second is flexible (or adaptive) licensing, including conditions that would facilitate modification of operations or mitigation efforts as needed to respond to environmental change over time.

Method

In preparing this report, we consulted primary legal sources (the relevant statutes, regulations, and case law), spoke to officials at FERC and the California State Water Resources Control Board, reviewed secondary sources, and examined the documents supporting several recent California licensing decisions through FERC's online library.

The Basics of Hydropower Relicensing

Relicensing standards

In 1920, the predecessor of the current Federal Power Act (FPA) created the Federal Power Commission, now called the Federal Energy Regulatory Commission. Non-federal dams, reservoirs, and related projects in waters under federal jurisdiction, that is waters subject to Congressional regulation under the commerce power, or on federal lands must have a license from the Commission. 16 U.S.C. §§ 792, 797(e). License renewals are subject to the same requirements as applications for new licenses. Confederated Tribes and Bands of Yakima Indian Nation, 746 F.2d 466, 476 (9th Cir. 1984).

In order to issue a license, the Commission must find that the project will be best adapted to a comprehensive plan for improving or developing the waterway for power and other purposes. 16 U.S.C. § 803(a)(1). The ultimate test is whether the project will be in the public interest. Udall v. Federal Power Commission, 387 U.S. 428, 440 (1967). In making that determination, the Commission must give equal consideration to energy conservation, fish and wildlife conservation, recreational opportunities, and other aspects of environmental quality as to the power and development purposes served by the project. 16 U.S.C. § 797(e). It must consider any comprehensive plan for the waterway that has been developed by a federal agency or the state in which the facility is located, and the views of relevant federal and state agencies and tribes. 16 U.S.C. § 803(a)(2).

In general the Commission has broad discretion to impose any license conditions it deems necessary to ensure that the project serves the public interest. Federal and state fish and wildlife agencies may recommend conditions for the protection, enhancement, and mitigation of damage to fish and wildlife affected by a project. 16 U.S.C. § 803(j)(1). While FERC must respond to such recommendations, it is not required to adopt them. American Rivers v. FERC, 201 F.3d 1186, 1201-1205 (9th Cir. 2000). Three types of conditions, however, are mandatory. First, if the project occupies federal land, the license must include any conditions the land management agency deems necessary for the protection and use of that land. 16 U.S.C. § 787(e). Second, the license must require the applicant to construct and operate any fishways, that is structures or devices needed to facilitate upstream or downstream fish passage, prescribed by the National Marine Fisheries Service or US Fish and Wildlife Service. 16 U.S.C. § 811. Third, under Clean Water Act section 401, the license must contain any conditions required by the state to ensure that project operation is consistent with state water quality standards. 33 U.S.C. § 1341. FERC must incorporate those conditions even if it disagrees with them or believes that they would be beyond its jurisdiction to impose on its own initiative. American Rivers, Inc. v. FERC, 129 F.3d 99 (2nd Cir. 1997); Roosevelt Campobello International Park Commission v. US EPA, 684 F.2d 1041 (1st Cir. 1982); FERC 2003a. In California, the agency responsible for 401 certification is the State Water Resources Control Board.

The Energy Policy Act of 2005 added two procedures that facilitate challenges to the mandatory conditions for federal land protection and mandatory prescriptions for fishways. The first allows the license applicant (or any other party to the licensing proceeding) to propose alternative conditions and prescriptions. The conditioning agency must accept the proposed alternatives if it finds that they will provide adequate (for federal lands conditions) or equivalent (for fishways prescriptions) protection and will cost significantly less or improve operation of the project for power production. 16 U.S.C. § 823(d). If it rejects the proposed alternatives, the agency must explain in writing its reasons for doing so. The second new procedure allows the license applicant, or any other party, to demand a trial-type hearing before the conditioning agency on any disputed issue of material fact. 16 U.S.C. § 797(e).

By statute, the term of a license renewal cannot be less than 30 or more than 50 years. 16 U.S.C. § 808(e). FERC's "general policy is to establish 30-year terms for projects with little or no redevelopment, new construction, new capacity, or environmental mitigative and enhancement measures; 40-year terms for projects with a moderate amount of such activities; and 50-year terms for projects with extensive measures." FERC 2002. During that term, a license may not be amended without the consent of the licensee. 16 U.S.C. § 799. In light of this statutory provision and the lengthy duration of licenses, FERC's standard licensing articles include a reopener clause which allows FERC to require changes in project operations if necessary to protect fish and wildlife. If FERC chooses not to reopen a license, however, outsiders cannot force it to do so. The Ninth Circuit recently held that federal action ended with issuance of the license notwithstanding a reopener clause, so that FERC was not required by the ESA to consult with the National Marine Fisheries Service over its failure to invoke the reopener clause. California Sportfishing Protection Alliance v. FERC, 472 F.3d 593 (9th Cir. 2006).

Relicensing procedures

Relicensing proceedings often take a long time and require the devotion of considerable resources by the licensee, federal and state fish and wildlife agencies, FERC staff, and interested stakeholders. FERC has revised its procedures several times over the last ten years in an effort to streamline the process.

The licensee must notify FERC five years before its existing license expires if it intends to seek renewal, and must file its application for renewal two years before the license expires. 16 U.S.C. § 808(b)(1), 808(c)(1). Pending resolution of relicensing proceedings, FERC must issue annual licenses on the same terms and conditions as the expired license. 16 U.S.C. § 808(a)(1). Delay is therefore advantageous to the licensee in some respects; it allows the licensee to put off accepting modern fish and wildlife protection conditions which, according to one commentator, can easily double the operating costs of a project. Kosnick 2006.

The Commission must provide an opportunity for a hearing before making a licensing decision. Typically, the Commission uses a paper hearing procedure, soliciting recommendations from relevant agencies, comments from any interested party and replies to those comments by the applicant before it considers the license application. See 18 C.F.R. § 4.34(b). Since 2005, applicants have generally been required to use the integrated licensing process, which means that environmental analysis is done concurrently with application preparation, instead of after the license application is formally submitted. Most of the process now occurs before the license application is filed. Licensees are encouraged to conduct early outreach and involve stakeholders from the outset. Any interested person or entity may participate in the process by submitting comments.

FERC looks with great favor on settlements in licensing cases. FERC 2006b. Settlement negotiations can provide the opportunity for broad agreements among interested parties that go well beyond ordinary license conditions. FERC will not necessarily include all negotiated conditions in the license itself. It will not, for example, include conditions it views as beyond its authority, or conditions that require action by anyone other than the licensee. The parties are free to incorporate such conditions in side agreements, but must take the responsibility to oversee and enforce them. FERC asserts that it gives no weight in its evaluation to any such side agreements, which it regards as strictly between the parties. Furthermore, negotiations among stakeholders do not bind FERC, which must independently determine that the project meets the standards of the FPA and that there is an adequate factual record to support any conditions. Once FERC makes a decision on the license, any participant may seek reconsideration and, after that, judicial review.

Aggregated or Coordinated Licensing

Hydropower facilities located within the same watershed, or even within the range of the same species, can have similar and cumulative environmental impacts. Under the FPA, licenses must be issued and evaluated for each individual "project," defined as a "complete unit of improvement or development, consisting of a power house" and all associated facilities. 16 U.S.C. § 796(11). Relicensing proceedings can be aggregated or coordinated, however, meaning that FERC can consider several projects in a single combined proceeding. Aggregated licensing of multiple projects within a watershed or region could potentially improve the analysis of environmental impacts and highlight opportunities to make more efficient and effective use of mitigation funds.

Although FERC has occasionally aggregated licensing procedures, the barriers to effectively regionalizing the FERC process are substantial. They include practical difficulties as well as legal limitations on trade-offs between projects.

Practical Barriers to Aggregated Licensing
FERC has occasionally conducted aggregated licensing. Examples include four Erie Boulevard Hydropower projects on the Raquette River, see FERC 2002, which were considered together at the request of the licensee, and relicensed on the same date for identical terms, and four of Southern California Edison's Big Creek projects. FERC has even conducted aggregated proceedings for projects with multiple licensees, see FERC 2003b, although in that particular case the licensees had been in competition for one of the licensed projects. Looking to the future, it is currently FERC's policy to coordinate the expiration dates of renewed licenses for facilities within a single river basin "to the maximum extent feasible" in order to facilitate consideration of their impacts together. FERC 1994.

Nonetheless, there are practical barriers to wider use of aggregated licensing. It requires the consent of the licensee(s), who must be willing to alter the term of one or more licenses. Depending upon the context, aggregated licensing could either increase or decrease the complexity of and transaction costs associated with licensing. It could potentially complicate settlement if it brings to the table too many stakeholders with conflicting interests. It appears that most aggregated licensing proceedings to date have been driven by the licensee's perception that the projects are functionally interrelated and by the desire to develop comprehensive settlement agreements.

Restrictions May Limit the Environmental Benefits of Aggregated Relicensing
Even where relicensing proceedings are regionally aggregated, legal restrictions may limit the extent to which mitigation measures can be aggregated or trade-offs made between projects.

FERC's mitigation practices
The FPA permits FERC to impose mitigation requirements as license conditions only if substantial evidence shows that the project being licensed will cause the effects FERC seeks to mitigate. See San Bernardino Valley Audubon Society v. FERC, ___ F.3d ___ (9th Cir. 2007); City of Centralia v. FERC, 213 F.3d 742 (D.C. Cir. 2000); FERC 2006. FERC cannot impose conditions on one license in order to mitigate harm caused by another. Therefore, in order to "regionalize" mitigation, FERC would have to be able to tie the mitigation requirements imposed to each individual project, or to calculate the contribution of each project to the harm.

FERC's usual practice is to limit mitigation requirements in hydropower licenses to actions that can be carried out within the project boundaries, to the point that it has sometimes refused to impose mitigation activities extending beyond project boundaries despite their inclusion in a settlement agreement. See FERC 2006c. FERC will impose mitigation requirements beyond the project boundaries only if it concludes that those requirements are necessary to address project effects. See FERC 2006a. Off-license settlement agreements, however, do not face this limitation. They can incorporate any mitigation efforts the parties agree to, without geographic limitation, and need not be supported by a demonstrable nexus between the impact and a specific project.

The Endangered Species Act
Section 7 of the ESA requires that federal agencies insure that actions they authorize, fund, or carry out are not likely to jeopardize the continued existence of any endangered or threatened species or adversely modify designated critical habitat. 16 U.S.C. § 1536(a)(2). The issuance of a hydropower license is a federal action that must comply with the ESA. Unless it seeks and obtains an exemption from the "God squad," see 16 U.S.C. § 1536(e), FERC may not impose a license condition that is likely to jeopardize the existence of a listed species. FERC cannot, in other words, allow a project to harm one listed species in exchange for protection for another. Settlement agreements cannot easily get around this restriction. First, federal land management and wildlife agencies are typically among the parties to settlement agreements; they could not participate in an agreement that would be likely to jeopardize a listed species. Second, private parties that entered into such an agreement would find themselves at risk of civil and criminal liability. Section 9 of the ESA prohibits any "taking," broadly defined, of endangered animal species without a permit, 16 U.S.C. § 1538(a)(1)(B), and by regulation most threatened animal species receive the same protection, 50 C.F.R. § 17.31(a).

The ESA will not always stand as a barrier to regional mitigation or to mitigation trade-offs. But it may limit the extent of those trade-offs, or impose additional permitting requirements.

The Clean Water Act
Under Clean Water Act section 401, FERC cannot issue a license for a hydroelectric project in California unless the relevant state agency has certified that the project is consistent with state water quality standards. 33 U.S.C. § 1341(a). The CWA mandates that the state water quality certification conditions become a part of the license which FERC issues. 33 U.S.C. § 1341(d). Like the ESA, the CWA contains no provision allowing water quality standards to be violated on one reach in order to improve protection on another.

California has designated the State Water Resources Control Board (SWRCB) as the agency responsible for section 401 water quality certification. Cal. Water Code § 13160. In order to certify a federal project, the SWRCB must find that it will comply with the water quality standards established by the appropriate Regional Water Quality Control Board. Cal. Water Code § 13240. Those plans set acceptable levels for a variety of physical and chemical characteristics of waterways, including: ammonia, bacteria, chemicals, dissolved oxygen, pH, pesticides, salinity, sediment, temperature, toxicity, and turbidity. They set general standards for all waterways within the basin, as well as targeted guidelines for specific waterways and reaches. Those standards place a floor under any mitigation trade-offs between projects.

An opportunity to promote aggregated licensing
There is one potentially significant opportunity to provide additional incentives for aggregated hydropower licensing, or to improve consideration of cumulative impacts in individual licensing proceedings. Under the Federal Power Act, in order to issue a license FERC must find that the project, as conditioned, "will be best adapted to a comprehensive plan for improving or developing" the waterway for power development and other purposes. 16 U.S.C. ' 803(a)(1).

In making that determination, FERC must consider comprehensive plans developed by state and federal agencies. 16 U.S.C. § 803(a)(2)(a). FERC does not require that "comprehensive plans" be very comprehensive in order to be considered. It maintains a list of plans that merit consideration, including various documents prepared by the California Department of Fish and Game, State Water Resources Control Board, Department of Water Resources, and Department of Parks and Recreation. None of those documents is "comprehensive" in the sense of taking a broad look at the waterways and their associated hydropower projects. Should it choose to do so, the state, presumably through the State Water Resources Control Board could influence the hydropower licensing process by engaging in regionally-focused waterway planning.

The Federal Power Act requires only that FERC consider comprehensive plans; such plans are not necessarily controlling. Section 401 of the Clean Water Act is stronger, in the sense that it requires that FERC impose any conditions the state deems necessary to achieve water quality standards. If California were to adopt a more consciously regional approach to water quality standards and section 401 certification, FERC would be bound by that approach. That could allow California to require more effective regional environmental performance by hydropower facilities, but it would not ease restrictions on mitigation trade-offs.

Flexible or Adaptive Licensing

"Adaptive" hydropower licenses would contain operational or mitigation terms that could be modified as necessary to accommodate changed environmental conditions or increased understanding of project impacts or environmental sensitivity. They would also need to include a mechanism to insure that needed modifications are implemented. Current law would permit adaptive licensing, and FERC's standard requirements provide much of the needed foundation for an adaptive approach. Off-license settlement agreements also can incorporate adaptive conditions. However, the desire of FERC and licensees to frame conditions clearly at the outset of the license, the inability to set definite boundaries, and the complexity of multi-stakeholder negotiations all stand as practical barriers to an adaptive approach.

Reopener Clauses

The inclusion of reopener clauses in FERC hydropower licenses presents an opportunity for adaptive management. It is now standard practice for FERC to include in the license a term that allows it to unilaterally make changes to license conditions. The courts have upheld FERC's authority to include reopener provisions. Wisconsin Public Service Corp. v. FERC, 32 F.3d 1165 (7th Cir. 1994). Such provisions may reserve Commission authority to, among other things: make changes to plans submitted, amend licenses in light of Forest Service determinations regarding § 4(e) conditions, require measures to protect endangered species, require licensees to construct and maintain fish passage facilities, or require licensees to undertake measures to protect water quality. We reviewed the conditions imposed on nineteen recently relicensed hydropower projects in California; all included reopener clauses reserving the Commission's authority to make changes to the license.

Reopener provisions could facilitate adaptive management, but that is not the way FERC uses them. FERC regulations mandate that it define its reserved authority narrowly and with as much specificity as possible, and require that it publish notice and provide opportunity for comment before invoking a reopener clause. 18 C.F.R. § 2.23. In its 2006 Policy Statement on Hydropower Licensing Settlements, FERC 2006b, p. 2, FERC explained:

> The Commission does include reopener provisions in hydropower licenses, but these are only exercised where environmental conditions have significantly changed. Were the Commission to assert a broad, general authority to reopen any part of a license during its term . . . this would sharply undercut the certainty sought by parties to licensing proceedings.

The Policy Statement repeatedly emphasizes the importance of ensuring that license conditions are clear and enforceable, and providing certainty to licensees.

In practice FERC has not shown a willingness to reopen licenses, nor have courts been inclined to force reopening. In California Sportfishing Protection Alliance, 472 F.3d 593 (2006), FERC refused to seek reopener despite a new ESA listing and a major die-off of fish downstream from the project. The Ninth Circuit held that although the reopener clause gave FERC the authority to modify the license, it was not required to consult with the Fish and Wildlife Service on its failure to do so. That seems to leave stakeholders with no way to force FERC to exercise a reopener clause if it chooses not to do so.

Monitoring and Study Requirements

Requirements for monitoring and study are common in hydropower licenses, but like reopener clauses FERC generally does not use them in an adaptive manner. Study requirements are often short-term; of six recent licenses we examined that incorporated study requirements, four required studies only during the first five years of the license term. Monitoring may extend throughout the license term, but does not always. Like other license conditions, study requirements must be supported by substantial evidence. FERC must weigh the cost of required studies against their expected benefits. City of Centralia v. FERC, 213 F.3d 742 (D.C. Cir. 2000). Licenses typically do not specify any consequences based on the outcome of studies or monitoring.

The need for sideboards

Although FERC is not openly opposed to adaptive management, it will not include open terms in a hydropower license. It requires that any adaptive provisions establish outer boundaries within which license conditions (such as flow requirements) will be adjusted. FERC 2006b. FERC is anxious to provide as much certainty as possible for licensees, who may be faced with substantial expenditures as a consequence of new environmental requirements imposed in the relicensing process. FERC is also concerned that license conditions be as clear and specific as possible so that the interpretation of the license does not change with staff turnover, not an insignificant concern for documents that must last for decades.

Settlement Agreements

Settlement agreements are constrained by FERC's resistance to incorporating truly adaptive terms in a license. With respect to operating parameters, which must be part of the license, settlement agreements must provide clarity, specificity and enforceability if they are to win FERC approval. Furthermore, FERC, not the parties to a settlement agreement, must have final authority to approve any changes to license conditions during the license term. FERC 2006a, FERC 2006b, FERC 2005. Since FERC will not alter a license without notice and opportunity to comment, requiring its approval adds time to the process.

As it does with aggregated licensing, FERC has some experience with adaptive license provisions, incorporated in response to settlement agreements. In 2001, it issued a new license for PG&E's Mokelumne Project based on a settlement agreement. FERC incorporated into the new license a requirement that PG&E form an Ecological Resources Committee, consisting of representatives of each of the parties to the settlement agreement and a liaison from the Forest Service, to design monitoring plans, review and evaluate data, and make preliminary decisions, subject to Commission approval, to adjust, within a specified range, requirements for minimum streamflows, reservoir temperature, and pulse flows. FERC 2001. The agreement provides that the Ecological Resources Committee will act by consensus, which may be difficult to achieve in a disparate group with conflicting interests. The licensee, which is a member of the Committee but also the party paying the bills, may have incentives to be uncooperative.

Settlement agreements can go beyond license provisions, incorporating additional mitigation measures and side agreements as the parties see fit. Such agreements are not subject to the constraints FERC puts on license conditions. However, they remain subject to the practical difficulty of combining flexibility with sufficient certainty to satisfy the licensee, and sufficient clarity to permit enforcement. They also frequently incorporate the kinds of consensus requirements for change incorporated into the Mokelumne Project license. Moreover, off-license agreements must be enforced by the stakeholders, a process that is likely to be difficult, time-consuming, and expensive.

State Water Quality Certification

State water quality certification provides an enticing opportunity for adaptive licensing because, as already explained, FERC must incorporate any conditions required by the State Water Resources Control Board in its section 401 certification, even if those conditions do not meet the requirements it has imposed on itself with regard to specificity, clarity, and sideboards. To date, SWRCB has not used its section 401 authority to require adaptive management of hydropower projects. According to the Senior Environmental Specialist for the Sacramento FERC Relicensing Team, the SWRCB shares FERC's preference for structuring license conditions clearly at the outset, but is willing to incorporate science-based adaptive terms within appropriate parameters when feasible (James Canaday, personal communication).

The short timeline for section 401 certification may complicate efforts to use this mechanism to develop adaptive license terms. The SWRCB must respond to a request for certification within one year or it waives its opportunity to condition the project. 33 U.S.C. § 1341(a)(1). That may make it difficult for the SWRCB to try an unfamiliar approach. Furthermore, in a substantial proportion of recent relicensings, the applicant filed for water quality certification ten years or more before the license was actually issued. SWRCB, in other words, might be faced with having to develop its conditions well in advance of the actual licensing decision.

Conclusions

Although FERC has experimented with both aggregated and adaptive licensing, for the most part the hydropower relicensing process is fragmented and creates rigid documents intended to govern operations decades into the future.

There are no substantial legal barriers to wider use of aggregated licensing. The barriers to aggregated licensing are primarily practical, chiefly the potential for increased cost, processing time, and complexity. The extent to which aggregated licensing would improve environmental performance or the efficiency of mitigation through opportunities for significant intra-project tradeoffs in operating conditions or mitigation measures is unclear. Aggregation surely would highlight the cumulative impacts of hydropower projects, and might allow the identification of useful trade-offs or combined mitigation measures. The ability to make trade-offs, however, will be limited by the Endangered Species Act and Clean Water Act. Better understanding of the environmental impacts of hydropower facilities could enhance the willingness and ability of FERC to effectively aggregate licensing proceedings, and perhaps could reduce licensee resistance. California could push FERC toward a more regional perspective by drafting formal comprehensive plans addressing the impacts of multiple projects on waterways, or by taking a more consciously regional approach to section 401 water quality certification.

Flexible or adaptive licensing is also feasible within the boundaries of current law, but inhibited by practical barriers and institutional resistance. FERC's practice of including reopener clauses could facilitate adaptive management, as could the routine inclusion of monitoring and study requirements as license conditions. FERC, however, is committed to providing as much certainty for licensees as possible, and therefore resists the sorts of open-ended conditions that would most facilitate truly adaptive management. To some extent, off-license settlement agreements can provide a path to work around FERC resistance, but because they are voluntary, settlement agreements will always be limited by licensee demands for certainty. California could impose adaptive conditions through the section 401 certification process, but the SWRCB is reluctant to do so without strong scientific backing and confining sideboards. Improved scientific understanding of changing aquatic ecosystems and the impacts of hydropower facilities on those systems could potentially improve the ability to craft effective adaptive provisions within sideboards that are sufficiently clear and limited to satisfy FERC, licensees, and the SWRCB.

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REGIONAL AGREEMENTS, ADAPTATION, AND CLIMATE CHANGE: NEW APPROACHES TO FERC LICENSING IN THE SIERRA NEVADA, CALIFORNIA: HYDROLOGIC MODELS OF SIERRA NEVADA IN WEAP

HYDROLOGIC ANALYSIS

PROJECT REPORT

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Introduction

For several years, there has been an accumulating body of evidence that climate change will reduce the volume of snow accumulating in the Sierra Nevada Mountains and accelerate the melt of that which does accumulate (Snyder et al. 2004). Other work has attempted to understand the implications of these potential changes for streamflow hydrology in the major rivers of the west slope of the Sierra Nevada (Maurer et al. 2002, Brekke et al. 2004, Vicuna et at. 2007). As the focus of these studies was on the implications of climate change for statewide water management, they focused on the downstream points in western Sierra watersheds where water flows into the major storage reservoirs in the system. Location specific information on hydrologic change in the upper portions of watershed in the western Sierra was not developed.

The current study is investigating how climate change can be factored into the re-licensing process of hydropower projects across the western Sierra by the Federal Energy Regulatory Commission (FERC), so that valuable aquatic ecosystems in the Sierra eco-region can be protected and enhanced. These projects are comprised of storage reservoirs, diversion works, conveyance structures, powerhouses and return flows that are spread across the Sierra from north to south and from the Sierra crest to the edge of the Central Valley, suggesting that a more refined assessment of the hydrologic implication of climate change, beyond those associated with inflows to the major downstream reservoirs, is needed. This report contains information on how such an assessment was conducted and how output from the resulting modeling tool reveals that climate change impacts will not be felt uniformly across the western Sierra. This has important implications for how strategies should be developed to pursue ecosystem objectives within the context of the FERC re-licensing process.

The report is organized to present the methodology used to develop a more refined characterization of the hydrologic implications of climate change in the western Sierra. It opens with a general description of how this work fits within a larger analytical continuum, which also includes water temperature, aquatic ecosystem and system operation considerations, that is in turn nested within an analysis of the legal and institutional context for the FERC re-licensing process. The report then continues to present the specifics of the components of the Water Evaluation and Planning (WEAP) system that was used for the hydrologic analysis. This section describes the basic structure of WEAP, the approach that was taken in developing WEAP applications for the major rivers in the western Sierra, and the process that was followed in calibrating these applications. The report also presents some early results on how climate change, as made manifest by increasing weekly average temperatures by 2°C, 4°C, and 6°C, translates into changes in the projected timing of runoff and patterns of snow accumulation for sub-watersheds across the Sierra. The final section of the report deals with recommendations for additional analysis.

Methodology

The methodology for hydrologic analysis presented in this section has been developed to contribute to a very specific management context. Prior to delving into the technical details of the approach, it is wise to present that context so that it motivates the analysis and the associated results. From the broadest perspective, the context that motivates this research is the factual progression that:

There are more than 95 FERC licensed hydropower projects in the western Sierra that dam or divert rivers.

These structures are operated in a fashion that significantly alters the flow in specific river reaches.

FERC re-licensing for 32 projects with more than 100 dams is underway, or will be initiated in the next 15 years, creating a unique opportunity to consider the tradeoffs associated with generation of hydroelectricity and the protection and enhancement of aquatic ecosystems in the western Sierra.

Superimposed on this progression are a number of factors that may influence how these tradeoffs should be analyzed. Included among these are:

The expectation that, over the terms of the licenses that will be granted by FERC for the operation of these projects, typically 30-50 years, climate change will alter the hydrology of the Sierra Nevada relative to that which was experienced in the past.

The expectation is that these changes will not be uniform across the Sierra.

The conviction that in face of this variability some aquatic ecosystems will be highly vulnerable to hydrologic changes induced by climate change while others will be less threatened.

The realization that the exact nature of the hydrologic change associated with climate change is uncertain.

In light of these factors, an effective strategy for engagement in FERC processes in the Sierra Nevada should allow for spatially differentiated application of mitigation actions in the terms of FERC licenses so that priority is given to portions of the Sierra where these actions will best protect and enhance valued aquatic ecosystems in the face of future climate change. The strategy should also include adaptive management flexibility that is appropriate for the level of uncertainty associated with climate change.

The first element of the research context, then, is an analysis of the legal and institutional barriers and opportunities that will either encourage or stymie spatial differentiation or adaptive management in the terms of FERC licenses.

Assuming that these elements could feasibly be incorporated into the FERC process, then the question would turn to defining the differential impacts of climate change and to analyzing opportunities to respond in terms of the manner in which hydropower generation infrastructure is operated. There is an analytical continuum that will allow this to occur. This continuum starts with a tool that can translate changes in climate into changes in hydrology at the points where management interventions could occur, primarily storage reservoirs and points of diversion from rivers into the power generation infrastructure. The second step in the continuum involves developing tools to understand how climate change and the associated hydrologic responses will impact water temperatures in rivers and streams in the Sierra. The third component involves developing tools to assess how the simulated changes in flow regime and water temperature at various points in the Sierra will impact components of valuable aquatic ecosystems such as invertebrates, amphibians, and fish.

As a first iteration, this continuum can be followed assuming that the response of the system is unmodified by the operation of hydraulic infrastructure. This analysis provides a baseline that can help us understand where the Sierra aquatic ecosystems are most vulnerable to climate change. Obviously very little of the Sierra is unaltered by the operation of hydraulic infrastructure and a second pass along the continuum can be filtered through analysis of how this infrastructure should be operated in order to appropriately manage the tradeoffs between the generation of hydroelectricity and the protection and enhancement of aquatic ecosystems. This will allow for the exploration of mitigating actions that could be incorporated into the terms of FERC licenses for the projects in the Sierra (Figure 1).

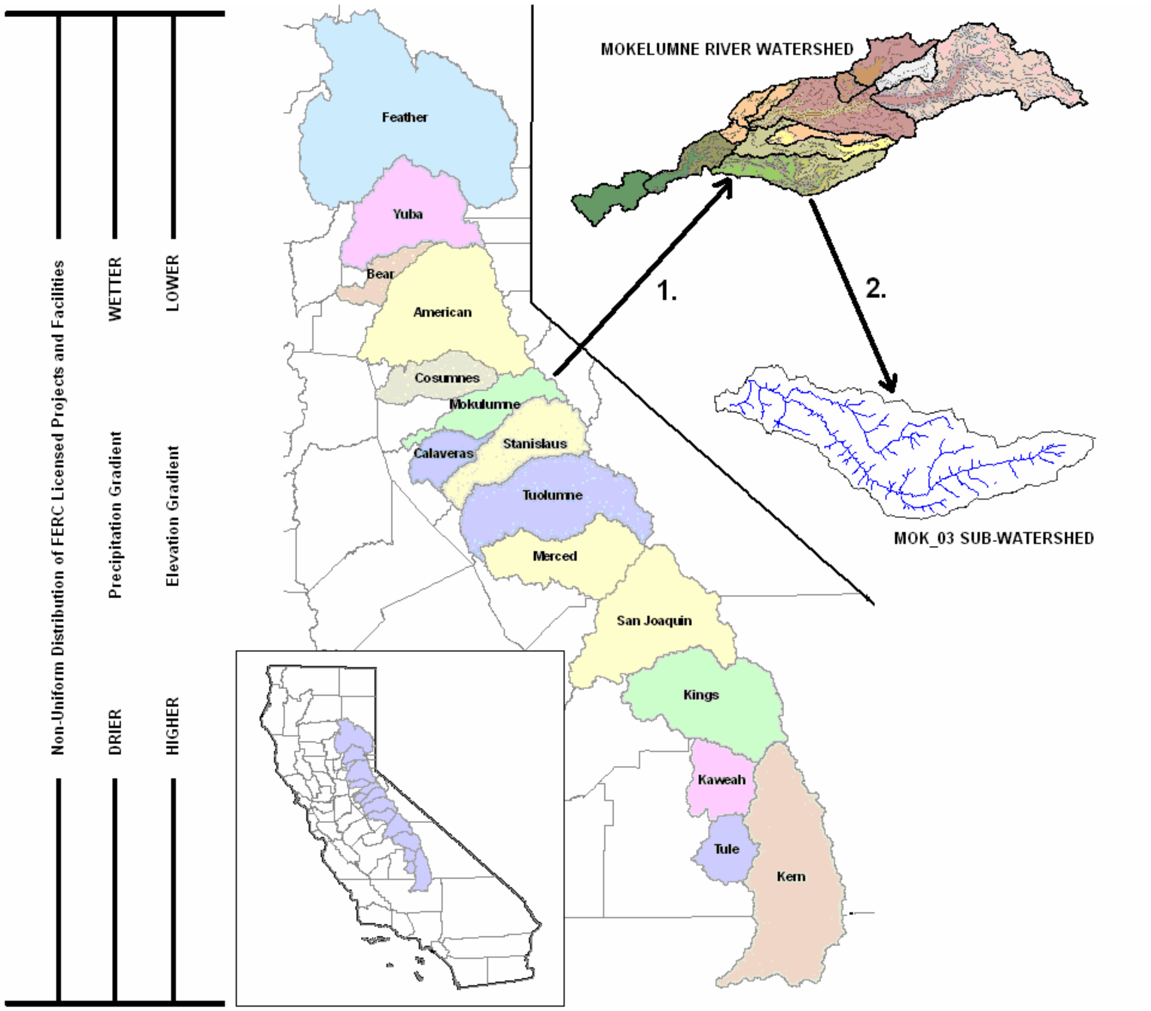


Figure 1. The principle hypothesis of the research is that owing to the non-uniform distribution of FERC projects across the Sierra Nevada and to north-south gradients in precipitation and maximum elevation, individual FERC projects will be differentially impacted by climate change. To test this hypothesis, individual models of each watershed (1.) were developed. In these models, each watershed was divided into sub-watershed based on topography, the location of hydraulic infrastructure and the location of flow measurements. Each sub-watershed was, in turn, dis-aggregated into 250m elevation bands. Simulated changes in snow accumulation, snow melt, and stream flow under different climate scenarios were assessed at the sub-watershed level. Within each sub-watershed (2.), these changes in hydrology were used to assess changes in water temperature, and together these simulate changes were used to assess changes in stream habitat quality at the reach level.

In terms of the hydrologic analysis, what has been undertaken here is a much more refined analysis of the impact of climate change than has previously been undertaken in California. Previous work focused on understanding potential changes in the inflow to the major Central Valley reservoirs. Because of the importance of these facilities to the statewide water planning, the California Department of Water Resources has developed monthly time series of the Full Natural Flow during the historical period. These time series are an attempt to back out of the observed inflow to these facilities the influence of operations in the upper watersheds of the Sierra, and as such are a model that has inherent uncertainty. It was against these time series that previous models used to evaluate the impact of climate change on California hydrology were calibrated. No effort was made to assure that the hydrologic response of sub-watersheds upstream was correct as long as the aggregate response downstream was valid. In addition, the parameters the various watershed models used to simulate the hydrologic response with respect the historic climate input data were all calibrated individually, such that the parameters for one river system differed from those developed for another.

This calibration approach provides limited grounding to support analysis of the potential climate change impacts at the various locations of hydropower infrastructure across the range. The hydrologic analysis described below represents the implementation of a calibration strategy whereby a single set of model parameters was developed that approximated the observed streamflow response in all sub-watersheds across the Sierra where the historical record is unaltered by upstream alteration. These parameters where then applied across all sub-watersheds in the Sierra, including the vast majority that is either altered by upstream operations or unmonitored by a stream gauge. The aggregate response of these sub-watersheds at the bottom of each watershed was then calculated and compared with the estimated Full Natural Flow as reported by the Department of Water Resources. This approach yields a final set of models that provide a much more refined take on climate change and hydrology in the Sierra, and a better grounding for analysis of strategies to balance hydropower generation with ecosystem protection and enhancement across the range.

Hydrologic Analysis

The WEAP21 modeling platform was used to model the hydrological processes of Sierra Nevada watersheds. WEAP21 consists of modules for both physical hydrology and infrastructure operations. Since the first goal of this project is to calculate unimpaired river flows under current and future climate regimes, only the physical hydrology portion of the model was used in the current phase. The physical hydrology module consists of several conceptually simple components that are combined to be computationally efficient, but with enough specificity to capture variability in the important terrestrial components of the hydrologic cycle and address key water resource issues. This is accomplished via a one dimensional, 2-storage soil water accounting scheme that uses empirical functions to describe evapotranspiration, surface runoff, sub-surface runoff or interflow, and deep percolation (Yates 1996). Figure 2 shows the components of this conceptual model that allow for the characterization of watershed controls on the hydrologic cycle.

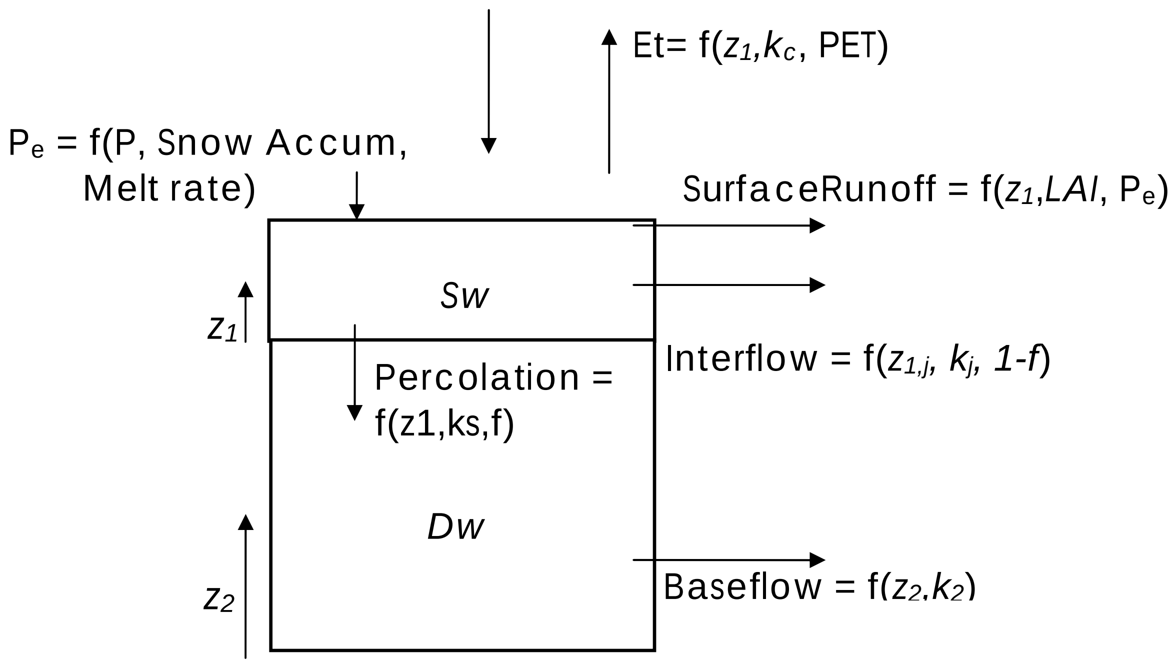


Figure 2. Schematic of the two-layer soil moisture store, showing the different hydrologic inputs and outputs for a given land cover or crop type.

To build a WEAP application, a watershed is first divided into sub-watersheds with outlets based on locations where total flow in a stream will be simulated. Sub-watersheds are further subdivided into bands of elevation which are then further divided into *N* fractional areas of unique soil and land cover characteristics, where a water balance is computed for each fractional area, *j* of *N*. Each unique elevation band within a sub-watershed is hereafter referred to as a catchment. This process is described in detail in Section 2.2. Climate is assumed uniform over each fractional area where a continuous mass balance equation is written as,

$$Sw_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t)(\frac{5z_{1,j} - 2z_{1,j}^2}{3}) - P_e(t)z_{1,j}^{\frac{LAI_j}{2}} - f_j k_j z_{1,j}^2 - (1 - f_j)k_j z_{1,j}^2 \qquad \text{Eq. 1}$$

with the relative soil water storage, $z_{1,j}$ given as a fraction of the total effective storage and varies between 0 and 1, where 0 represents the permanent wilting point and 1 field capacity. The total effective storage of the upper layer is approximated by an estimate of the soil water holding capacity (Sw_j in mm) prescribed for each fractional area, *j*.

WEAP21 includes a simple temperature-index snowmelt model which computes an effective precipitation P_e. The model estimates snow water equivalent and snowmelt from an accumulated snowpack in the sub-catchment, where m_c is the melt coefficient given as,

$$m_c = \begin{cases} 0 & T_i < T_s \\ 1 \quad \text{if} & T_i > T_l \\ \dfrac{T_i - T_s}{T_l - T_s} & T_s \le T_i \le T_l \end{cases} \qquad \text{Eq. 2}$$

with T_i the observed temperature for period i, and T_l and T_s are melting and freezing temperature thresholds, with the melt rate is given as

$$m_i = \min(Ac_i m_c, Em) \qquad \text{Eq. 3}$$

Snow accumulation, Ac_i is a function of m_c and the observed total precipitation, P_i

$$Ac_i = Ac_{i-1} + (1 - m_c)P_i - m_{i-1} \qquad \text{Eq. 4}$$

Em is the available melt energy converted to an equivalent water depth/time. The available melt energy is computed as

$$Em = Rnet + Eother \qquad \text{Eq. 5}$$

Rnet is the net radiation and *Eother* represents additional forms of energy that contribute to snow melt beyond the incoming solar radiation. This lumped parameter includes sensible, latent, advective, and ground energies. It is calculated as the net radiation *Rnet* multiplied by an additional radiation factor, *Rf*, which was adjusted during calibration. The calculation for net radiation considers the albedo which is modeled using a simple algorithm that decreases albedo through time to represent the "ripening" of the snow surface (USACE, 1998, Fig 5-5). The model user specifies a "new" snow albedo value, A_N, and the lowest or "old" snow albedo, A_O, value as a fraction. Albedo is set at the "new" value following snow fall, it is then decreased by 0.1 for each simulation week with a minimum of the "old" snow albedo value. When no snow cover is present, albedo is a constant 0.15 and is used in the calculation of the Penman-Montieth reference evapotranspiration.

The effective precipitation, P_e is then computed as

$$P_e = P_i m_c + m_i \qquad \text{Eq. 6}$$

The second term in Eq.1 is evapotranspiration from the fractional area, *j* where *PET* is the Penman-Montieth reference crop potential evapotranspiration given in mm/day and k_c^j is the crop/plant coefficient for each fractional land area. When the model is run with longer time steps, *PET* is scaled to an appropriate depth/time (Allen et al. 1998). The third term represents surface runoff, where *LAI* is the Leaf and Stem Area Index (LAI), with the lowest LAI_j values assigned to the land cover class that yields the highest surface runoff response, such as bare soils. The third and fourth term are the interflow and deep percolation terms, respectively, where the parameter k_j ,is an estimate of the upper storage conductivity (mm/time) and f_j is a quasi-physical tuning parameter related to soil, land cover type, and topography that fractionally partitions water either horizontally, f_j or vertically (1- f_j). The surface and interflow runoff contributions from the upper store, *Ro* from each sub-catchment at time *t* is,

$$Ro(t) = \sum_{j=1}^{N} A_j \left(P_e(t) z_{1,j}^{\frac{LAI_j}{2}} + f_j k_j z_{1,j}^2 \right) \qquad \text{Eq. 7}$$

where A_j is the contributing area of each fractional area, *j*. A mass balance for the second store is given as,

$$Dw \frac{dz_{2,j}}{dt} = (1 - f_j) k_j z_{1,j}^2 - k_2 \; z_{2,j}^2 \qquad \text{Eq. 8}$$

where the inflow to this deep storage is the deep percolation from the upper storage given in Eq. 1, and k_2 is the conductivity rate of the lower storage (mm/time) which is given as a single value for the catchment, and *Dw* is the deep water storage capacity (mm). Equations 1 and 8 are solved using a fourth-order runge kutta algorithm (Chapra and Canale 1998). Baseflow is simply,

$$Bf(t) = \sum_{j=1}^{N} A_j (k_2 \; z_{2,j}^2) \qquad \text{Eq. 9}$$

Spatial Analysis

Hydrologic models for 15 Sierra watersheds were developed in the Water Evaluation and Planning platform, WEAP21 (Figure 3). Each of the watersheds was assigned a three-letter watershed code and was assumed to terminate at the watershed outlets shown in Table 1. In order to develop these models GIS-based data was acquired and used to define analysis units within the WEAP models. The following steps were carried out for each modeled watershed:

1. Delineate watershed.
2. Delineate sub-watersheds.
3. Develop polygons of elevation bands using the DEM (digital elevation model).
4. Intersect elevation bands and sub-watersheds.
5. Classify vegetation into trees, shrubs, etc.
6. Classify soils into deep and shallow.
7. Intersect soils, vegetation, sub-watersheds, and elevation bands.
8. Create WEAP catchments for each sub-watershed - elevation band combination.
9. Create sub-catchments (or fractional area) for each vegetation - soil combination in each catchment.

Figure 4 illustrates steps 1-4 of the GIS analysis used in delineating the WEAP catchments. Figure 4a illustrates the sub-watershed delineation based on sub-watershed outlets chosen by the project team. Figure 4b illustrates the intersection of the sub-watersheds and DEM derived elevation bands to determine the area represented by individual catchments in the WEAP models (Figure 4c).

With the catchments delineated, the associated areas intersected with land use and soil depth data for the region define the distribution of land class throughout each catchment. These steps are described in more detail in the following sections.

Watershed Code	**Watershed Outlet**	**Model Name**	**Number of sub-watersheds**	**Number of catchments**
AMR	FOLSOM RESERVOIR	AMR_COS	46	185
BAR	CAMP FAR WEST RESERVOIR	YUB_BAR	6	19
CAL	N HOGAN LAKE	CAL	3	14
COS	COSUMNES R AT MICHIGAN BAR	AMR_COS	5	27
FEA	LAKE OROVILLE	FEA	38	164
KAW	LAKE KAWEAH	KAW	8	61
KNG	PINE FLAT RESERVOIR	KNG	15	103
KRN	RIO BRAVO PP NR BAKERSFIELD CA, 11193010	KRN	10	68
MER	LAKE MCCLURE	MER	6	42
MOK	PARDEE RESERVOIR	MOK	13	56
SJN	MILLERTON	SJN	38	185

Watershed Code	Watershed Outlet	Model Name	Number of sub-watersheds	Number of catchments
	LAKE			
STN	NEW MELONES RESERVOIR	STN	25	109
TUL	LAKE SUCCESS	TUL	9	56
TUO	NEW DON PEDRO RESERVOIR	TUO	19	97
YUB	DEER CREEK NR SMARTVILLE 11418500 AND HARRY L ENGLEBRIGHT LAKE	YUB_BAR	20	82

Table 1. Watershed and model information.

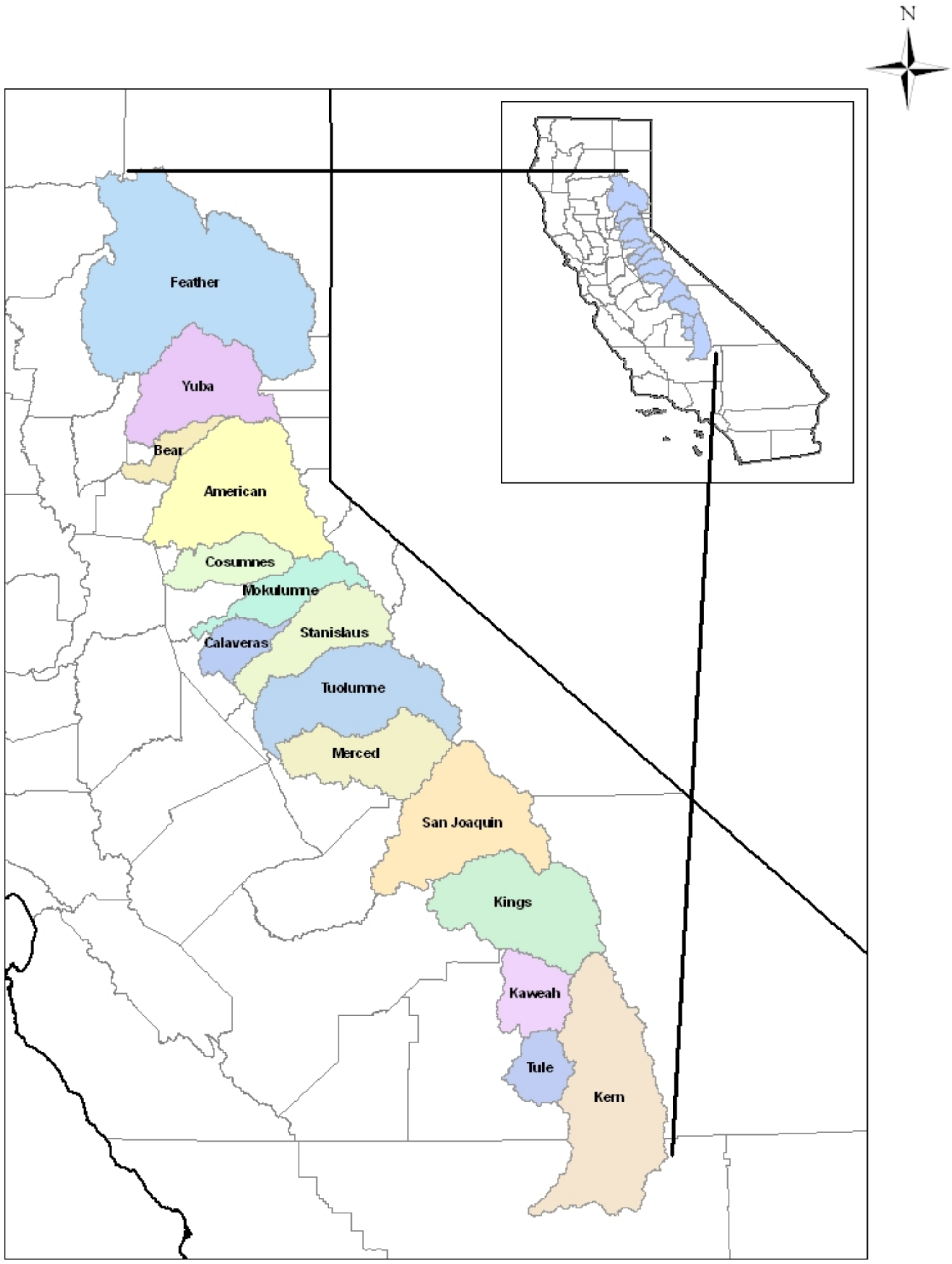


Figure 3. Project Watersheds

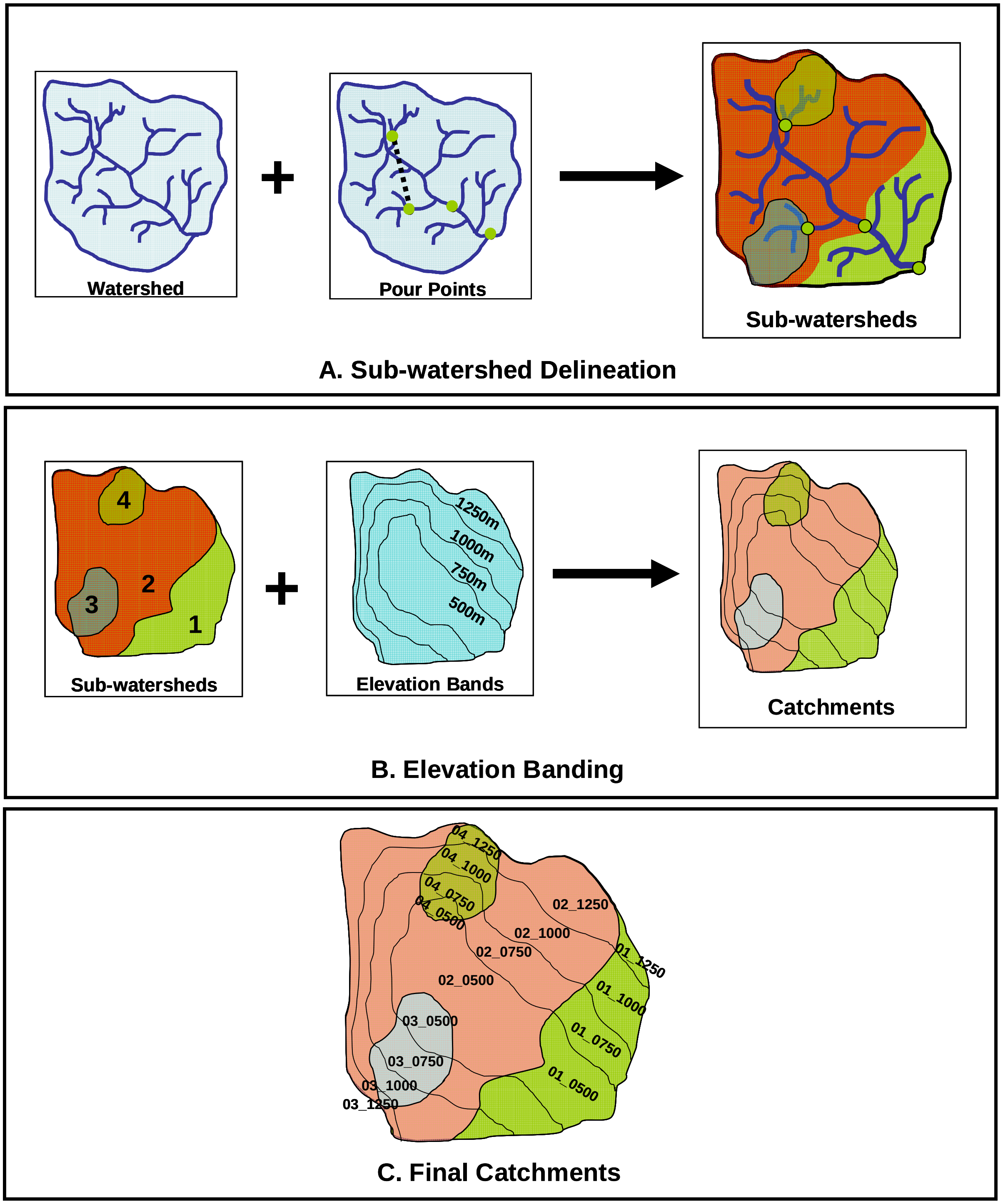


Figure 4. Sub-watershed Delineation , Elevation Banding and Catchment Definition

GIS Analysis

In this section a more detailed explanation of how the spatial analysis was conducted is presented. An example of the Mokelumne Watershed is used to demonstrate the process.

Watershed Delineation

Digital elevation data for the Sierra region was obtained from the USGS National Elevation Data Set. The data set provides ground surface elevation values on a 10 m by 10 m grid. Using this digital elevation data, water flow direction and accumulation values were calculated and used to delineate the watersheds for each of the major rivers in the Sierra. All spatial analysis operations were conducted in the ArcGIS software. The data associated with the watershed delineation process can be found in the Watersheds folder of the digital data that accompany this report. The prefix for each file is the three letter code defining the watershed (i.e. MOK for the Mokelumne; MOK_Watershed.shp). All GIS data output is in the Teale-Albers, NAD83 projection (See Appendix A).

Sub-watershed Delineation

Sub-watershed delineation was also carried out using the watershed function in the ArcGIS Hydrology tool set, which requires a water flow direction raster data set for the region, as well as defined watershed outlets, or pour points. The pour points for each watershed were defined through a series of exercises based on locating key features in each watershed.

Because the hydrologic models will eventually be used to assess potential hydropower operations in response to climate change, the primary determinant of watershed pour points (outlets) was the existence of infrastructure such as dams, diversion works and points of powerhouse discharge. The State of California Jurisdictional Dams and National Hydrography data sets were employed in identifying the significant infrastructural elements, as were the narrative titles of USGS gage stations. These we used to define sub-watershed pour points

The availability of calibration information was another primary determinant in the process of sub-watershed delineation. The United States Geological Survey (USGS) has a wide range of historical data available including daily streamflow information on a large number of river reaches. USGS records were analyzed in order to determine those gauging stations with a significant period of record to be used in calibration (between 1980 and 2000 in this study). The location of gages that had data for continuous periods of at least 5 years were chosen as sub-watershed outlet points.

The flow direction grid (Figure 5) was used along with the pour points (Figure 6) to delineate the watershed boundaries (Figure 7). This process of sub-watershed delineation was carried out for each watershed separately and resulted in the definition of 261 sub-watersheds within the 15 larger watersheds of the Sierra (Table 1).

The data associated with the sub-watersheds throughout the region can be found in the Sub-watersheds folder (i.e. MOK_subwatersheds). The pour points used to define the sub-watersheds can be found in the same folder as *_ppoints.shp files (i.e. MOK_ppoints.shp). The end product is the definition of sub-watershed that corresponds to a particular USGS streamflow gage or infrastructural element. The corresponding names of the sub-watersheds are presented in Appendix B.

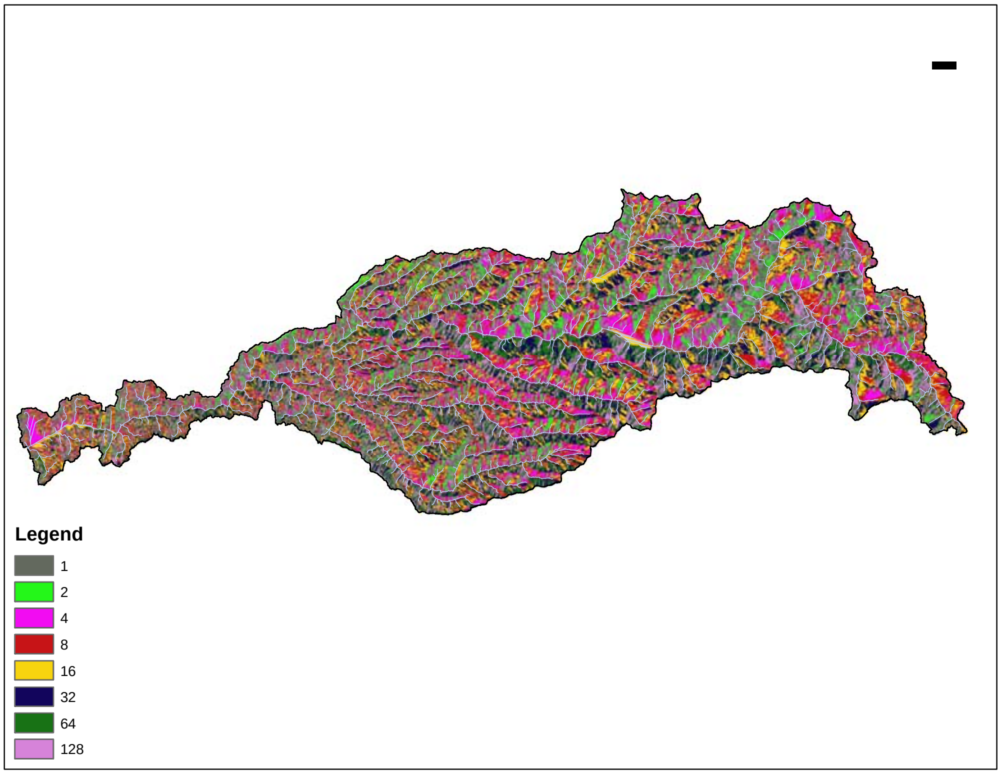


Figure 5. Flow Direction Raster (Mokelumne Watershed)

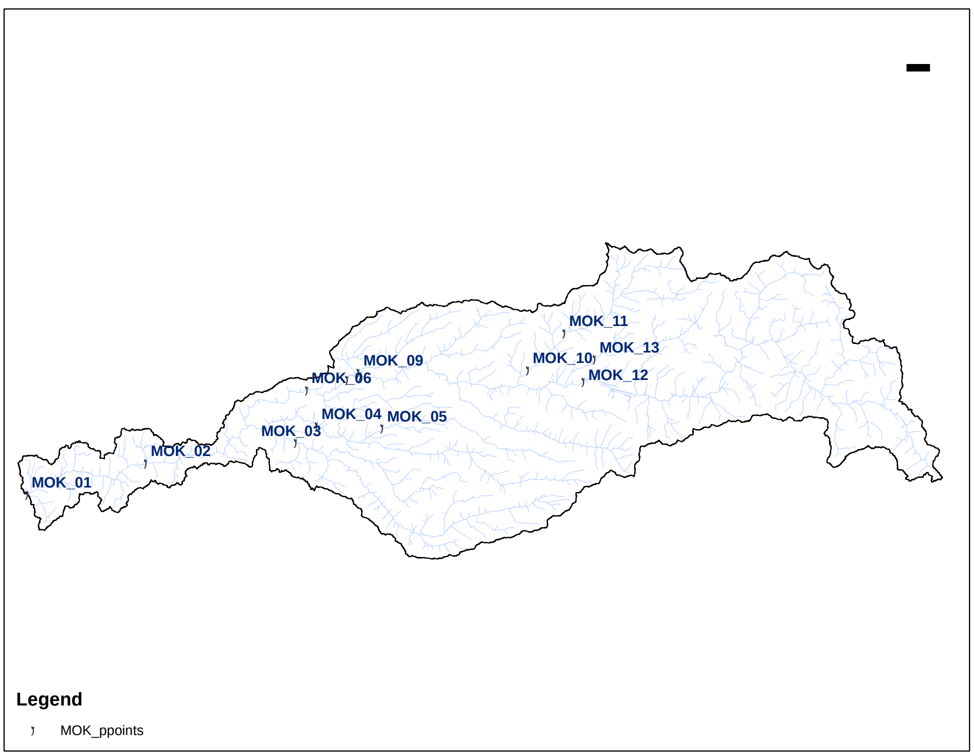


Figure 6. Mokelumne Sub-watershed Pour Points

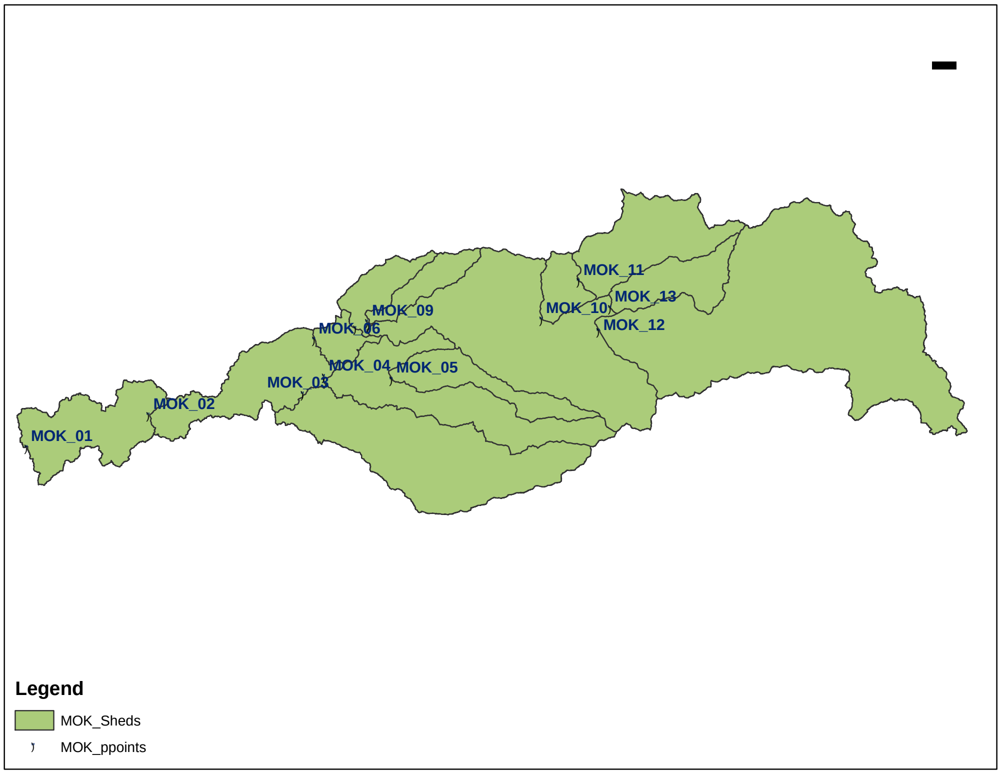


Figure 7. Sub-watersheds Mokelumne Watershed

Elevation Banding

The USGS digital elevation data used to delineate the watersheds and subwatersheds was also used to develop elevation bands for the region (Table 2 and Figure 8).

Elevation Range (m)	Band
0-500	500
501-750	750
751-1000	1000
1001-1250	1250
1251-1500	1500
1501-1750	1750
1751-2000	2000
2001-2250	2250
2251-2500	2500
2501-2750	2750
2751-3000	3000
3001-3250	3250
3251-3500	3500

Elevation Range (m)	Band
3501-3750	3750
3751-4000	4000
4001-4250	4250

Table 2. Elevation Banding

Intersection of Elevation Bands and Sub-Watersheds

These elevation bands were then intersected with the sub-watersheds, as shown in Figure 8, in order to further disaggregate the sub-watersheds, resulting in a total of 1268 catchments representing a particular elevation range within a sub-watershed. Figure 9 depicts the banding results in the Mokelumne Watershed, with a total of 56 catchments. The catchment data can be found in the Catchments folder. The prefix for each file is the three letter code defining the watershed (i.e. MOK for the Mokelumne; MOK_Catchments.shp).

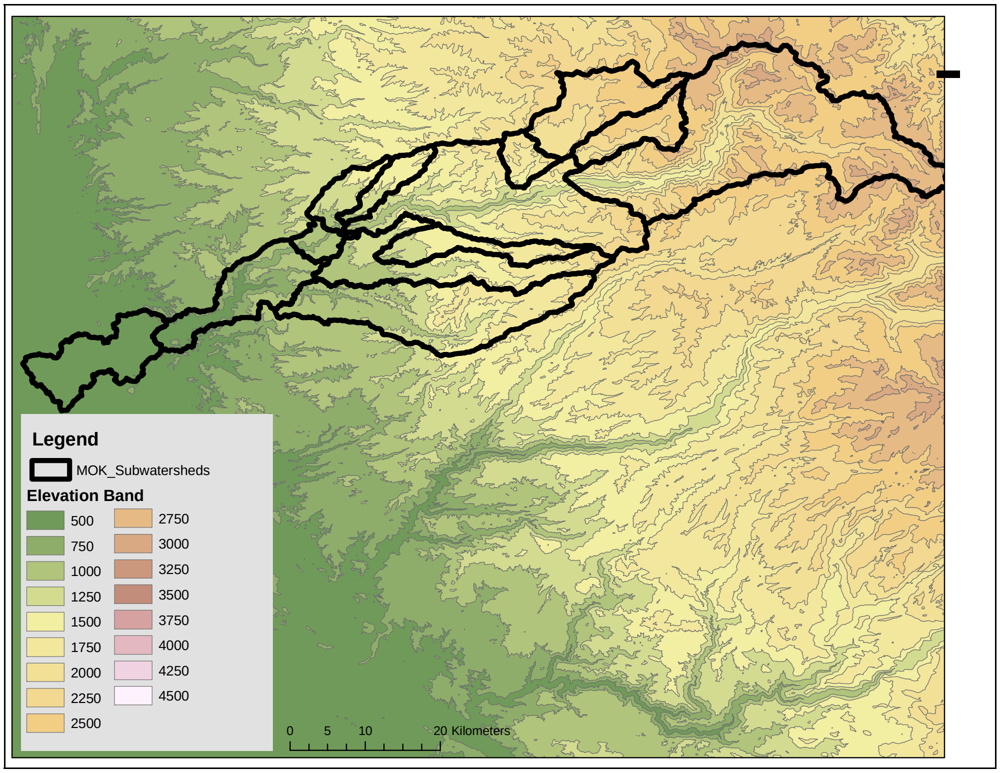


Figure 8. Intersection of Elevation Bands and Sub-watersheds

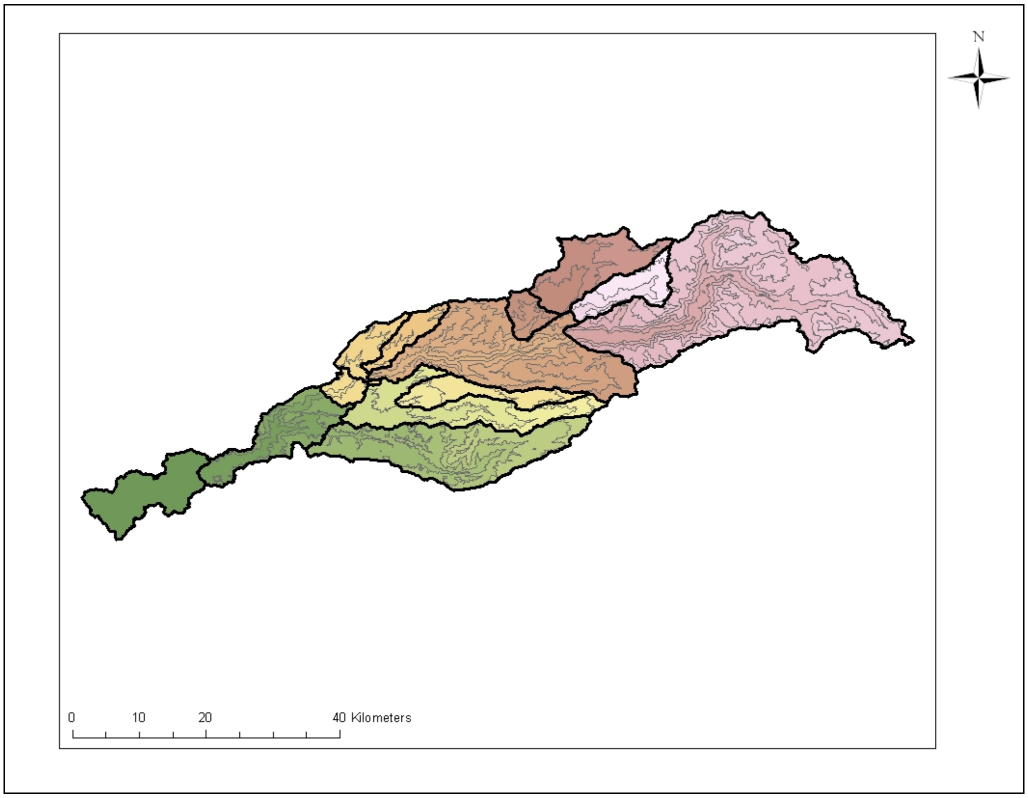


Figure 9. Results of Elevation-Sub-watershed Intersection

Vegetation Classification

The National Land Cover Data (NLCD) set (2001) was used for information on vegetation cover for the entire region. The NLCD vegetation data included 29 land cover classes which were aggregated into the seven land classes used in the project; barren land, trees, agriculture, grasslands, shrubs, urban, and water. Figure 10 provides an example of vegetation distribution (in the Mokelumne Watershed). The NLCD vegetation shapefiles (i.e. MOK_Veg.shp) can be found in the Vegetation folder. NLCD classifications and corresponding vegetation types used in the analysis are presented in Appendix C.

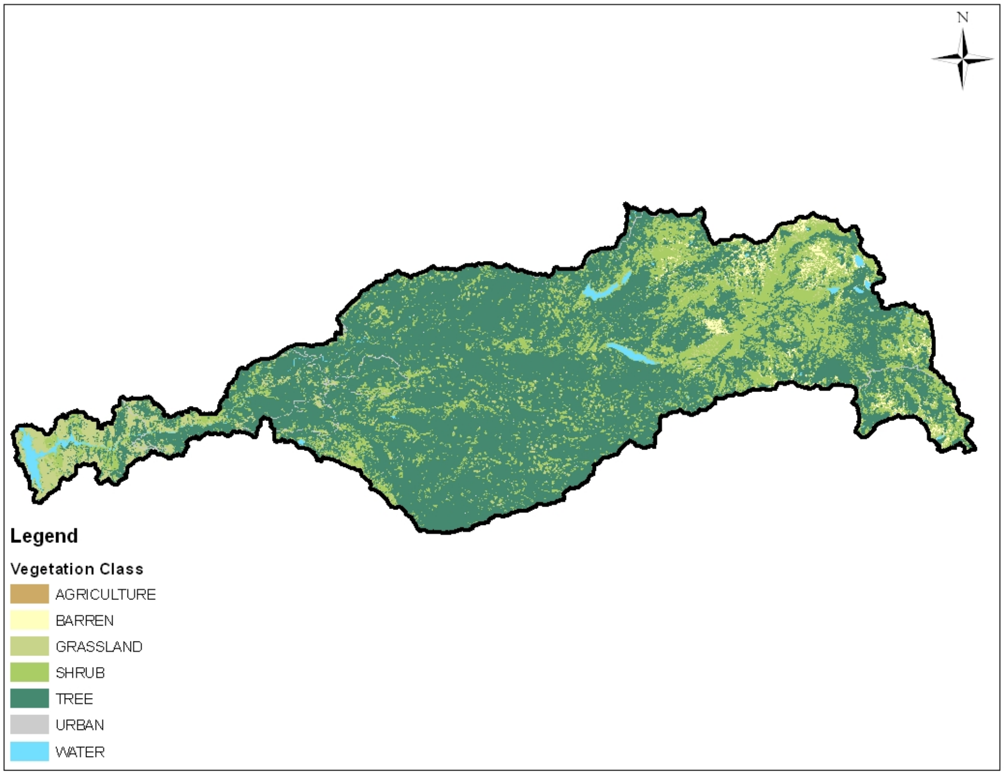


Figure 10. Vegetation Distribution Mokelumne Watershed

Soil Classification

Soil depth and soil classification throughout the Sierra region was gathered from the National Resources Conservation Service (NRCS) data set. The NRCS provides a Soil Survey Geographic Database (SSURGO) for some of the Sierra region and where such data was not available, the U.S. General Soil Map (STATSGO) was used to define soil depth. Figure 11 depicts the soil depth classification throughout the Mokelumne Watershed. The SSURGO database provides much higher resolution data than the STATSGO database. This difference in resolution can be clearly seen in the area outlined by the dashed box in Figure 11. The SSURGO data is located to the north of the Mokelumne River and the STATSGO data is located to the south of the river.

Soil depth data was extracted from the Muaggat tables in each of these two data sets which included a “brockdepmin” (minimum depth to bedrock) parameter. Using this soil depth parameter, map units were classified as either deep “D” (deeper than 50cm) or shallow “S”. The soil depth files for each of the watersheds (with depth in cm) can be found in the Soils folder (i.e. MOK_Soils.shp). In some instances map units were not assigned “brockdepmin” values. In such cases the map unit name (“muname”) was referenced, if it included the term “outcrop” it was assumed that the mapunit had shallow soil. Otherwise, in cases where the brockdepmin” value was Null and there was no mention of outcrop in the map unit name, the map unit was assumed to be deep.

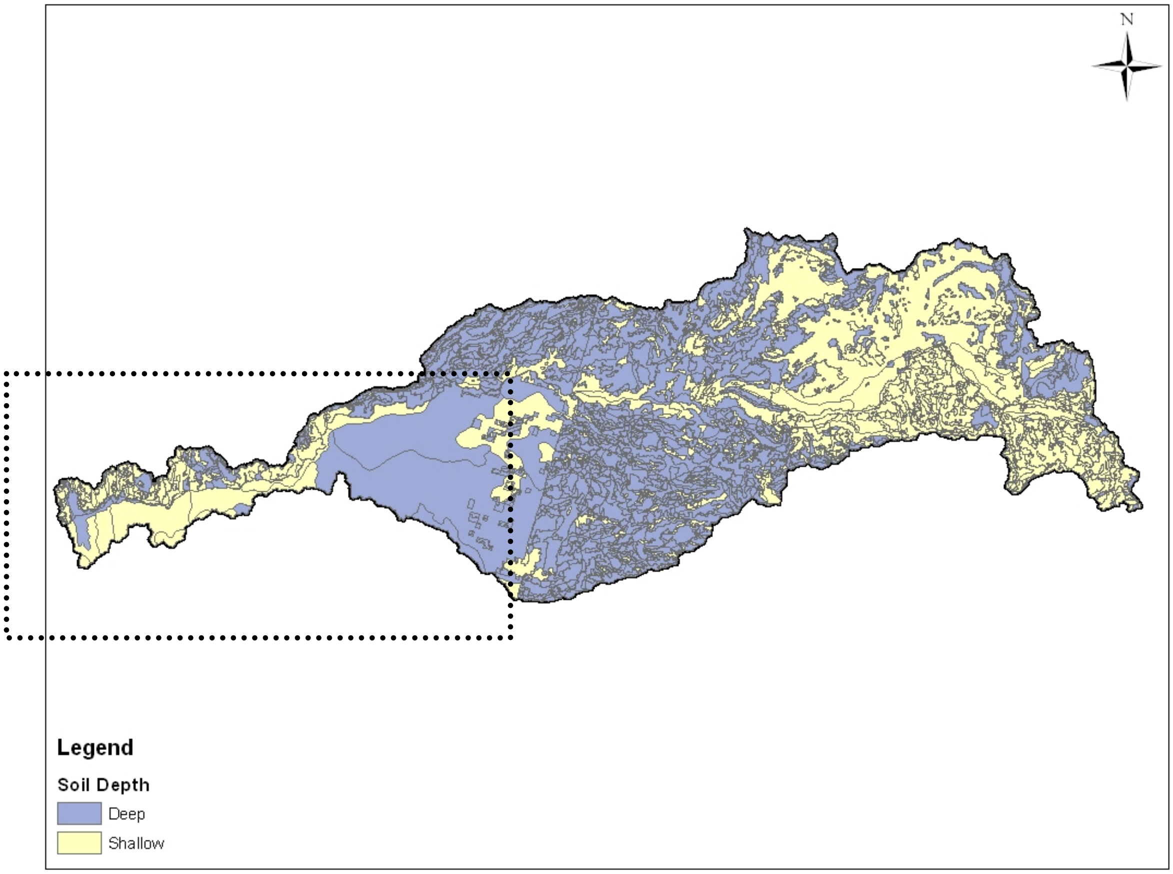


Figure 11. Soil Depth Mokelumne Watershed

Intersection of Soils, Vegetation, Sub-watersheds and Elevation

Soil and vegetation information was intersected in order to classify land cover in the Sierra region into one of thirteen land classes (Table 3). Through the calibration process, unique parameters associated with each of these land classes were calculated, including soil coefficients, leaf area index, and other elements determining the land classes affect on the hydrology of the system.

Barren Land / Deep Soil
Barren Land / Shallow Soil
Tree / Shallow Soil
Tree / Deep Soil
Agriculture / Shallow Soil
Agriculture / Deep Soil
Grasslands / Shallow Soil
Grasslands / Deep Soil
Shrubs / Shallow Soil
Shrubs / Deep Soil
Urban / Shallow Soil
Urban / Deep Soil
Water

Table 3. Land Classes

WEAP Model Development

WEAP Catchment Development

With the sub-watersheds, banded catchments, and land cover distribution defined, a WEAP hydrology model was developed for each of the 15 watersheds. The catchments were entered into WEAP with the following naming convention: AAA_##_####; where AAA is the three letter watershed code (i.e. MOK), ## in the two digit sub-watershed code, and #### is the four digit elevation band code (i.e. 0500).

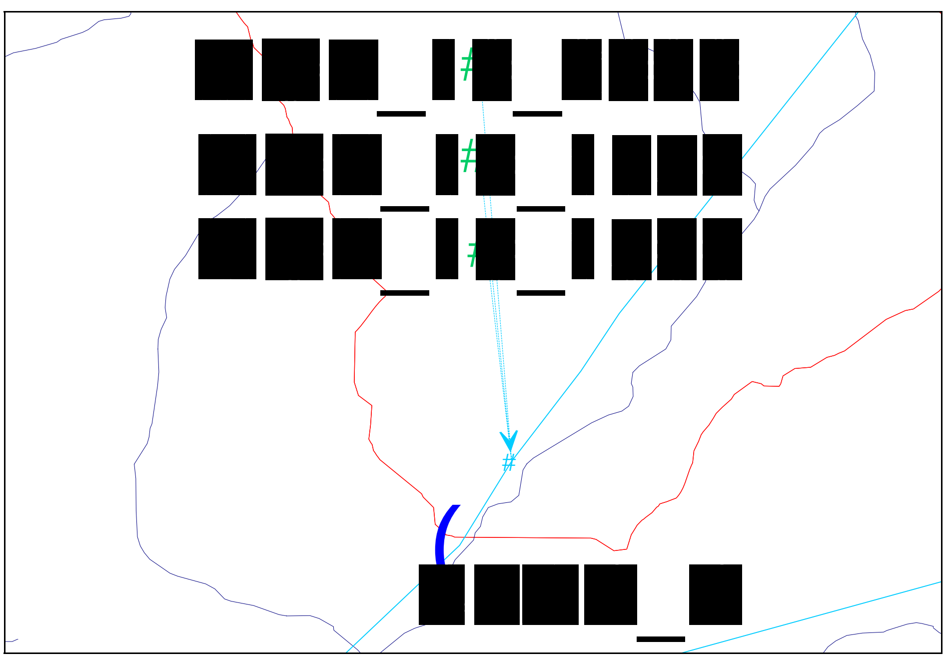


Figure 12. WEAP Catchment Structure

The catchments were each entered into the model and were then linked (via runoff/infiltration lines, in blue) to the river network, as shown in Figure 12.

Create Sub-catchments for each Land Class

Each of the sub-watersheds was further disaggregated in WEAP using the 13 land classes. Figure 13 shows the structure of the land use data; the percentage of total catchment land area is entered for each land class.

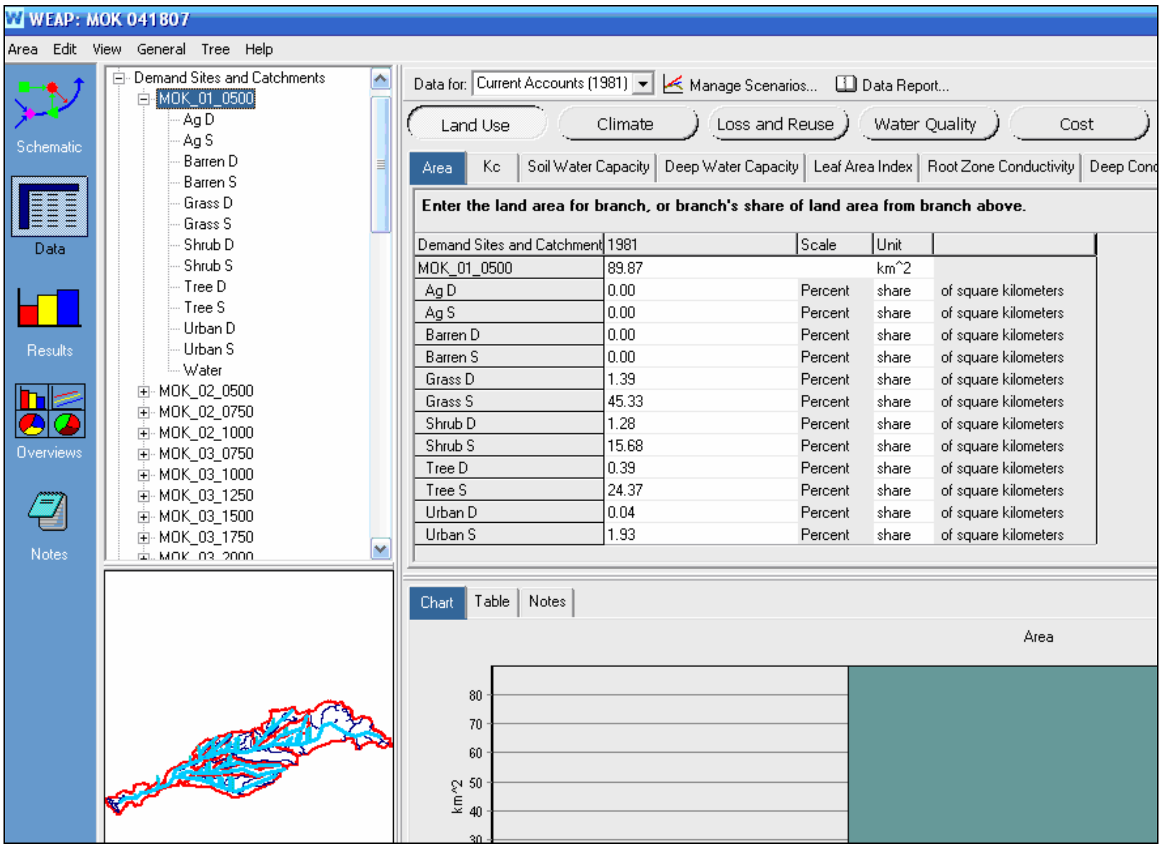


Figure 13. WEAP Catchment Disaggregation

DAYMET Weather Data

Due to the large variation in temperature and precipitation over the Sierra Nevada and the relative scarcity of actual climate observation data, it is necessary to use interpolated weather data as input to the models. The DAYMET data set (Thornton, et. al., 1997) was chosen for this project due to its spatial resolution (1 km grid) which is fine enough to provide different temperature and precipitation values to catchments that may be close in proximity but at very different elevations.

DAYMET temperature and precipitation time-series were obtained for a single location within each catchment. The locations were determined by creating a narrow polygon centered on the mid-elevation contour for the elevation band, i.e. along the 250 m contour for the 0-500 m band.

A point was then place within that polygon either automatically using GIS software or by hand. The coordinates from that point were then used to download the weather time-series from the DAYMET web site.

Model Calibration

The goal of the calibration was to find a consistent set of parameters (Table 4) that would reproduce sub-watershed flows throughout the Sierra at a reasonable level of accuracy. This effort differs from previous efforts at modeling the hydrology of the Sierras in that a uniform set of model parameters were sought instead of individually calibrating each watershed. In fact, this approach would not be possible as only a small number of sub-watersheds in the Sierra have an associated streamflow record that reflects natural conditions.

To arrive at a consistent parameter set, calibration was carried out in a series of four steps. The first step (Initial) consisted of setting land cover parameters (*Kc* and *LAI*) and the preferred flow direction (*f*) using knowledge gained by team members during previous modeling exercises conducted on portions of the Sierra study area (Table 2). Throughout the calibration process, these parameters were reassessed to determine if they were providing the correct model behavior. The second step was to calibrate the snow accumulation/melt parameters using observed snow water equivalent data. This approach is justified by the fact that in WEAP the snow accumulation/melt model is independent of the remaining catchment processes. Once the snow processes were calibrated, the catchment parameters were adjusted using recorded stream flows as the calibration target. This process was done in two stages with a focus on the Mokelumne watershed since it was the primary focus during this first phase of the project. In the first stage, a sub-watershed with predominately shallow soils was calibrated. In the second stage, a sub-watershed with predominately deep soils was calibrated. Finally, the parameters affecting late season base flow were assessed. The resulting model parameter set was then applied universally to all watersheds, sub-watershed and catchments across the Sierra. The entire calibration process is described in detail below.

Model Parameter	**Value**	**Calibration Step**
Crop Coefficeint, *kc*	1.1	Initial
Leaf and stem area index, *LAI*	Ag = 8, Bare = 4, Grass = 12, Shrubs = 14, Trees = 20, Urban = 4, Wet = 4	Initial
Preferred flow direction, *f*	0.8	Initial
Melting threshold, t_l (°C)	5.0	Snow accum./melt
Freezing threshold, t_s (°C)	0.0	Snow accum./melt
Radiation factor, *Rf*	4.5	Snow accum./melt
Albedo, new snow, A_N	0.7	Snow accum./melt

Model Parameter	Value	Calibration Step
Albedo, old snow, A_O	0.3	Snow accum./melt
Root zone water capacity – shallow	283 mm	Shallow soil
Root zone hydraulic conductivity – shallow, k_j	77 mm/wk	Shallow soil
Root zone water capacity – deep	1200 mm	Deep soil
Root zone hydraulic conductivity – deep, k_j	10 mm/wk	Deep soil
Deep water capacity, z_2	5000 mm	Baseflow
Deep hydraulic conductivity, k_2	10 mm/wk	Baseflow

Table 4. Calibration parameters.

Initial calibration

During the initial calibration step, crop coefficients, leaf and stem area index, and preferred flow direction were set based on previous WEAP modeling experience in the Sierra. Crop coefficients were set at a value of 1.1 which is typical of fully developed canopy structures such as trees and shrubs which dominate the land cover types in the Sierras. Leaf and stem area index values were set at levels that experience has shown produces the correct amount of surface runoff. The values make physical sense in that the land cover types that have the most complex above ground structures (trees) have the highest LAI value. As canopy structure complexity decreases so too does the *LAI* (Table 4). Preferred flow direction was set at a value of 0.8 which creates a higher proportion of horizontal flow relative to vertical flow in the subsurface. This makes sense due to the steep slopes found in much of the study area.

Snow accumulation/melt calibration

In the second calibration step, model parameters in the snow accumulation/melt model were adjusted so that calculated values of snow water equivalent matched observed values. The calibration parameters were the melt and freeze thresholds (*Tl, Ts*), the new and old snow albedo values (A_N, A_O), and the additional radiation factor (*Em*).

Nine weather stations were selected from the Feather, Mokelumne, and San Joaquin basins covering a wide range of elevation and latitude (Table 5). Snow water content time-series were downloaded from the California Department of Water Resources (DWR) California Data Exchange Center (CDEC) for each of the stations.

Watershed	DWR Code	Elevation (m)	Latitude	Longitude
Feather	FOR	1570	39.813	-121.321
Feather	HMB	1981	40.115	-121.368
Feather	KTL	2225	40.140	-120.715
Mokelumne	BLK	2438	38.613	-119.931
Mokelumne	BLS	1981	38.375	-120.192

Mokelumne	MDL	2408	38.615	-120.140
San Joaquin	GRM	2408	37.755	-119.238
San Joaquin	GRV	2103	37.465	-119.290
San Joaquin	VLC	3063	37.388	-118.903

Table 5. Snow observation stations used in snow accumulation/melt calibration.

Hand calibration of the snow model was conducted using observed data from 1991 – 1998, the period during which reliable data could be found for many stations. The calibrated values were 0 and 5 degrees Celsius for the *Ts* and *Tl* thresholds, 4.5 for the additional radiation factor, and 0.7 and 0.3 for the new and old snow albedo values. The parameter values of the snow accumulation/melt model are all within physically realistic ranges. *Ts* and *Tl* values are close to the freezing point of water. The *Tl* value of 5 degrees is not unexpected since weekly averaged temperature data was used as input. The additional radiation factor is justified by observations made at the Sierra Snow Laboratory (as shown in Table 3.7.1 of Maidment, 1992) which show that 60 to 80% of the energy contributed to the snow pack was from turbulent forms of energy (sensible and latent energies) with the remainder consisting of radiative energy. The albedo model maximum and minimum values are consistent with the data reported by the US Army Corps of Engineers (USACE, 1998, Fig 5-5) for the albedo of new and ripening or aging snow.

The calculated and observed values are shown in Figure 14.

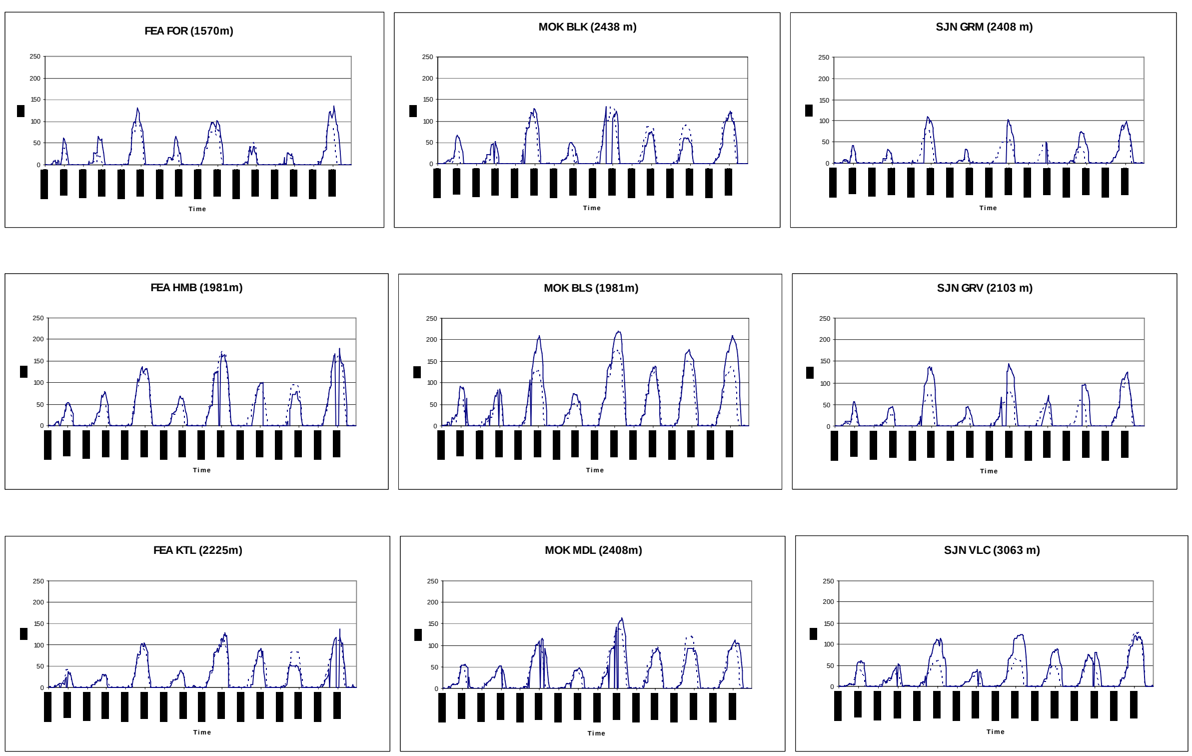


Figure 14. Observed and simulated (dashed lines) snow water content values for 9 sites in the Sierra Nevada. Graph titles provide watershed code, CDEC station code, and elevation.

Simulated timing and magnitude of snow accumulation and melt in the Feather watershed was very good. In the Mokelumne watershed, simulated snow accumulation and melt values were good, however, under-prediction of peak accumulation did occur at the Mud Lake (MDL) observation point during 1993, 1995, and 1998. Examination of the DAYMET climate data for the MDL location reveals predicted total precipitation for those water years was of 179, 238, and 184 cm which was less than observed snow accumulation of 209, 220, and 209 cm. These discrepancies may be due to a combination of the fact that the CDEC station is a point measurement which may not represent average snow accumulation in the elevation band, and that the DAYMET interpolation algorithm may be under predicting precipitation at these times. The plots of snow water equivalent for the San Joaquin watershed show a reasonable match except for water years 1993 and 1995. Again, examination of the DAYMET data shows that there is not enough precipitation in the input climate record to produce the observed snow during those years. Since the simulated values at all stations compare well with the observations, except in the cases outlined above, and those stations cover a wide range of elevation and latitude, the calibration of the snow model was considered adequate.

Root zone soil parameter calibration

Values for the root zone water capacity and hydraulic conductivity in the top layer of the two layer soil water model were calibrated using a two step approach. First, shallow root zone capacity and hydraulic conductivity values were calibrated in the Cole Creek sub-watershed of the Mokelumne River watershed. This watershed consists mostly of shallow soils (Figure 15). Deep root zone capacity and hydraulic conductivity values were calibrated for the South Fork sub-watershed of the Mokelumne River watershed which is dominated by deep soils (Figure 15).

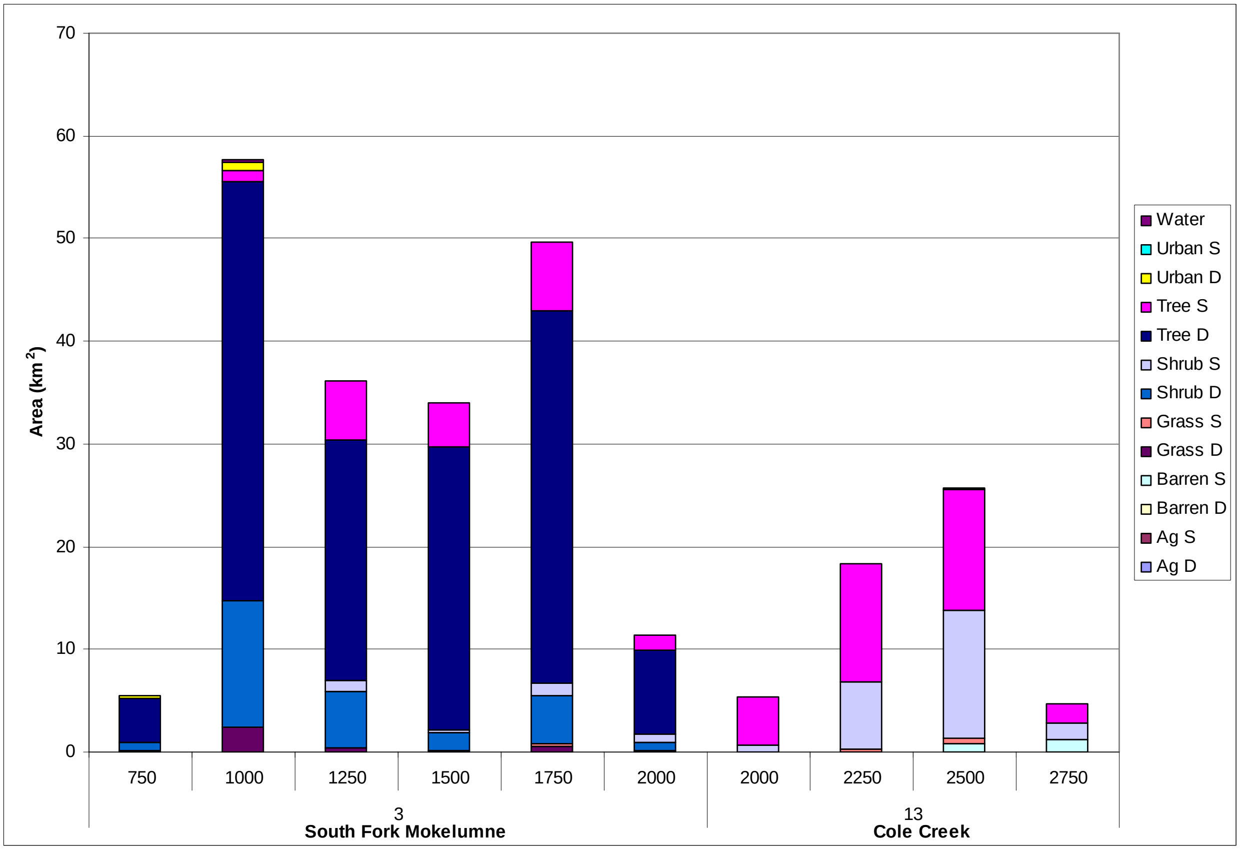


Figure 15. Area proportions in root zone parameter calibration sub-watersheds. Categories on x–axis are elevation bands.

Shallow soil catchment parameters

Calibration of the shallow soil parameters, soil capacity and conductivity, was done using observed stream flows from Cole Creek in the Mokelumne watershed. Daily stream flow data for water years 1982 - 2000 from USGS gage 11315000 was converted to weekly volumes and used as the calibration target. Calibration was done using hand and automated calibration techniques during which shallow soil capacity and conductivity were adjusted until an acceptable match was made with the stream flow observations. Calibration resulted in a shallow root zone water capacity of 283 mm which is reasonable considering that soils were classified shallow if bedrock depth was less than 500 mm. Shallow root zone conductivity was estimated as 77 mm/wk which is in the range of observed soil conductivity values (see p. 38, Bouwer, 1978). Observed and simulated average weekly flows at the Cole Creek gage for water years 1982-2000 match well (Figure 16). There is some under prediction of winter time flow events but the dominant snow melt events in the spring are captured well both in magnitude and timing. Here it is important to point out that the rainfall runoff routine in WEAP has been developed to produce a reasonable representation of the continuous streamflow, not as a tool to estimate the peak runoff associated with a single storm event. Thus it is not unusual that the model underestimates some peak flows.

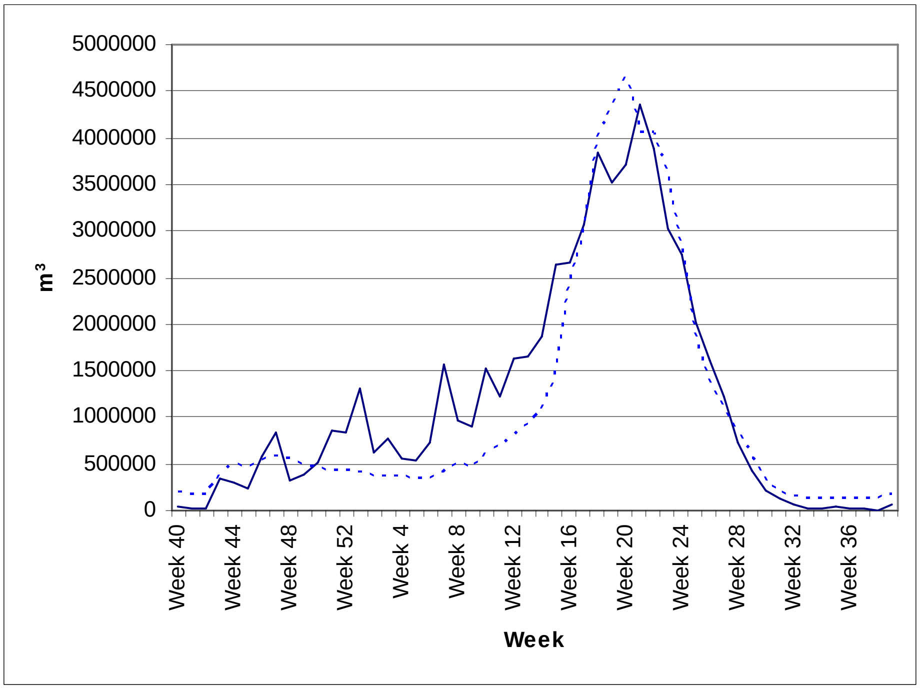


Figure 16. Observed and simulated (dashed lines) average weekly flows (1982-2000) for Cole Creek.

Deep soil catchment parameters

Calibration of the deep soil capacity and hydraulic conductivity was done using weekly flows derived from daily flows obtained from the USGS stream gage 11318500 located on the South Fork of the Mokelumne River. Similar to the calibration of the shallow soil parameters, a combination of hand and automated calibration was used to estimate the values. Estimated values of deep soil capacity and hydraulic conductivity were 1200 mm and 10 mm/wk. The estimated soil capacity value is physically realistic considering that deep rooted trees and shrubs can have rooting depths on the order of 1 to 2 meters. The hydraulic conductivity value is also within the physically realistic range. The plot of simulated and observed average weekly flow at the South Fork gage shows a good match (Figure 17). As with the Cole Creek simulation, there was some under prediction of winter time flow events. It is also interesting to note that this sub-watershed experiences a less pronounced snow melt signal than Cole Creek. This is explained by the lower elevations and higher temperatures present in this sub-watershed.

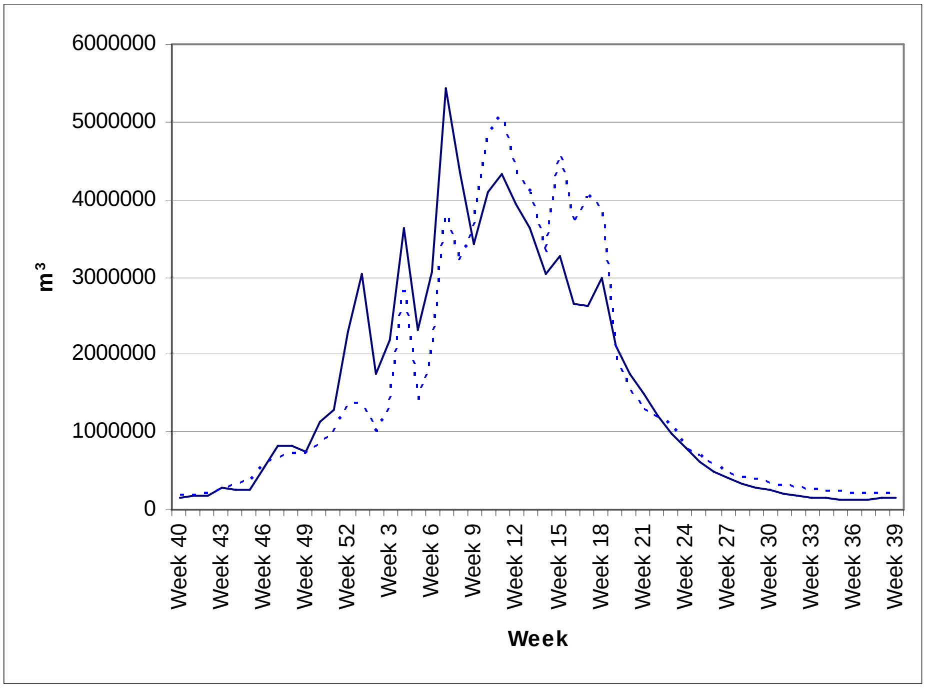


Figure 17. Observed and simulated (dashed lines) average weekly flows (1982-2000) for SF Mokelumne River.

Baseflow calibration

The final calibration step was the adjustment of deep water capacity and deep hydraulic conductivity parameters for the 2nd layer of the two layer soil model. This calibration was done by matching the flows observed during the low flow season (Weeks 33 – 42). The estimated values were 5000 mm of deep storage and a hydraulic conductivity of 10 mm/wk.

Calibration Assessment

Following calibration of the model parameters in Table 4 using snow water equivalent data from 9 locations and stream flow in two locations in the Mokelumne River watershed, the parameters were applied universally to all 13 models listed in Table 1. To assess the calibration, simulated weekly flows were compared with observed gage flows at 17 sites other than the Cole Creek and SF Mokelumne River comparisons which recorded natural flow responses unaltered by upstream operations. The results of these comparisons are shown in Figure 17. In addition to the 17 gage sites, simulated monthly flows at the watershed outlets were compared to DWR derived "Full Natural Flows" which are estimates of river flows after withdrawals or storage in the watershed is back calculated out of the record. The simulated monthly flows and Full Natural Flows for each watershed are presented in Figure 18.

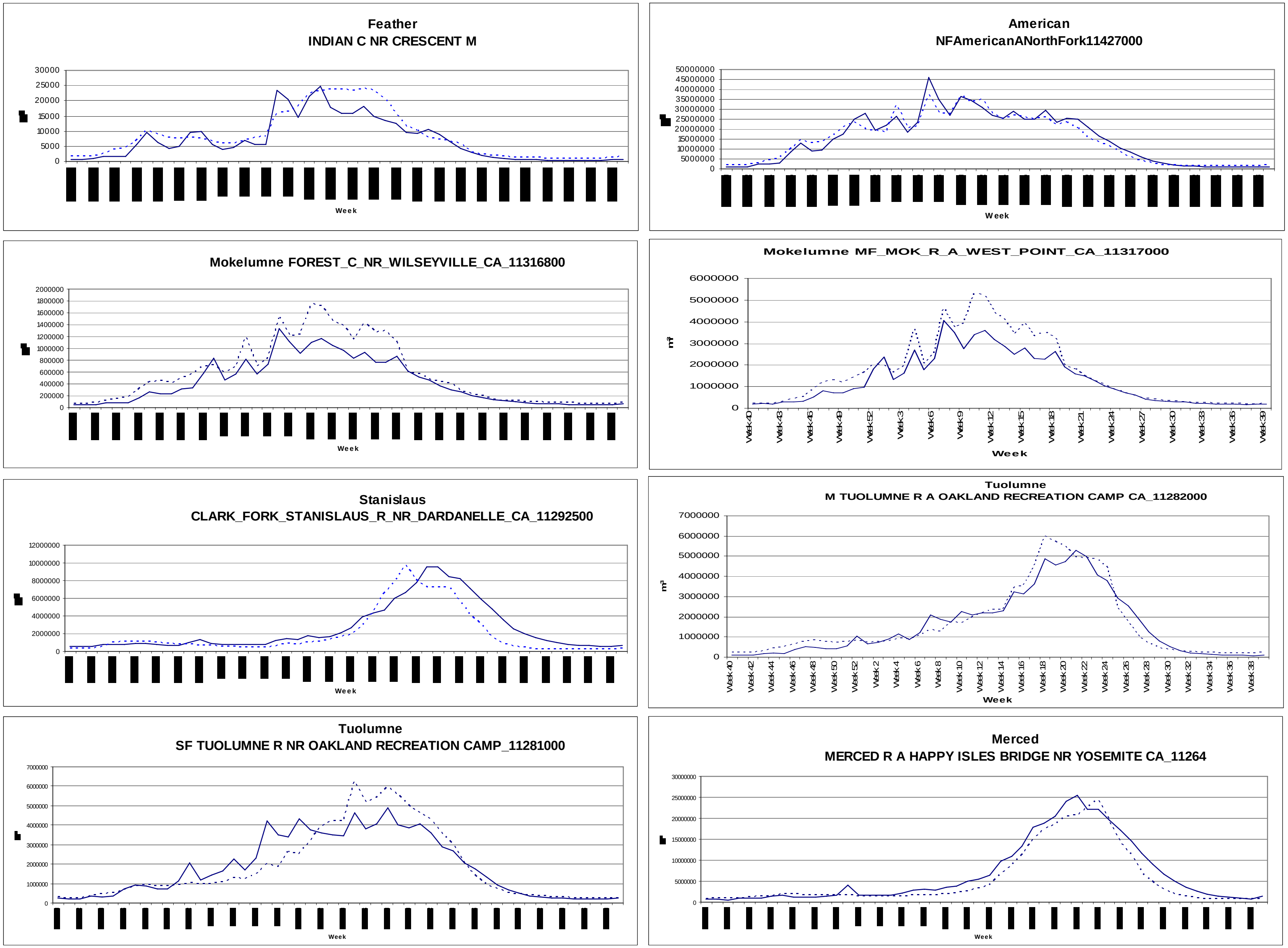


Figure 17. Observed and simulated (dashed lines) average weekly flows (1982-2000) for 17 remaining sites (page 1 of 3).

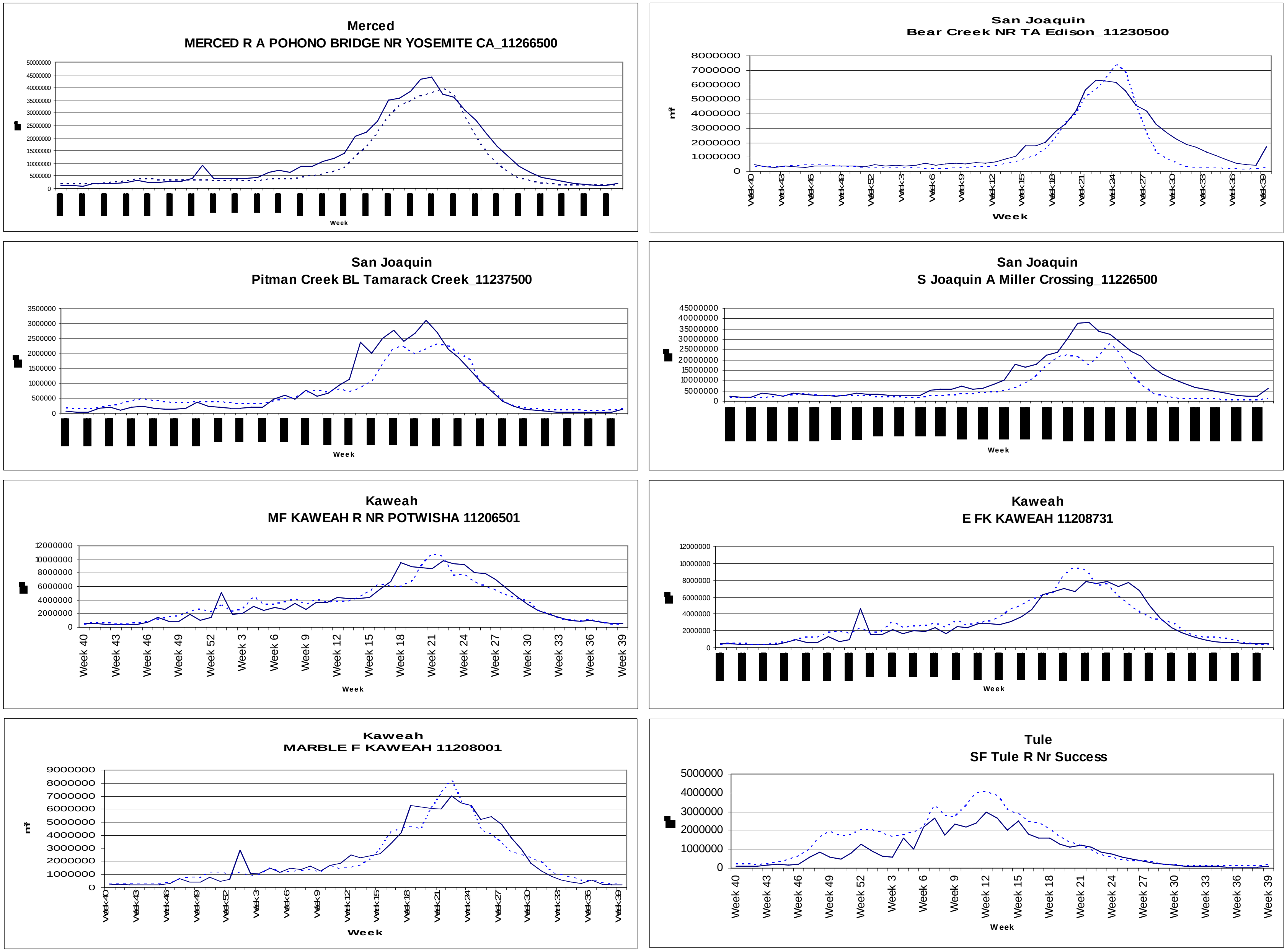


Figure 17. Observed and simulated (dashed lines) average weekly flows (1982-2000) for 17 remaining sites (page 2 of 3).

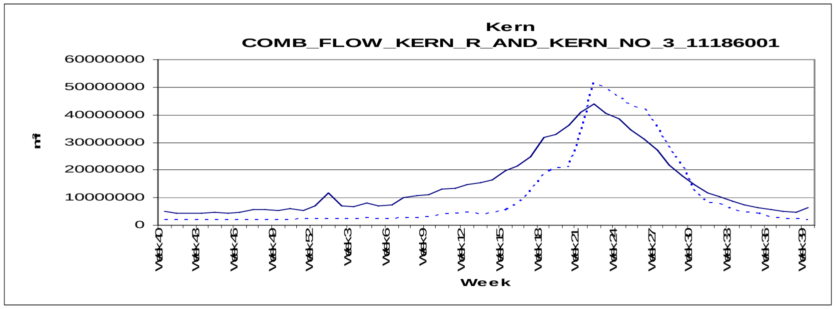


Figure 17. Observed and simulated (dashed lines) average weekly flows (1982-2000) for 17 remaining sites (Page 3 of 3).

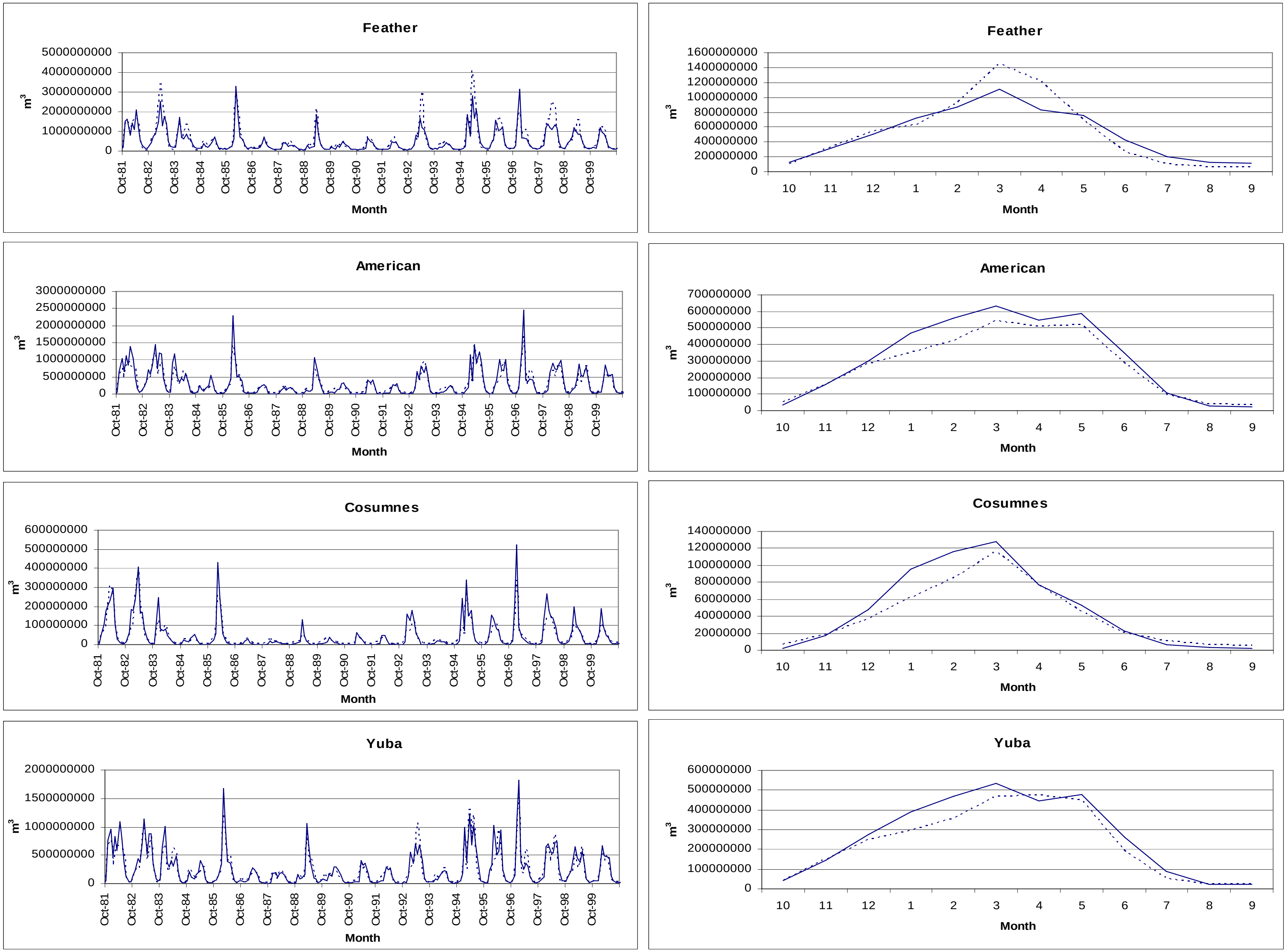


Figure 18. Simulated (dashed line) and DWR estimated monthly full natural flows (Page 1 of 4).

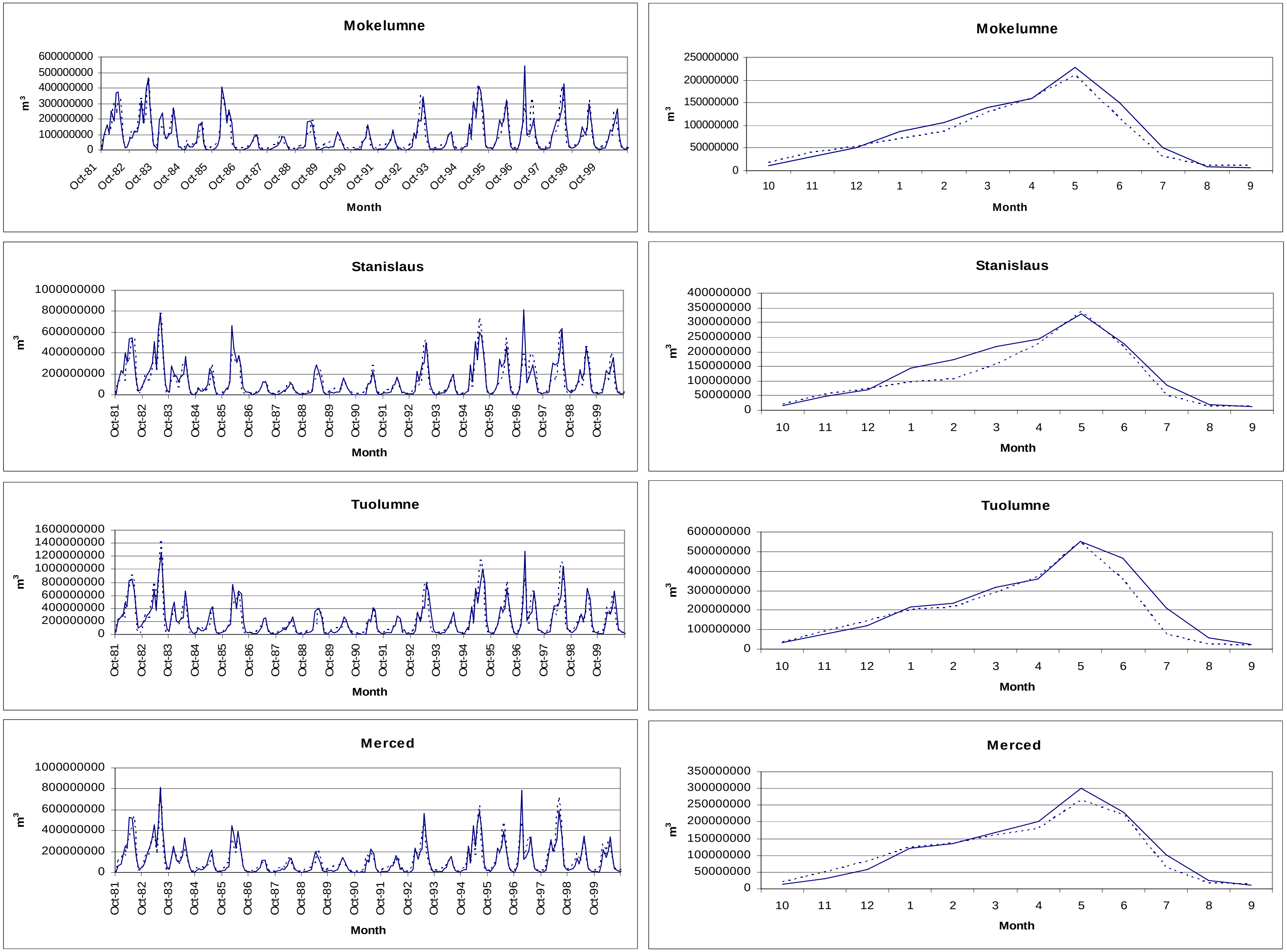


Figure 18. Simulated (dashed line) and DWR estimated monthly full natural flows (Page 2 of 4).

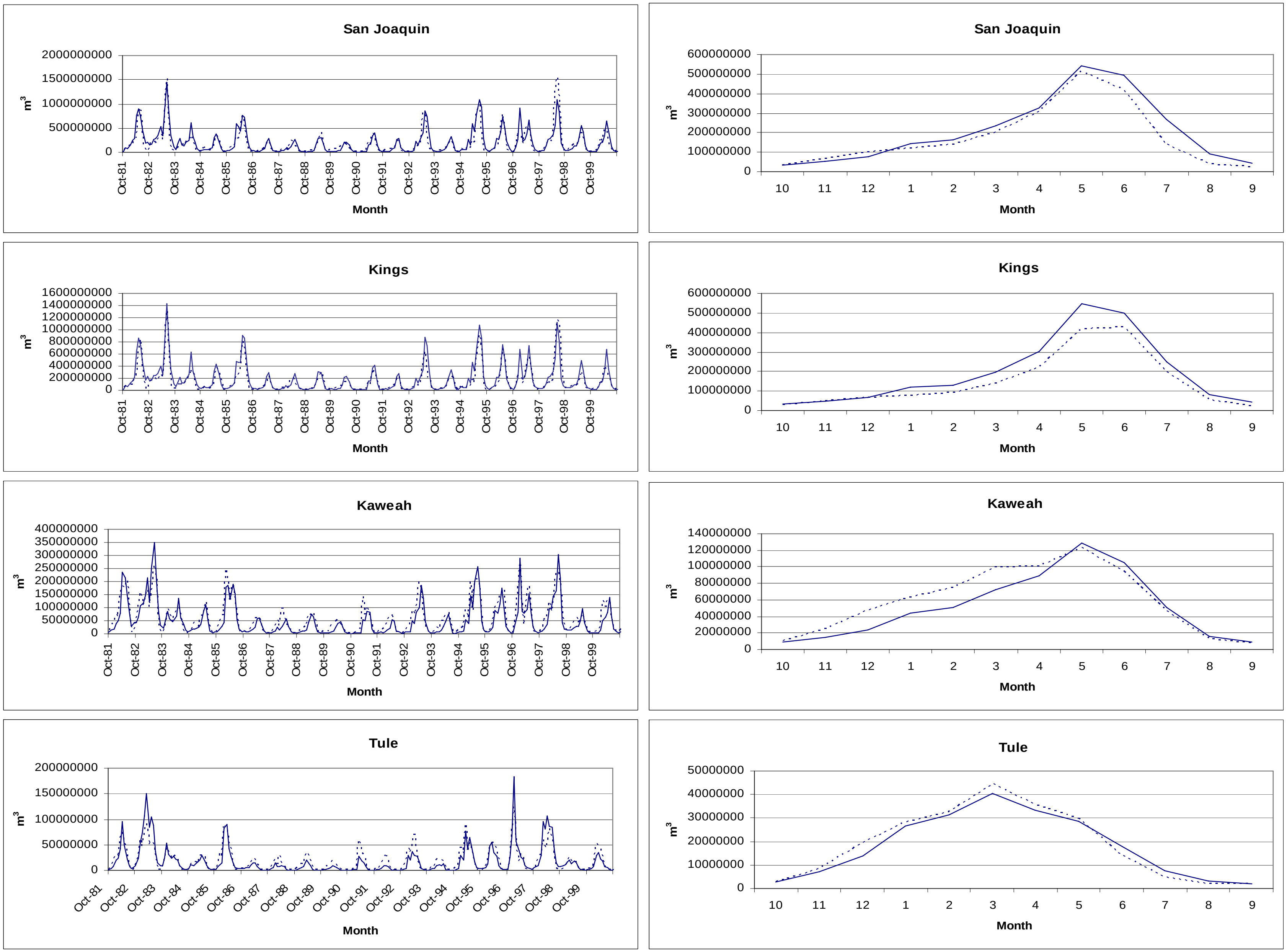
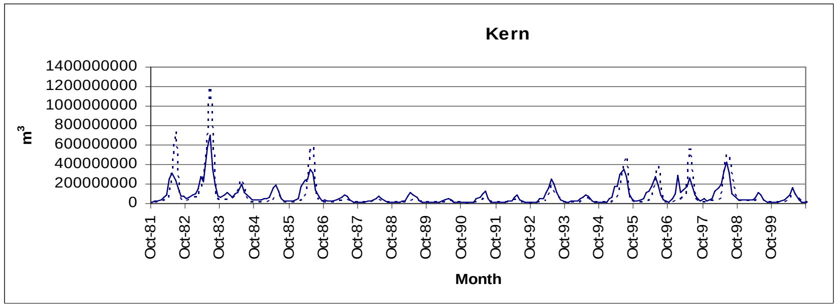


Figure 18. Simulated (dashed line) and DWR estimated monthly full natural flows (Page 3 of 4).



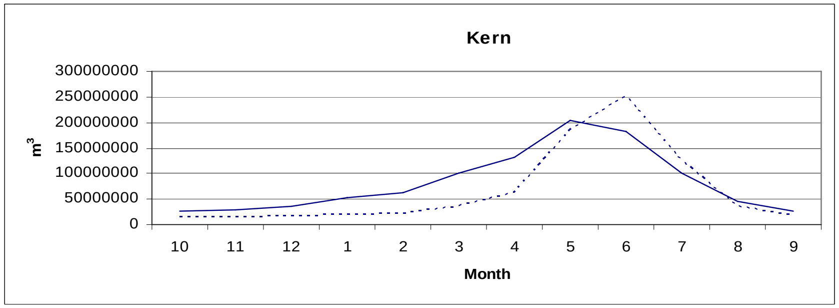


Figure 18. Simulated (dashed line) and DWR estimated monthly full natural flows (Page 4 of 4).

The graphs in Figure and Figure show the models generally capture the major features of the average weekly hydrographs at validation sub-watersheds and monthly hydrographs at the watershed outlets. The monthly predictions shown in Figure show a better correspondence than those in Figure which are weekly predictions. These observations are confirmed by the goodness of fit statistics presented in Table 6 and Table 7. Generally, the RMSE, BIAS, and Nash-Sutcliffe statistics show a better match for the monthly flow predictions at the outlet of the watersheds. The RMSE and BIAS values compare favorably with those published by other researchers that modeled a similarly large portion of the Sierra (Maurer, et. al., 2002).

During the calibration process it was discovered that the DAYMET weather data under-predicted precipitation in some locations (see discussion in Section 2.3.2). This observation was also made when studying the comparisons of total watershed outflow and DWR estimated Full Natural Flow. For 5 watersheds there was under prediction of flow to such an extent that a corrective area multiplier was used to effectively increase the amount of runoff in a linear fashion. This was done in order to preserve the "shape" of the hydrographs which were largely correct. This correction, while less than ideal, is not a major concern since the models will be used to study differences between model runs. Analyses that require estimates of the total stream flow will need to take this adjustment into account.

Watershed	**USGS Gage**	**RMSE (%)**	**BIAS (%)**	**Nash-Sutcliffe Efficiency Index**
FEA	INDIAN C NR CRESCENT MILLS CA 11401500	128	19	0.58
AMR	NF AMERICAN A NORTH FORK DAM_11427000	79	-6	0.79
MOK	COLE_C_NR_SALT_SPRINGS_DAM_11315000	130	-11	0.38
MOK	FOREST_C_NR_WILSEYVILLE_CA_11316800	129	34	0.52
MOK	MF_MOK_R_A_WEST_POINT_CA_11317000	117	58	0.59
MOK	SF_MOK_R_NR_WEST_POINT_CA_11318500	124	-3	0.61
STN	CLARK FORK STANISLAUS R NR DARDANELLE CA_11292500	116	-23	0.40
TUO	M TUOLUMNE R A OAKLAND RECREATION CAMP CA_11282000	125	5	0.42
TUO	SF TUOLUMNE R NR OAKLAND RECREATION CAMP_11281000	122	1	0.41
MER	MERCED R A HAPPY ISLES BRIDGE NR YOSEMITE CA_11264500	103	-17	0.55

Watershed	USGS Gage	RMSE (%)	BIAS (%)	Nash-Sutcliffe Efficiency Index
MER	MERCED R A POHONO BRIDGE NR YOSEMITE CA_11266500	99	-21	0.59
SJN	BEAR CREEK NR TA EDISON_11230500	125	-22	0.31
SJN	PITMAN CREEK BL TAMARACK CREEK_11237500	125	-7	0.65
SJN	SAN JOAQUIN A MILLER CROSSING_11226500	98	-44	0.53
KAW	E FK KAWEAH_11208731	90	7	0.61
KAW	MARBLE F KAWEAH 11208001	81	-4	0.67
KAW	MF KAWEAH R NR POTWISHA 11206501	68	-2	0.68
TUL	SF TULE R NR SUCCESS 11204500	122	40	0.66
KRN	COMB_FLOW_KERN_R_AND_KERN_NO_3_11186001	127	-25	-0.02

Table 6. Goodness of fit statistics for 19 locations with USGS stream flow gages.

Watershed	RMSE (%)	BIAS (%)	Nash-Sutcliffe Efficiency Index	Area Multiplier
FEA	58	4	0.74	1.46
YUB	49	-13	0.84	1.0
AMR	49	-13	0.85	1.0
COS	68	-14	0.84	1.0
MOK	58	-9	0.79	1.0
STN	57	-14	0.78	1.05
TUO	54	-11	0.77	1.35
MER	51	-4	0.84	1.1
SJN	64	-15	0.71	1.45
KNG	55	-23	0.81	1.25
KAW	55	15	0.81	1.0
TUL	70	4	0.79	1.0
KRN	98	-20	0.31	1.0

Table 7. Goodness of fit statistics for predicted monthly full natural flows.

Note: $RMSE = \frac{100}{\overline{Q_o}}\sqrt{\frac{\sum_{i=1}^{n}(Q_{s,i} - Q_{o,i})^2}{n}}$, $BIAS = 100[(\overline{Q}_s - \overline{Q}_o)/\overline{Q}_o]$, and

$E_f = 1 - \frac{\sum_{i=1}^{n}(Q_{s,i} - Q_{o,i})^2}{\sum_{i=1}^{n}(Q_{o,i} - \overline{Q_o})^2}$ where $Q_{s,i}$ and $Q_{o,i}$ are simulated and observed flow rates for each timestep, i. n = 988 for Table 6 and n = 228 for Table 7.

Climate Change Analysis

In order to assess the effects of an increase in temperature on the snow melt/accumulation pattern in the western Sierra, a series of simulations (1982 – 2001) were run with 2, 4, and 6 degree Celsius increases in temperature. The temperature increases were implemented by adding a fixed value (2, 4, or 6) to the input temperature time-series. Precipitation was left the same as it was during the calibration exercise.

The implications of an increase in temperature were assessed by studying the changes in timing of the center of mass of the runoff hydrograph and in the volume of precipitation that fell as snow. Historically, the center of mass in runoff for the studied watersheds occurred during spring months (see column 2 of Table 8). Watersheds consisting mostly of lower elevation sub-watersheds, such as the Tule, have a center of mass that occurs earlier in the year while high elevation watersheds, such as the Kings, have a center of mass that occurs later in the spring or summer. This is due to the effect of accumulated snow in the higher elevations melting later in the year resulting in a later center of mass.

Additional analysis of runoff from simulated elevation bands in the WEAP applications show there is a non uniform effect in the shift of the center of mass that is a function of the elevation (Figure 18).

Watershed	0 deg Center of Mass	2 deg Center of Mass	4 deg Center of Mass	6 deg Center of Mass	Δ 2 deg	Δ 4 deg	Δ 6 deg
FEA	23.5	21.6	20.7	20.3	1.9	2.8	3.2
YUB	23.9	21.6	20.2	19.8	2.4	3.7	4.2
BAR	20.6	20.4	20.2	20.2	0.3	0.4	0.5
AMR	24.7	22.5	21.1	20.4	2.1	3.6	4.3
COS	23.5	22.6	22.3	22.1	0.9	1.2	1.4

Watershed	0 deg Center of Mass	2 deg Center of Mass	4 deg Center of Mass	6 deg Center of Mass	Δ 2 deg	Δ 4 deg	Δ 6 deg
MOK	26.8	24.3	22.2	21.0	2.4	4.6	5.7
STN	27.5	24.9	22.6	21.0	2.6	5.0	6.5
TUO	27.0	24.8	22.8	21.3	2.2	4.2	5.7
MER	27.1	25.1	23.2	21.7	2.0	3.9	5.4
SJN	29.1	26.6	24.3	22.6	2.5	4.8	6.5
KNG	30.9	28.6	26.3	24.4	2.3	4.5	6.5
KAW	26.9	24.9	23.2	21.9	2.0	3.7	5.1
TUL	23.7	22.2	21.1	20.5	1.5	2.6	3.2
KRN	33.5	31.9	29.9	27.9	1.6	3.6	5.7
CAL	21.5	21.2	21.1	21.0	0.2	0.3	0.4

Table 8. Runoff center of mass at watershed outlets in weeks from Oct 1 (columns 2 – 5) and shift in timing of center of mass in weeks (columns 6 - 8) under 2, 4, and 6 degree temperature increase scenarios (1982-2001).

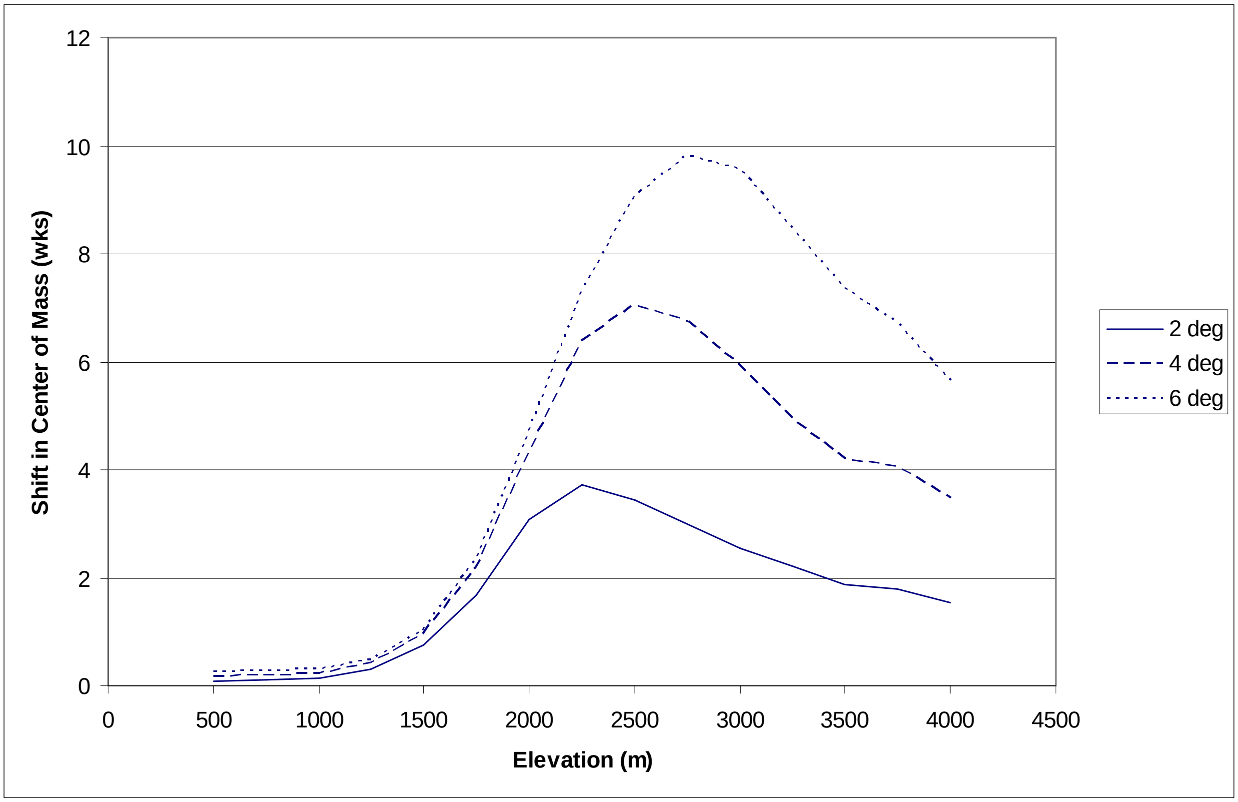


Figure 18. Shift in weekly hydrograph center-of-mass due to 2, 4, and 6 degree increases in temperature over a range of elevation (1982 – 2001). Graphed values represent averages for each elevation band over the entire Sierra. Positive shift indicates an earlier snowmelt peak flow.

Figure 18 shows that lower elevations, 500 – 1500 meters, show little shift as would be expected since these elevations have little snow accumulation and therefore are not affected by temperature very much. The mid-elevation bands, 1750 – 3250 meters, show the most shift in the center-of-mass timing. This is for two reasons: 1.) the higher temperatures result in less precipitation falling as snow thereby increasing winter-time flows, and 2.) the increase in temperature results in an earlier Spring melt of the snow that does accumulate. Both of these reasons result in shifting the runoff hydrograph center-of-mass to earlier in the year (a positive shift on the graph).

This pattern is also shown in a graph of the change in snow melt versus elevation (Figure 19). It can be seen that mid-elevations (2000 – 3000 m) show the largest decrease in snow melt which confirms that the mid-elevations experience the largest change in snow accumulation due to increasing temperatures.

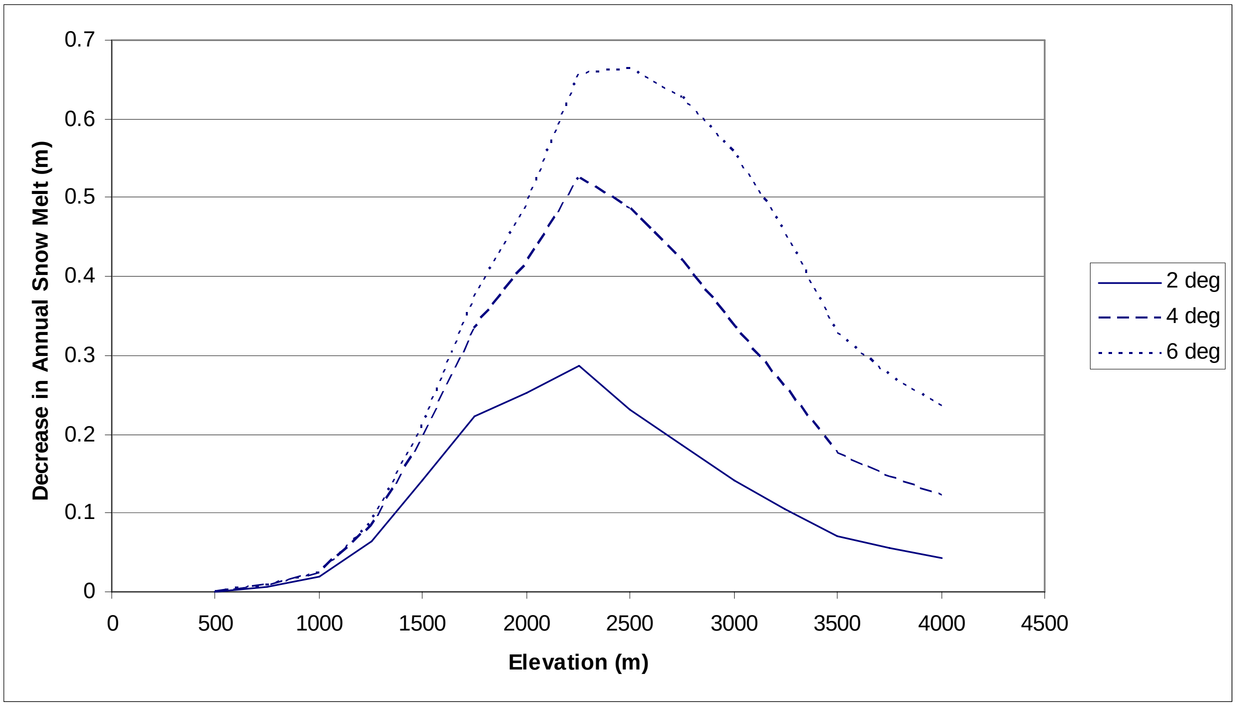


Figure 19. Decrease in average annual snow melt (1982 – 2001) under 2, 4, and 6 degree temperature scenarios.

The high spatial resolution of these models allows for a more detailed view of the changes in runoff center of mass (Figure 20). It can be seen that the shift in the runoff center of mass will be most pronounced in the Yuba through Stanislaus River watersheds. This is due to the prevalence of mid elevation regions (1750 – 3250 m) in these watersheds. These regions are high enough to currently accumulate snow; however, they are relatively lower than the southern watersheds and therefore will experience the effects of climate change sooner (see Figure 22).

Another view of this spatial difference is shown in Figure 21 which shows the percent reduction in snow accumulation under the 2, 4, and 6 degree temperature increase scenarios. It can be seen that the northern watersheds experience greater reduction in snow accumulation as compared to the southern, higher watersheds (Tuolumne to Kern River).

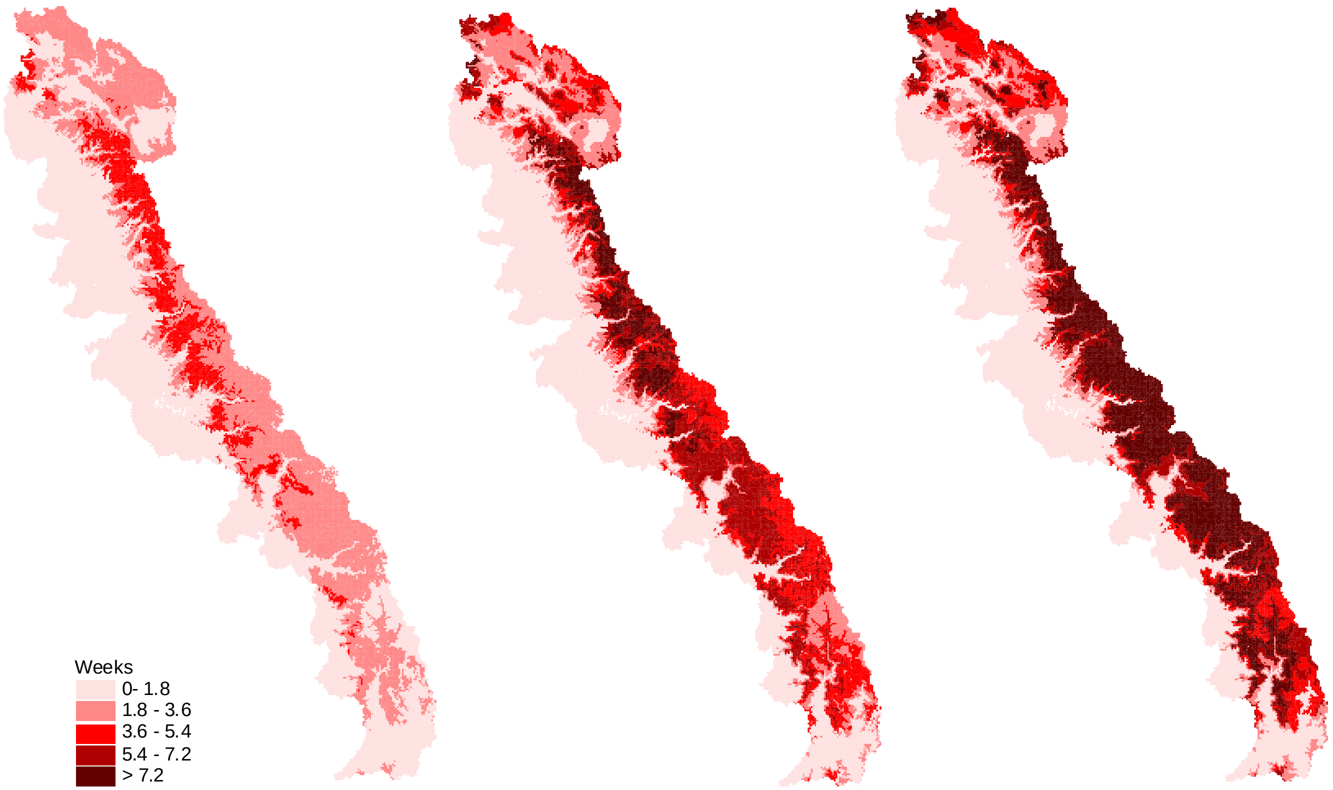


Figure 20. Shift in runoff center of mass for 2, 4, and 6 degree increases in temperature (from left to right). Values are averages for 1982 – 2001.

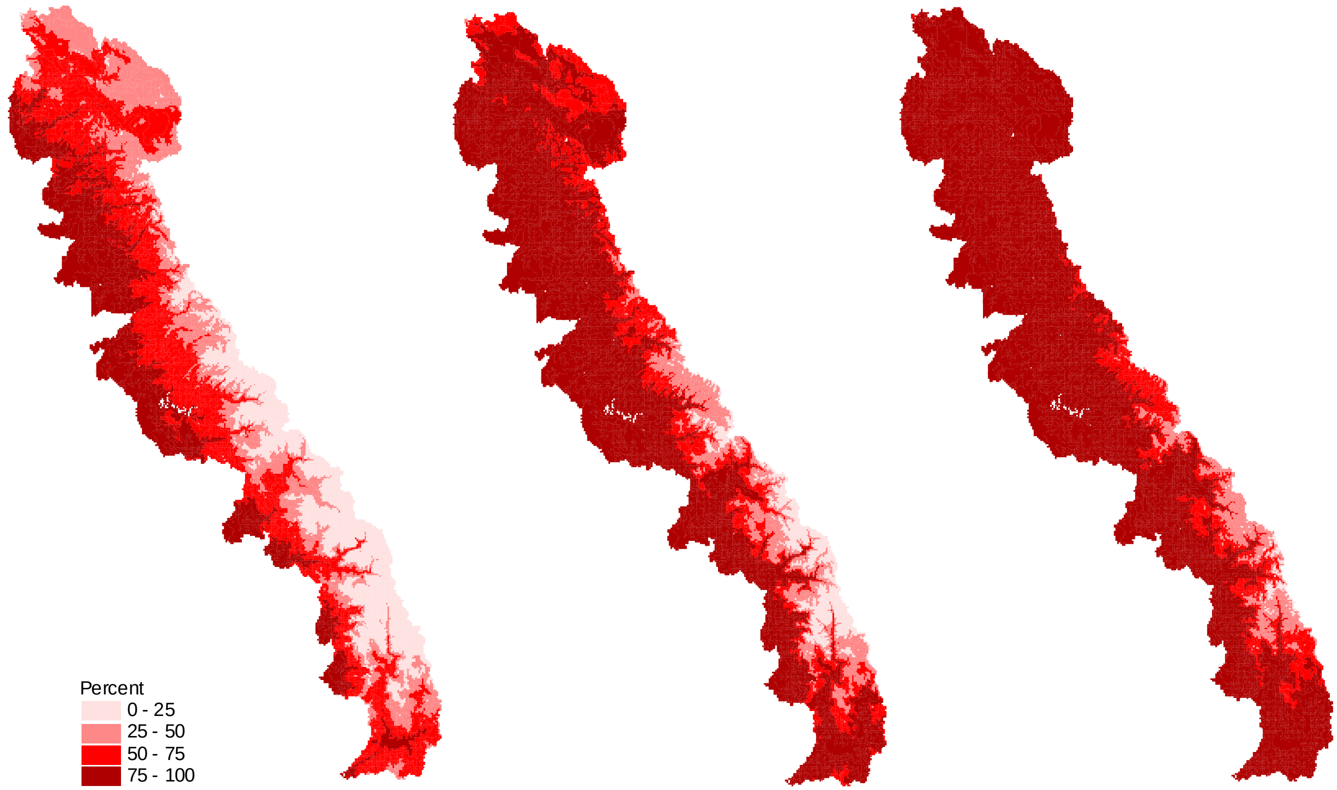


Figure 21. Percent reduction in snow accumulation for 2, 4, and 6 degree temperature increases (from left to right). Values are averages for 1982-2001.

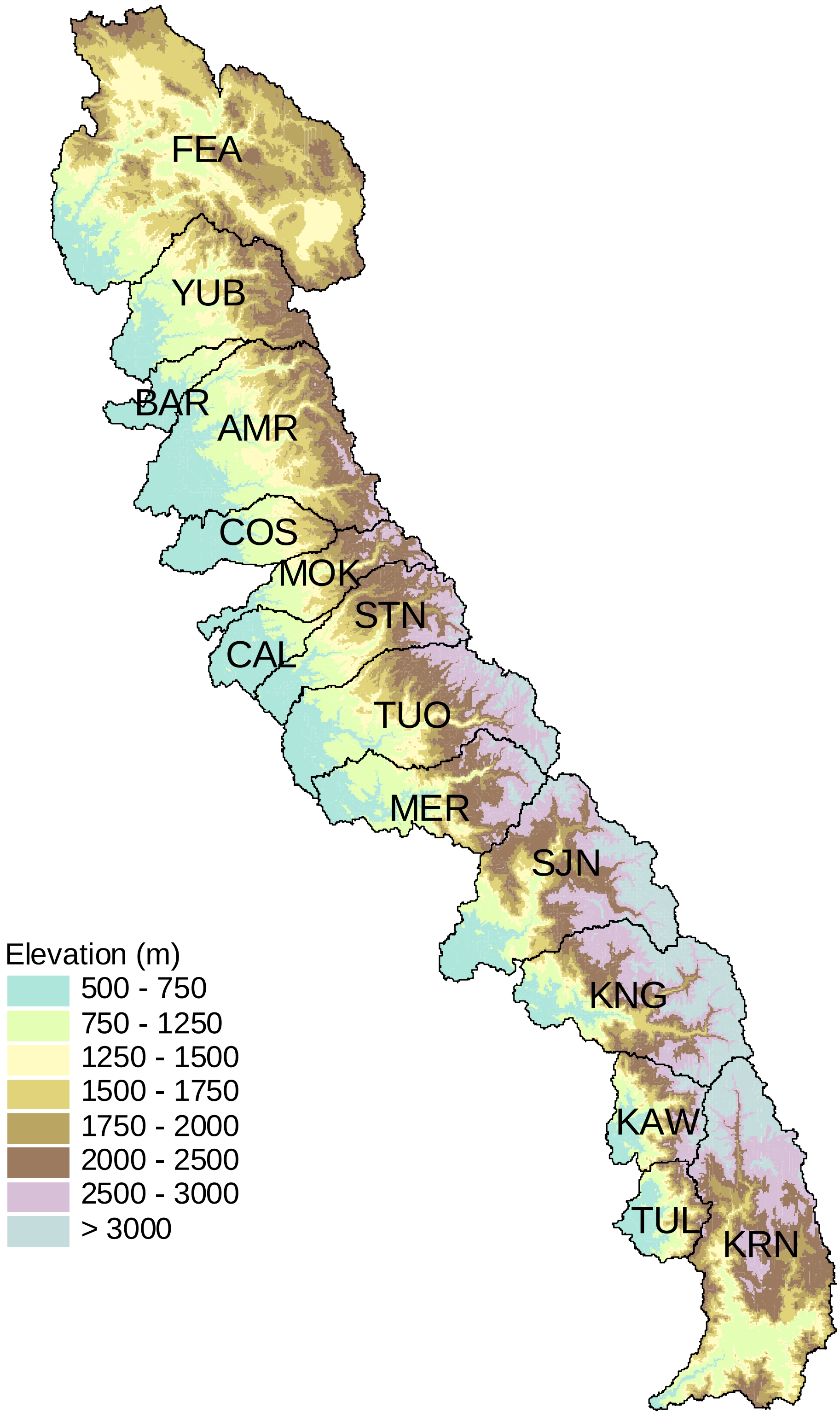


Figure 22. Topographic map of modeled watersheds.

Conclusions

A set of 13 WEAP models have been developed that represent hydrological processes for 15 watersheds in the Sierra Nevada. The models were developed to provide information at a spatial scale useful for studying the implications of climate change and infrastructure operations within the watershed boundaries. This is a departure from previous efforts that have only calculated runoff at the terminal reservoirs.

Analysis of a 2, 4, and 6 degree increase in temperature indicate that the watersheds in the northern portion of the study area, specifically the Yuba through Stanislaus, will experience a larger shift in the timing of the runoff center of mass than watersheds to the south. The reason for this is the prevalence of land within the 1750 to 3250 m bands of elevation. Land above these elevations is colder and will accumulate snow even under temperature increases. This has important ramifications for analysis of hydropower operations. It is clear that projects relying on snow melt water from mid-elevation regions will experience an altered inflow hydrograph as the effects of climate change become more pronounced.

Recommendations for Additional Analysis

The initial phase of this effort has established the rainfall-runoff model and incorporated changes in runoff characteristics associated with climate change. This work forms the foundation for Phase II efforts described in the accompanying proposal. These efforts may include the following.

Additional Calibration Refinement

In any model development exercise the calibration is never complete as no model can be perfectly calibrated. There may be an opportunity to revisit the calibration to improve performance of the models used in this analysis. This would likely entail allowing some of the model parameters that have been linked to the two classes of soil defined in the model to vary according land cover distribution as well.

Compare with Standard FERC Method of Defining Natural Flow

An early step in most FERC processes is the definition of natural flows for the historic period of record. This is typically done in the manner employed by the Department of Water Resources to back out the influence of operations and arrive at an estimate of Full Natural Flow which entails a series of mass balance calculations made based on streamflow observations and operational records. There is typically a closure term related to unknown exchanges with aquifers and undocumented diversions. It may be worthwhile to investigate how the simulated historic flows in WEAP correspond with these values. As these reconstructed natural flows cannot be used to construct future hydrologic time series, understanding the differences between WEAP and this method could provide insights for when WEAP is used so simulate future flow regimes associated with particular climate scenarios.

Add Operations to WEAP

At the current time, WEAP is only being used to simulate the natural rainfall-runoff processes in the Sierra Nevada watersheds. It would be possible to add objects representing the elements of the built infrastructure so that adaptation options could be explored for various time series. The graphical user interface in WEAP could allow the tool to be accessible to members of the stakeholder community that are involved in the FERC process

Develop Ensembles of Future Climate Scenarios

At the current time, we have only done the most simple climate change experiments based on increasing recently observed temperatures by +2^{o}C, +4^{o}C, +6^{o}C while holding constant recently observed patterns of precipitation. One promising research opportunity would be to develop a more robust set of climate scenarios. On other WEAP applications this has been done in collaboration with the National Center for Atmospheric Research. This partnership could be organized for the current applications as well.

Internalize temperature dependent operating rules

If operations are added to the WEAP applications it we be possible to develop reservoir operating logic that seeks to manage infrastructure to meet downstream temperature requirements. This would be a very exciting step as many of the intream flow requirements downstream of hydropower facilities have been set in order to preserve some temperature objective. It would be interesting to see how these requirement work in maintaining acceptable water temperatures in the face of climate change.

Investigate how changes in land cover associated with climate change interact with changes in climate

The current WEAP applications in the Sierra have been run assuming a static distribution of land use and land cover. There is some indication that these patterns will change under future climate scenarios, with pine forest perhaps giving way to grasslands and chaparral. There is also an indication that urbanization will be widespread in the future. These changes could lead to different patterns of watershed hydrology. It may be of interest to explore the sensitivity of the models to potential shifts in land use and land cover.

Investigate how changes in the occurrence of forest fires associated with climate change interact with changes in climate

A standing forest exerts a different control on watershed processes then a burned forest. There is some indications that the incidence of major forest fires will increase with climate change. It may be possible to explore the sensitive of Sierra watershed to an increased incidence of fire that would be superimposed on changes in climate.

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APPENDIX A. GIS Projection

```
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120.0],PARAMETER["Standard_Parallel_1",34.0]
PARAMETER["Standard_Parallel_2",40.5]
UNIT["Meter",1.0]]
```

APPENDIX B. Sub-Watershed Names

Watershed	Sub-Watershed	Name
AMR	AMR_1	BELOW FOLSOM
AMR	AMR_10	BRUSH CREEK RES
AMR	AMR_11	EL DORADO FOREBAY
AMR	AMR_12	CAMINO DIV
AMR	AMR_12	CAMINO DIV
AMR	AMR_13	JAYBIRD PH
AMR	AMR_14	JUNCTION RES
AMR	AMR_15	UNION VALLEY PH NR PACIFIC
AMR	AMR_16	JONES FORK PH
AMR	AMR_17	ROBBS PEAK PH
AMR	AMR_18	ICE HOUSE RESERVOIR
AMR	AMR_19	ALDER CREEK
AMR	AMR_2	WEBER CR
AMR	AMR_20	SILVER FORK AMERICAN
AMR	AMR_21	LOWER SILVER FORK
AMR	AMR_22	SILVER LAKE
AMR	AMR_23	CAPLES LAKE
AMR	AMR_24	NORTH FORK AMERICAN
AMR	AMR_25	LOWER MIDDLE FORK AMERICAN
AMR	AMR_26	MF AMERICAN BL OXBOW
AMR	AMR_27	OXBOW PH
AMR	AMR_28	MIDDLE FORK N FK AMERICAN/RALSTON DIV
AMR	AMR_29	RUBICON
AMR	AMR_3	NEWCASTLE POWERPLANT
AMR	AMR_30	INTERBAY DAM RALSTON DIVERSION
AMR	AMR_31	BELOW FRENCH MEADOWS
AMR	AMR_32	DUNCAN CANYON CREEK DIV
AMR	AMR_33	DUNCAN DIV ABOVE FRENCH MEADOWS
AMR	AMR_34	LONG CANYON CANAL
AMR	AMR_35	NF LONG CANYON CN DIV TUN
AMR	AMR_36	SF LONG CANYON CN DIV TUN
AMR	AMR_37	PILOT ABOVE STUMPY MEADOWS
AMR	AMR_38	RUBICON BL HELL HOLE
AMR	AMR_39	HH INFLOW
AMR	AMR_4	SOUTH FORK AMERICAN
AMR	AMR_40	SF RUBICON
AMR	AMR_41	ROBBS PEAK PENSTOCK OUTFLOW
AMR	AMR_42	GERLE CREEK RES
AMR	AMR_43	BL LOON LAKE
AMR	AMR_44	BUCK-LOON TUNNEL
AMR	AMR_45	UPPER RUBICON
AMR	AMR_46	RUBICON-ROCKBOUND TUNNEL BL RUBICON LK
AMR	AMR_5	SOUTH FORK AMERICAN PLACERVILE

Watershed	Sub-Watershed	Name
AMR	AMR_6	WHITEROCK PH NR PLACERVILLE
AMR	AMR_7	ROCK C OVERFLOW WEIR A DIV NR PLACERVILLE
AMR	AMR_8	SLAB CREEK
AMR	AMR_9	CAMINO / EL DORADO PH
BAR	BAR_1	CAMP FAR WEST
BAR	BAR_2	COMBIE
BAR	BAR_3	BEAR RIVER LOWER
BAR	BAR_4	BEAR RIVER MIDDLE
BAR	BAR_5	BEAR RIVER UPPER
BAR	BAR_6	BOARDMAN CANAL
CAL	CAL_1	CALAVERAS R BL N HOGAN DAM
CAL	CAL_2	SF CALAVERAS R NR S ANDREAS
CAL	CAL_3	NF CALAVERAS R NR S ANDREAS
COS	COS_47	LOWER COSUMNES RIVER
COS	COS_48	MIDDLE FORK COSUMNES RIVER
COS	COS_49	NF COSUMNES RIVER NR EL DORADO CA
COS	COS_50	CAMP CREEK AND SLY PARK
COS	COS_51	SLY PARK
FEA	FEA_1	FEATHER BL OROVILLE (OUTLET)
FEA	FEA_10	BL ROCK CREEK DIV DAM
FEA	FEA_11	BELDEN PH AT BELDEN
FEA	FEA_12	EB OF NF FEATHER NR RICH BAR
FEA	FEA_13	BELDEN DAM
FEA	FEA_14	CARIBOU PH NO.1 & 2
FEA	FEA_15	BUTT C NR CARIBOU
FEA	FEA_16	ALMANOR BUTTE C TU OUTLET
FEA	FEA_17	NF FEATHER NR. PRATVILLE BELOW ALMANOR
FEA	FEA_18	CHESTER DIVERSION
FEA	FEA_19	BL MOUNTAIN MEADOW RES
FEA	FEA_2	WEST BRANCH FEATHER ABOVE PARADISE
FEA	FEA_20	INDIAN CREEK NR. CRESCENT MILLS
FEA	FEA_21	INDIAN CREEK NR. TAYLORSVILLE
FEA	FEA_22	INDIAN C NR BOULDER C BELOW ANTELOPE
FEA	FEA_23	SPANISH CREEK AT BLACKHAWK
FEA	FEA_24	BUCKS DIVERSION
FEA	FEA_25	GRIZZLY PP NR STORRIE
FEA	FEA_26	BUCKS C TUNNEL OUTLET
FEA	FEA_27	FEATHER R ABOVE MERRIMAC
FEA	FEA_28	MF FEATHER NR CLIO
FEA	FEA_29	MF FEATHER NR PORTOLA
FEA	FEA_3	HENDRICKS DIV DAM
FEA	FEA_30	BIG GRIZZLY C AT GRIZZLY VALLEY DAM
FEA	FEA_31	BELOW FRENCHMAN DAM
FEA	FEA_32	KANAKA PH NR FEATHER FALLS AB OROVILLE
FEA	FEA_33	FORBESTOWN PH NR FORBESTOWN
FEA	FEA_34	FORBESTOWN DIVERSION

Watershed	Sub-Watershed	Name
FEA	FEA_35	WOODLEAF PH
FEA	FEA_36	LOST CREEK
FEA	FEA_37	SF FEATHER DIVERSION
FEA	FEA_38	BL LITTLE GRASS VALLEY
FEA	FEA_4	COMBINED FLOW NF FEATHER R + POE PP
FEA	FEA_5	NF FEATHER R A PULGA
FEA	FEA_6	POE PH
FEA	FEA_7	CRESTA PH NR PULGA
FEA	FEA_8	ROCK CREEK PH NR STORRIE
FEA	FEA_9	BUCK CREEK PH AT STORRIE
KAW	KAW_1	KAW R OUTLET BL TERMINUS
KAW	KAW_2	SF KAW R A 3 RIVERS
KAW	KAW_3	KAW R A 3 RIVERS CA
KAW	KAW_4	KAW R COND NO.2 NR HAMMOND
KAW	KAW_5	MF KAW R
KAW	KAW_6	MARBLE F KAW R (TOTAL) A POTWISHA
KAW	KAW_7	MARBLE F KAW (R ONLY) A POTWISHA
KAW	KAW_8	EF KAWEAH R NR 3RIVERS
KNG	KNG_1	KINGS R BL PINE FLAT D
KNG	KNG_10	NF KINGS R BL WISHON RES
KNG	KNG_11	HELMS C BL COURT RIGHT DAM CA
KNG	KNG_12	NF KINGS R BL MEADOWBROOK
KNG	KNG_13	KINGS R AB NF NR TRIMMER
KNG	KNG_14	KINGS R MIDDLE FK
KNG	KNG_15	KINGS R SOUTH FK
KNG	KNG_2	COMBINED FLOW KINGS R BL N F & KINGS R PP
KNG	KNG_3	NF KINGS R BL DINKEY C NR BALCH CAMP
KNG	KNG_4	DINKEY C SIPHON FISH REL A BALCH CAMP
KNG	KNG_5	DINKEY C A DINKEY MDW NR SHAVER LK
KNG	KNG_6	NF KINGS R AB DINKEY C A BALCH CAMP
KNG	KNG_7	BALCH PH NR FRESNO (NO1 & NO2 COMB)
KNG	KNG_8	NF KINGS R BL BALCH DIV DAM
KNG	KNG_9	BALCH DIVERSION
KRN	KRN_1	KERN R A RIO BRAVO PP BYP IN DAM
KRN	KRN_10	KERN R NR KERNVILLE (RIVER ONLY
KRN	KRN_2	KERN R BL K CNY PH DIV DAM NR BAKERSF
KRN	KRN_3	KERN CONDUIT NR DEMOCRAT SPRINGS
KRN	KRN_4	KERN R DIVERSION NO.1
KRN	KRN_5	KERN R BL ISABELLA DAM
KRN	KRN_6	BOREL CN BL ISABELLA DAM
KRN	KRN_7	SF KERN R NR ONYX
KRN	KRN_8	KERN R A KERNVILLE
KRN	KRN_9	KERN R NO.3 CN NR KERNVILLE
MOK	MOK_1	MOKELUMNE OUTLET
MOK	MOK_10	BEAR R BL BEAR R DIV DAM
MOK	MOK_11	BEAR R BL LO BEAR R DAM

Watershed	Sub-Watershed	Name
MOK	MOK_12	TIGER C PH COND BL SALT SPRINGS DAM
MOK	MOK_13	DIV DAM NR SALT SPRINGS
MOK	MOK_2	MOKELUMNE R NR MOKELUMNE HILL
MOK	MOK_3	SF MOKELUMNE R NR WEST POINT
MOK	MOK_4	MF MOKELUMNE R A WEST POINT
MOK	MOK_5	FOREST C NR WILSEYVILLE
MOK	MOK_6	ELECTR DIV DAM NR WPT
MOK	MOK_7	NF MOK R BL TIGER C RES NR WPT
MOK	MOK_8	NF MOKELUMNE R AB TIGER C
MOK	MOK_9	TIGER C PH NR WEST POINT
BAR	NEV CITY GRASS VALLEY CAMP FAR WEST	NEV CITY GRASS VALLEY CAMP FAR WEST
YUB	NEV_CITY_GRASS_VALLEY	NEWV
SJN	SJN_1	SAN JOAQUIN R BL FRIANT CA
SJN	SJN_10	SAN JOAQUIN PH NO3 NR NORTH FORK
SJN	SJN_11	NF WILLOW C NR BASS LAKE
SJN	SJN_12	NF WILLOW C NR SUGAR PINE
SJN	SJN_13	SAN JOAQUIN R AB WILLOW CNR AUBERRY CA
SJN	SJN_14	BIG C PH NO 3 NR SHAVER LK
SJN	SJN_15	STEVENSON C AT SHAVER LK
SJN	SJN_16	EASTWOOD PP AB SHAVER LK NR BIG CR
SJN	SJN_17	HUNT-SHAV CONDUIT OTLT NR SHAVER LK
SJN	SJN_18	SAN JOAQUIN R AB STEVENSON C NR BIG CREEK
SJN	SJN_19	MAMMOTH POOL PP NR BIG CREEK
SJN	SJN_2	MADERA CN A FRIANT
SJN	SJN_20	SAN JOAQUIN R AB SHAKEFLAT C NR BIG CREEK CA
SJN	SJN_21	MAMMOTH POOL FISHWATER TURBINE
SJN	SJN_22	GRANITE C NR CATTLE MOUNTAIN
SJN	SJN_23	SAN JOAQUIN R A MILLER CROSSING
SJN	SJN_24	BIG C NR MOUTH NR BIG CR
SJN	SJN_25	BIG C PH NO 2 NR BIG CREEK CA
SJN	SJN_27	PITMAN C NR TAMARACK MOUNTAIN
SJN	SJN_28	HUNTINGTON-SHAVER COND IT A HUNTINGTON LK
SJN	SJN_29	BIG C BL HUNTINGTON LK
SJN	SJN_3	FRIANT-KERN CN A FRIAT
SJN	SJN_30	PORTAL POWERPLANT AT HUNTINGTON LK
SJN	SJN_31	MONO CREEK DIVERSION
SJN	SJN_32	PORTAL PH FOREBAY
SJN	SJN_33	BOSILLO C DIV DAM
SJN	SJN_34	CAMP 62 C BL DIV DAM NR BIG C
SJN	SJN_35	CHINQUAPIN C BL DIV DAM NR BIGC
SJN	SJN_36	BEAR C DIVERSION
SJN	SJN_37	SF SAN JOAQUIN R BL HOOPER C NR FLORENCE LK
SJN	SJN_38	SF SAN JOAQUIN R NR FLORENCE LK
SJN	SJN_4	KERCKHOFF PH NO 2 A MILLERTON LK NR AUBERRY CA

Watershed	Sub-Watershed	Name
SJN	SJN_5	KERCKHOFF PH NR AUBERRY
SJN	SJN_6	SAN JOAQUIN R NR AUBERRY
SJN	SJN_7	BIG C PH NO 4 NR AUBERRY
SJN	SJN_8	WILLOW CR AT MOUTH NR AUBERRY
SJN	SJN_9	SAN JOAQUIN PH NO2 NR NORTH FK
STN	STN_1	BL NEW MELONES
STN	STN_10	Utica
STN	STN_11	New Spicer Mdw
STN	STN_12	NF Stanislaus Div Tunnel and Hobart Div
STN	STN_13	Beaver Ck Div
STN	STN_14	Below Sand Bar Div Dam
STN	STN_15	MF STANISLAUS R BL BEARDSLEY DAM CA
STN	STN_16	BEARDSLEY PH NR STRAWBERRY CA
STN	STN_17	Donnell PH and Hells Half Acre Gage
STN	STN_18	Donnells Dam
STN	STN_19	CLARK FORK STANISLAUS R NR DARDANELLE CA
STN	STN_2	ANGELS C BL D DIV DAM NR MURPHYS CA
STN	STN_20	MF STANISLAUS R AT KENNEDY MDWS NR DARDANELLE CA
STN	STN_21	Relief Reservoir
STN	STN_22	Lyons Reservoir
STN	STN_23	PHILADELPHIA CN NR STRAWBERRY CA
STN	STN_24	SF STANISLAUS R A STRAWBERRY CA
STN	STN_25	Pinecrest Lake/Main Strawberry Dam
STN	STN_3	STANISLAUS PP
STN	STN_4	UTICA PRESSURE TAP
STN	STN_5	NF STANISLAUS R BL BEAVER C NR HATHAWAY PINES CA
STN	STN_6	MCKAYS DIV
STN	STN_7	UTICA C IN
STN	STN_8	CAMP WOLFBORO GAGE
STN	STN_9	NF STANISLAUS R BL DIV DAM NR BIG MDW CA
TUL	TUL_1	TULE R OUTLET BL SUCCESS
TUL	TUL_2	TULE R A HWY 190 + DIV
TUL	TUL_3	MF TULE R AB SPRINGV
TUL	TUL_4	MF TULE R INTAKE AB SPRINGV
TUL	TUL_5	PGE TULE R PH NR SPRINGV
TUL	TUL_6	NF OF MF TULE R NR SPRINGV
TUL	TUL_7	NF MF TULE BL DOYLE SPRINGS DIV
TUL	TUL_8	NF OF MF TULE R BL DIV DAM
TUL	TUL_9	SF TULE R NR SUCCESS
TUO	TUO_1	Don Pedro Dam
TUO	TUO_10	CHERRY C BL VALLEY DAM NR HETCH HETCHY CA
TUO	TUO_11	ELEANOR C NR HETCH HETCHY CA
TUO	TUO_12	Early Intake
TUO	TUO_13	TUOLUMNE R NR HETCH HETCHY CA
TUO	TUO_14	M TUOLUMNE R A OAKLAND RECREATION CAMP CA
TUO	TUO_15	SF TUOLUMNE R NR OAKLAND RECREATION CAMP CA

Watershed	Sub-Watershed	Name
TUO	TUO_16	Pine Mountain Lake
TUO	TUO_17	BIG C AB WHITES GULCH NR GROVELAND CA
TUO	TUO_18	Moccasin Res
TUO	TUO_19	Priest Res
TUO	TUO_2	Phoenix Reservoir
TUO	TUO_3	Tuolumne R Above New Don Pedro Res
TUO	TUO_4	NF TUOLUMNE R NR LONG BARN CA
TUO	TUO_5	CLAVEY R NR BUCK MEADOWS CA
TUO	TUO_6	CLAVEY R NR LONG BARN CA
TUO	TUO_7	REED C NR LONG BARN CA
TUO	TUO_8	CHERRY C BL DION R HOLM PH, NR MATHER CA
TUO	TUO_9	CHERRY C NR EARLY INTAKE CA
YUB	YUB_1	DEER CREEK NR SMARTVILLE
YUB	YUB_10	CANYON CREEK / B-S CN INTAKE
YUB	YUB_11	MILTON-BOWMAN TUN OUTLET
YUB	YUB_12	NEW COLGATE PH NR FRENCH CORRAL
YUB	YUB_13	OREGON CREEK
YUB	YUB_14	UPPER MIDDLE YUBA
YUB	YUB_15	MILTON DIVERSION
YUB	YUB_16	MIDDLE YUBA AT MILTON
YUB	YUB_17	POKER FLAT/NEW BULLARDS BAR
YUB	YUB_18	DEADWOOD C PP NR STRAWBERRY
YUB	YUB_19	SLATE CREEK DIVER / BEL DIV
YUB	YUB_2	SCOTTS FLAT
YUB	YUB_20	NORTH YUBA RIVER
YUB	YUB_3	DEER C PH NR WASHINGTON
YUB	YUB_4	YUBA RIVER (BL ENGLEBRIGHT)
YUB	YUB_5	LOWER SOUTH YUBA
YUB	YUB_6	UPPER SOUTH YUBA
YUB	YUB_7	SPAULDING NO.1 and NO.2 PH NR EMIG. GAP
YUB	YUB_8	FORDYCE CREEK
YUB	YUB_9	TEXAS CREEK

APPENDIX C. Vegetation Classification

Vegetation Classes		
Veg Code (GIS)	**NLDC Codes**	**Codes**
1	**11,12, 90-99**	**WATER**
2	**21,22,23,23**	**URBAN**
3	**31,32**	**BARREN**
4	**41,42,43,**	**TREE**
5	**52**	**SHRUB**
6	**71**	**GRASSLAND**
7	**81,82**	**AGRICULTURE**

NLDC 2001 Codes
11. Open Water - All areas of open water, generally with less than 25% cover of vegetation or soil.
12. Perennial Ice/Snow - All areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover.
21. Developed, Open Space - Includes areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot si
22. Developed, Low Intensity - Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20-49 percent of total cover. These areas most commonly include single-family housing units.
23. Developed, Medium Intensity - Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50-79 percent of the total cover. These areas most commonly include single-family housing units.
24. Developed, High Intensity - Includes highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to100 percent of the total cover.
31. Barren Land (Rock/Sand/Clay) - Barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for les

NLDC 2001 Codes
32. Unconsolidated Shore* - Unconsolidated material such as silt, sand, or gravel that is subject to inundation and redistribution due to the action of water. Characterized by substrates lacking vegetation except for pioneering plants that become establis
41. Deciduous Forest - Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75 percent of the tree species shed foliage simultaneously in response to seasonal change.
42. Evergreen Forest - Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75 percent of the tree species maintain their leaves all year. Canopy is never without green foliage.
43. Mixed Forest - Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75 percent of total tree cover.
51. Dwarf Scrub - Alaska only areas dominated by shrubs less than 20 centimeters tall with shrub canopy typically greater than 20% of total vegetation. This type is often co-associated with grasses, sedges, herbs, and non-vascular vegetation.
52. Shrub/Scrub - Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditio
71. Grassland/Herbaceous - Areas dominated by grammanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
72. Sedge/Herbaceous - Alaska only areas dominated by sedges and forbs, generally greater than 80% of total vegetation. This type can occur with significant other grasses or other grass like plants, and includes sedge tundra, and sedge tussock tundra.
73. Lichens - Alaska only areas dominated by fruticose or foliose lichens generally greater than 80% of total vegetation.
74. Moss - Alaska only areas dominated by mosses, generally greater than 80% of total vegetation.
81. Pasture/Hay - Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20 percent of total vegetation.
82. Cultivated Crops - Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20 percent of total veg
90. Woody Wetlands - Areas where forest or shrubland vegetation accounts for greater than 20 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
91. Palustrine Forested Wetland* -Includes all tidal and non-tidal wetlands dominated by woody vegetation greater than or equal to 5 meters in height and all such wetlands that occur in tidal areas in which salinity due to ocean-derived salts is below 0.5

NLDC 2001 Codes
92. Palustrine Scrub/Shrub Wetland* - Includes all tidal and non-tidal wetlands dominated by woody vegetation less than 5 meters in height, and all such wetlands that occur in tidal areas in which salinity due to ocean-derived salts is below 0.5 percent.
93. Estuarine Forested Wetland* - Includes all tidal wetlands dominated by woody vegetation greater than or equal to 5 meters in height, and all such wetlands that occur in tidal areas in which salinity due to ocean-derived salts is equal to or greater th
94. Estuarine Scrub/Shrub Wetland* - Includes all tidal wetlands dominated by woody vegetation less than 5 meters in height, and all such wetlands that occur in tidal areas in which salinity due to ocean-derived salts is equal to or greater than 0.5 perce
95. Emergent Herbaceous Wetlands - Areas where perennial herbaceous vegetation accounts for greater than 80 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
96. Palustrine Emergent Wetland (Persistent)* - Includes all tidal and non-tidal wetlands dominated by persistent emergent vascular plants, emergent mosses or lichens, and all such wetlands that occur in tidal areas in which salinity due to ocean-derived
97. Estuarine Emergent Wetland* - Includes all tidal wetlands dominated by erect, rooted, herbaceous hydrophytes (excluding mosses and lichens) and all such wetlands that occur in tidal areas in which salinity due to ocean-derived salts is equal to or gre
98. Palustrine Aquatic Bed* - The Palustrine Aquatic Bed class includes tidal and nontidal wetlands and deepwater habitats in which salinity due to ocean-derived salts is below 0.5 percent and which are dominated by plants that grow and form a continuous
99. Estuarine Aquatic Bed* - Includes tidal wetlands and deepwater habitats in which salinity due to ocean-derived salts is equal to or greater than 0.5 percent and which are dominated by plants that grow and form a continuous cover principally on or at t

SIERRA'S HIGH-ELEVATION HYDROPOWER AND CLIMATE CHANGE: Temperature Simulation

PROJECT REPORT

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Introduction

The Sierra Nevada is expected to undergo changes in hydrology under global climate change scenarios. Future conditions may include different timing of precipitation events (rain and snow), different quantities and distribution, and/or warmer air temperatures leading to earlier runoff of snowmelt from the higher elevations. To assess the possible impacts of a future climate change on water temperature a conceptual model was formulated identifying the forcing function associated with water temperature conditions in streams and reservoirs. This conceptual model was subsequently developed into a numerical model representing water temperature conditions with elevation in the Sierra Nevada.

Additionally, change(s) in operation of water facilities may impact water temperatures and the tool presented here can be used to assess the impacts of those changes. This operational gaming ability with temperature would support efforts to evaluate the feasibility of grouped hydropower re-licensing, as well as other measures to mitigate or adapt to climate change conditions.

Charge

The water temperature theory and modeling work presented herein represents an initial foray into a challenging arena of thermal assessment: large scale impacts related to large scale processes such as climate change over the entire Sierra Nevada. The general methodology, modeling algorithm, and an application of a beta model to a sample watershed are addressed. While the physics of water temperature modeling are well understood the application to a large spatial domain covering multiple watershed ultimately requires the simplification of the governing equations and deviation from standard models and methods.

Methods

The temperature model developed herein is one element of a larger project, utilizing GIS, watershed models, operations optimization models, and habitat relationships (Figure). Currently, these elements are discrete units and data sharing is a manual exercise. The focus herein is solely on the temperature model, with model integration proposed for a future phase.

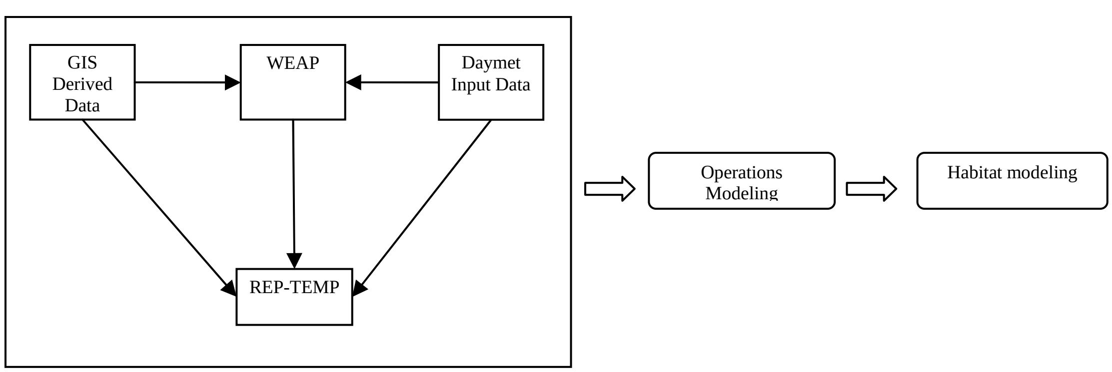

Figure 1. Sierra Nevada global model elements and relationships

General

The fundamental approach adopted herein is to develop a regional, equilibrium based temperature model (RTEMP) using regionally available meteorological data and digital elevation models to develop weekly equilibrium water temperature (EWT) throughout the Sierra Nevada for the various stream reaches. (EWT is the water temperature that would be attained if the water body were in equilibrium with meteorological conditions.)

The production of an EWT map of the Sierra Nevada in itself will prove insightful, but not representative of actual conditions. Adjustment of the EWT values is necessary to account for deviations from equilibrium. For example, snowmelt runoff in proximity of the snow pack may be well below EWT. There are three deviations from EWT that are currently accommodated within RTEMP: snowmelt, reservoir releases, and groundwater spring flow. All three of these are assumed to occur within the domain and, at certain times of year, to result in deviation from EWT. Further, physical and hydrological conditions vary throughout the watershed from the crest to the lower elevations. To incorporate these into the EWT calculation, stream order, stream length and estimated water velocity were used.

Water quantities were provided by the Water Evaluation and Planning (WEAP) model in the form of reach specific weekly unimpaired flow conditions. These flows were provided based on contributions from elevation "bands" for every 250 meters of vertical change from approximately 500 meters to the Sierra Crest. Water temperatures for each contributing area (or band) were estimated based on source water temperatures (e.g., snow melt at approximately 0^{o} Celsius), distance from source, and the EWT.

For these initial analyses, WEAP output represented an unimpaired hydrology with no infrastructure. Other features are proposed for future phases of this work, including representing reservoirs, canals, tunnels, powerhouses, and other water resources development. Reservoirs can modify water temperature by moderating short term variations (small reservoirs), as well as providing cool water releases during warm periods of the year (larger reservoirs). These modifications to the thermal regime are manifest in aquatic systems as deviations from EWT. Incorporating reservoirs into future versions of RTEMP will most likely consider reservoir volume, depth, and contributing watershed area. Any notable heat gain in conveyance facilities such as tunnels and canals will be represented empirically.

The Heat Budget

To model water temperatures the sources of heat flux in and out of the system need to be quantified. The stream water temperature model used for this study considers the surface heat exchange that consists of five principal heat fluxes as described below:

1. J_{sn} = net solar shortwave radiation (calculated for this study),
2. J_{an} = atmospheric longwave radiation,
3. J_{br} = water longwave or back radiation,

4. J_c = conduction and convection and
5. J_e = evaporation.

The total heat flux J_n, is shown in equation (1):

$$J_n = J_{sn} + J_{an} - (J_{br} + J_c + J_e) \qquad (1)$$

Flux terms one and two are net absorbed radiation, while terms three, four and five are water temperature dependant terms. All terms are generally applied on a per unit area basis. Multiplying the total flux by the surface area of the water body results in the net energy change in the water body over a given time period. Average weekly meteorological conditions derived from DayMet daily data (database maintained by Oak Ridge National Laboratory) were applied in the heat budget equations.

Other fluxes that operate on a water body include heat exchange with the bed itself through conduction and hyporheic flow. Bed conductance has been found to have a relatively minor influence on most systems and is often left out of the heat budget. However, bed conduction and/or hyporheic flow may play and important role in buffering extreme winter and summer time temperatures. A short discussion of these heat exchange mechanisms is given below.

Ground or bed conductance is a flux that takes heat between the streambed and the water. Both Hauser and Schohl (2003) and Meier et al. (2003) cite the parameters necessary to perform the calculation for the ground conductance term of the heat budget. These parameters are difficult to estimate and Meier et al. (2003) report the integration of these parameters into a single calibration parameter. This parameter integration would then effectively reduce the ground conductance term to a non-physical parameter to be used as a sort of tuning knob for overall model calibration. Chapra (1997) and Edinger et al. (1974) do not use ground conductance, they only discuss surface heat exchange terms. Brown and Barnwell (1987) do not use a ground conductance term either, stating the term is of relative unimportance.

Brown (1969) discusses using an energy balance for small streams. He describes bed conduction as important only in a small bedrock stream unlike the gravel bed streams where little influence of bed conductance was noticed due to the low thermal conductivities of the bed gravels. The stream bed acted as a heat sink during the day and released heat during nighttime hours. Potentially this term may have significance in headwater streams flow is low and bed rock channels exist. Further sensitivity testing of bed conduction is proposed for future phases of this work.

Hyporheic flow is that portion of stream flow occupying the interstitial pathways of the bed and banks and can have an impact on stream temperatures. However, the difficulty in quantifying the hyporheic flow and temperature interactions often precludes its use. Poole and Berman (2001) describe the potential influence of hyporheic flow on stream temperatures depending on its travel time. Hyporheic flow may be on the order of one to 1000 days. The shorter the flow time the less buffering effect the hyporheic flow will have on the stream temperatures. Poole also states that since there is intra day and inter-day variation in stream temperature any hyporheic flow may buffer stream temperatures. For example, water taken into a hyporheic flow path at night and re-emerging during the day would buffer the daytime temperatures to some degree. The same mechanism would hold true for hyporheic flow paths that are on a seasonalal scale. This is different than groundwater which is relatively constant temperature due to the insulation from even seasonal affects of temperature change. Malard et al. (2002) describe variations in substrate, geomorphology and flow having effects on the amount of hyporheic flow. The result is that hyporheic flow heat flux is taken up in other parts of the heat budget during calibration or it is part of the uncertainty in results after calibration. This study is too broad in nature to consider this heat transfer process.

Estimating Water Equilibrium Temperature

As noted previously, in applying the equilibrium concept to predict a future temperature we calculate the equilibrium temperature and a potential deviation from the equilibrium temperature. The method of estimation equilibrium temperature may utilize the entire surface heat budget or an approximation of some terms. Three potential approaches were explored for calculating either the equilibrium temperature and/or the deviation from equilibrium temperature that could be expected given an initial water temperature and imposition of weekly average meteorological conditions.

Equilibrium temperature is a loosely defined term. One definition is the resulting water temperature when all heat fluxes in equation 1 sum to zero. In effect, this approach allows the water to emit as much energy as it is absorbing. The important assumptions when determining this "theoretical" equilibrium temperature, T_e, are that it is independent of initial water temperature, volume of water, and time of exposure. Another method is to assess "dynamic" equilibrium temperature, T_{de}, wherein initial water temperature, volume, and time of exposure are explicitly addressed. These terms are more fully discussed in the various approaches outlined below.

Heat Transfer Coefficient

Edinger (1968) linearized the heat budget to ease computational and data storage burdens, and developed a heat transfer coefficient formulation in early temperature modeling work. To calculate a change in temperature from some arbitrary temperature a heat transfer coefficient, *K* was determined. The result is what is can be referred to a deviation from equilibrium water temperature as shown is equation (2).

$$\frac{dT_w}{dt} = K(T_e - T_w^i) \qquad (2)$$

Where:

T_w is water temperature

t is time

K is the heat transfer coefficient derived from meteorological data, and
T_e is the theoretical equilibrium temperature
T_w^i is the initial water temperature

To find the new water temperature one adds that starting temperature and the derivative calculated with equation 2. Values for K may be calculated by means suggested in Edinger (1968), but vary with meteorological conditions. However, linearization of the heat budget, which is truly an exponential relationship, results in increasing error in the approximation of equation 2 the farther T_w^i deviates from T_e.

A method developed by Caissie et al. (2005) makes an estimation of certain heat budget terms in order to simplify calculation of a theoretical equilibrium temperature. For the evaporative heat flux calculation, they followed Edinger (1968) in assuming that over small incremental changes in water temperature the vapor pressure deficit is related to the inverse of the difference between starting water temperature and the dew point temperature. Further, their simplification replaces water temperature with T_e in all flux equations thereby equating T_e and T_w on the vapor pressure/temperature curve. The assumption is valid over small increments where the relationship may be considered linear but the relationship is in fact an exponential, increasing with temperature. This approach of using slope will potentially add error to the evaporation calculation.

Caissie et al. use an equation similar to equation 2 in application, multiplying the right hand side by channel width divided by cross-sectional area to account for the variability in thermal mass between, say, wide shallow streams and narrow deep streams. For a rectangular channel this relationship would reduce to the inverse of channel depth.

Grand Canyon Temperature Model: an Empirical Approach

The second approach, developed by Walters et al. (2000), utilizes a departure from equilibrium temperature in the form of equation 3. This model was developed for looking at water temperatures downstream of Glen Canyon Dam and is a unique in that it considers distance from the upstream condition.

$$T_{i+L} = T_{eq} + (T_i - T_{eq})\exp(-vW_i L_i / Q_i) \qquad (3)$$

Where:

Q_i is the flow rate for the reach
W_i is representative reach width
T_{eq} is theoretical equilibrium temperature
T_i is initial temperature at the top of the reach
L_i is reach length
v is a heat exchange coefficient
T_{i+L} is the temperature at the end of the reach

This formulation makes use of the basic tenant that water temperature approaches equilibrium asymptotically, i.e., as an exponential, where the deviation from equilibrium is multiplied by the exponent of a dimensionless number. Application essentially requires a curve fitting exercise. The authors gave little guidance on the determination of heat exchange coefficient or guidance on values used. During testing the method described by Walters et al., results similar to the heat transfer coefficient (previous section) could be attained simply by varying the heat exchange coefficient. The success of this model may rely on the fact that in the Grand Canyon, managers are manipulating very large quantities of water under generally stable meteorological conditions (at least over the short term).

A Dynamic Equilibrium Approach

The third approach, and the one utilized in this study, utilizes a simplified version of the advection dispersion equation, wherein only the source/sink term is retained (equation 4). This approach utilizes the full form of the heat budget and retains critical geometric information about the system in question. Retention of the time derivative takes into account the initial water temperature and change over a specific time period. Further, the surface area and volume, coupled with the density and specific heat of water, allow site specific information to populate the model and allow the "thermal mass" of the water body to play a role. This approach produces a time series of "dynamic equilibrium temperature," wherein water temperature may not achieve complete equilibrium with meteorological conditions over the specified time period. This model produces results akin to a natural system where water temperature varies dynamically over a day in an attempt to reach equilibrium with dynamic meteorological conditions.

$$\frac{dT_w}{dt} = S = \frac{J_n A}{C_p \rho V} \qquad (4)$$

where:

- T_w is water temperature
- t is time step
- S represents sources/sinks
- J_n the net heat flux (see equation 1)
- V water body volume
- C_p specific heat of water
- ρ density of water
- A is water body surface area

For a rectangular channel surface area divided by volume reduced to the inverse of depth, d(i.e., $d = A/V$). This assumption is incorporated in RTEMP to approximate the ratio of surface heat exchange to the volume of water, thus accounting for thermal mass in the system, but reducing data input to an estimate for stream depth. Within RTEMP each time a new flow (Q) is input or calculated, a new depth is calculated. A power function equation in the form $d = aQ^b$ is applied, where a and b are empirically derived coefficients from rating data for gages in or representative of the watershed. A power function developed for the Kern River was used for this study. Proposed future work will include identifying and utilizing the appropriate power function relationships for depth estimation on a watershed by watershed basis.

Weekly average meteorological conditions are applied in calculating the heat budget. Finally, solution of equation 4 employs a fourth order Runge-Kutta. Four time step divisions were found to be generally adequate for stable temperature calculations.

Physical Representation

To apply the temperature modeling logic, a physical representation of the basin was applied. The representation of elevation bands, sub-watersheds, and stream order were arrived at through extended discussion with project team members. Physical basin characterization was completed for surface flow temeprture modeling and watersheds/sub-watersheds as outlined below.

Surface flow temperature modeling

Individual river basins within the global Sierra Nevada model are represented as a watersheds and sub-watersheds reduced to bands of 250 meter elevation change. Conceptually as water is produced from a band it will accumulate in a channel. Both the channel size and flow volume will increase in the downstream direction. For the beta version of RTEMP, a linear distribution/accumulation in the downstream direction as assumed. Each component of runoff (groundwater, rainfall, snowmelt) employs values for length and depth of the local conveyance channel. If water enters a band from another band immediately upstream, that water will be conveyed through a main channel. So within a band both intra-band and inter-band flow can occur. That is, inter-band flow is flow generated from an upstream band, while intra-band flow is flow that originates in the current band. Characterizing the flow produced within an elevation band is most important in those catchments were there is greater travel time.

Watersheds/sub-watersheds

A watershed may have up to three sources – groundwater, rainfall, and snowmelt – for water and corresponding temperature. All water quantities were provided from WEAP. Groundwater flow is composed of the combination of interflow and base flow as defined in the under the WEAP description/documentation.

Each watershed is subdivided into sub watersheds and again by elevation bands corresponding to 250 m elevation changes (discussed in more detail under the WEAP application). Starting from the highest elevation band and working down the watershed water temperature and flow accumulates in two principal ways. First, flow produced from within a particular band (intra-band flow) is distributed linearly over the length of a representative channel. The representative channel length is obtained by the total length of first order streams in a band derived from GIS data sets. Second, flow produced from upstream band(s) (inter-band flow) is constant and flowing in a "separate" representative channel. The representative channel length is obtained by the total length of second order and higher streams in a band. A few bands contained no first order streams; therefore a simple average value from the other bands was used for this study. Future work proposes to explore improvements on these estimating approaches.

The amount of heating in a channel is dependant upon how long the water is exposed to the meteorological conditions. In a stream system the residence time is a function of velocity. WEAP does not produce velocity output and an estimated of velocity is 0.5 meter/second was used. Future improvements on this estimate will explore depth-discharge relationships based on stream order and flow observations.

Flow from each source (rainfall, groundwater, snowmelt) experiences heating in a channel en route to the downstream terminus of the band. Rainfall runoff is assigned current week's air temperature. For groundwater inflows Bartholow (1989) suggests using mean annual air temperature as an approximation if no actual data is available. Exploration if this method at high altitudes suggests this approach may skew the estimate toward colder than actual temperatures because snow insulates the earth and maintains soil temperatures near 0°C – considerably warmer than air temperatures. For this demonstration a value of 7.5 °C was used as an initial estimate. Finally, snowmelt runoff was assigned an initial temperature of 1°C. Literature values suggested that snow melt runoff may experience a small diel variation and that a mean of 1°C is an adequate representation for this purpose. The three sources are blended on a volumetric basis using a mass balance (equation 5) with the final flow and temperature assigned to a "receiving node" at the bottom of each band.

$$T_w = \frac{T_{SW}Q_{SW} + T_{Rw}Q_{RW} + T_{SG}Q_{GW}}{Q_{TOT}} \qquad (5)$$

where:

T_w is temperature of combined outflow

Q_{TOT} is combined total outflow (=Q_{SW} + Q_{RW} + Q_{GW})

Q_{SW} the snow melt flow contribution

Q_{RW} the rainfall flow contribution

Q_{GW} the groundwater flow contribution

T_{SW} the snow melt flow temperature

T_{RW} the rainfall flow temperature

T_{GW} the groundwater flow temperature

The final temperature of the combined flow from one band forms the flow and temperature input to the subsequent, downstream band.

This inter-band inflow water will then be blended with water that originates in the current band (i.e., new intra-band flow), and once again reported at the outlet of the current band. This process is repeated throughout the watershed, and is shown schematically in Figure 2. The general computational steps are presented in Table 1.

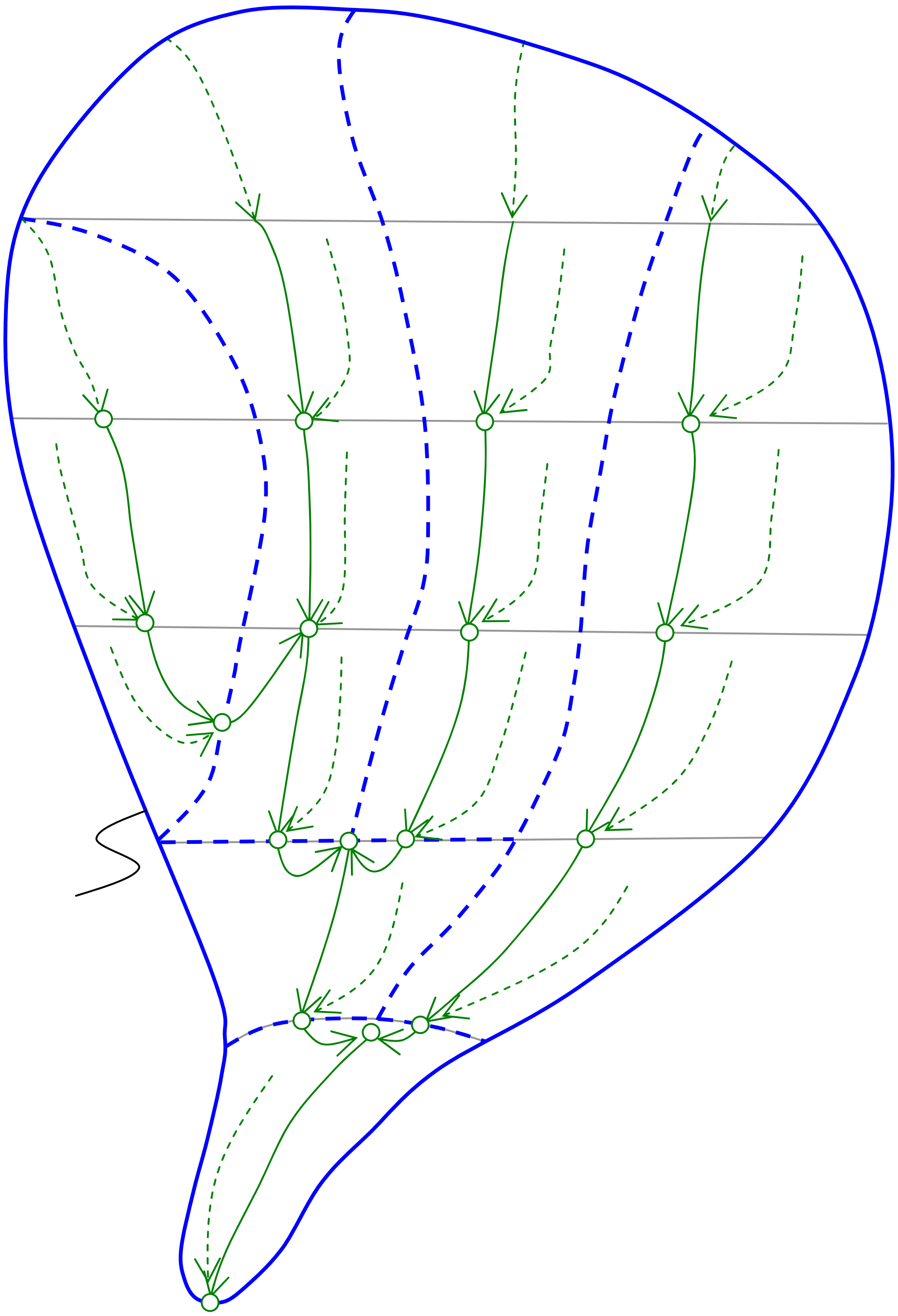

Figure 2. Generic watershed schematic showing intra-band flow (dashed arrow) and inter-band flow (solid arrow). Basin Boundary delineated with solid heavy line and sub-watersheds delineated with

dashed heavy line. Circles represent blending nodes located at the bottom of all elevation bands (light, horizontal lines) except headwater bands that only include intra-band flow.

A node collects flows and temperatures from many sources (*k*) and the resulting temperature is calculated as shown in equation (6). An example of this would be collecting all the intra-band flows and then blending with any inter-band flow at the bottom of an elevation band.

$$T_w = \frac{\sum_{k=1}^{n} T_k Q_k}{\sum_{k=1}^{n} Q_k} \qquad (6)$$

The temperature model logic produced negative temperatures for flow values less than 0.1 cubic meters/second (cms). For this study a minimum water temperature of 0.2°C was imposed on water temperatures. This condition will be explored further in the proposed future phase, and can possibly be addressed more precisely with a dynamic shortening of the time step of the Runge-Kutta approximation.

Table 1. General computational steps for intra- and inter-band flow and temperature computations

Type of Flow	Step	Description
Intra-band flow	1	At a headwater band or any band with intra-band flow, the flows from each of the different source types, i.e. groundwater, rain and/or snow melt, are assign initial water temperature.
	2	Approximate an evenly distributed inflow for each flow source by adding flow at evenly spaced points spaced (each 1/10th of the total reach length) along the channel length through the band. Apply the equilibrium heating equation between each input point.
	3	Check if the residence time is sufficient to apply the full heating effect. If not, perform a linear interpolation between the current time step and the previous time step.
	4	As new incremental flows with corresponding temperature are added use a mass balance to calculate the resulting starting temperature for the current segment. Repeat for each of the input points (spaced at intervals of 1/10th reach length) until the bottom of the band is reached.
Inter-band flow	1	Check if current band has flow coming in from another band. If not, then the current intra-band flow now becomes the inter-band flow for the next downstream band. If flow from another band is contributing, then apply the equilibrium heating equation for the full flow entering the band. Again, check if the residence time is enough to apply the full heating effect. If not perform a linear interpolation between the current time step and the previous time step.
	2	Calculate water temperature, T_w, from equation (4) for current band. Apply equation (6) to obtain blended intra-flow and inter-flow temperature at the band "outlet."
	3	In the next downstream band, combine flows from all source bands. Generally, a band at the top of a new sub watershed may receive inter-band flow from multiple sources. These are blended prior to being treated for changes in water temperature as inter-band flow.
	4	Repeat steps 1-7 joining bands with the proper physical connectivity derived from GIS data sets.

As water flows downstream through the series of bands, water temperatures that deviate from equilibrium will seek to warm or cool towards equilibrium. Because meteorological conditions change with elevation, equilibrium temperatures likewise change, generally increasing with decreasing elevation. The importance of using a dynamic equilibrium approach versus a theoretical equilibrium approach is apparent when considering that certain inputs may contribute flows that result in a deviation of stream temperature from equilibrium conditions (e.g., groundwater and snowmelt). Further, tributary confluences from high and low elevations may likewise contribute waters that result in a deviation of stream temperature from equilibrium conditions. In sum, critical to this approach is tracking water "parcels" as they pass through elevation bands, accumulating contributions from sources with differing temperatures, experiencing variable meteorological conditions largely in response to elevation change, all while the river is increasing in volume and thus increasing its thermal inertia.

Results and Discussion

The Mokelumne watershed was chosen to test the temperature model. The model logic was developed in Visual Basic and implemented in and Excel spreadsheet. While reasonable parameter estimates were made, the model uncalibrated at this time. Nonetheless, the tool is useful for general comparative analysis for climate change scenarios. Three runs were considered with the temperature model: (1) a base case using historic data, (2) a two degree rise in air temperature rise (+2C), and (3) a four degree rise in air temperature (+4C). The test basin for these simulations was the Mokelumne River Watershed in the central Sierra Nevada.

RTEMP results are presented for two bands (3,000m and 1,500 m) in sub-watershed12 of the Mokelumne River basin. The 3,000m band is a headwater band and the 1,500m band is the outlet for the sub-watershed. Two longitudinal temperature profiles were constructed for the sub-watershed: one representing winter conditions (week 4, January, 1990), and one representing summer conditions (week 32, late July and early August, 1990).

Both temperature profiles include the base case water temperature as well as deviations from the base case (2^{nd} y-axis) for the two climate change scenarios (+2C and +4C). For both winter (Figure) and summer (Figure), both profiles heat in the downstream direction with decreasing elevation. The winter profile indicates that under a +2C condition, headwater conditions are slightly warmer than baseline, and then for lower elevations temperature increases are fairly uniform,. For the +4C case, headwater conditions are considerably warmer, suggesting considerable loss of snowpack and a shift to precipitation as rainfall, and downstream temperatures are uniformly higher and approximately twice that of the +2C case. Simulated summer conditions suggest a disproportionate increase at higher elevations, but overall warmer conditions throughout the lower elevations as well.

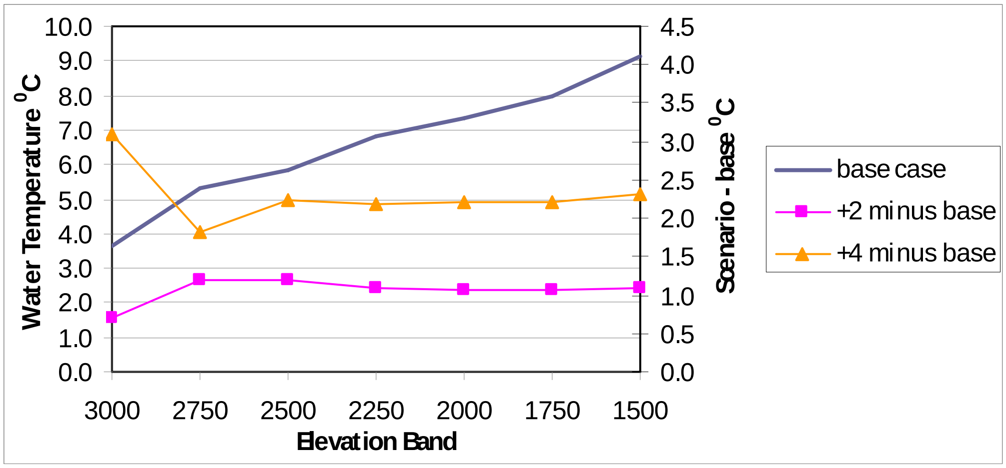

Figure 2. Longitudinal profile of base case and deviations from base case for the +2C and +4C cases during week 4 (January) in 1990

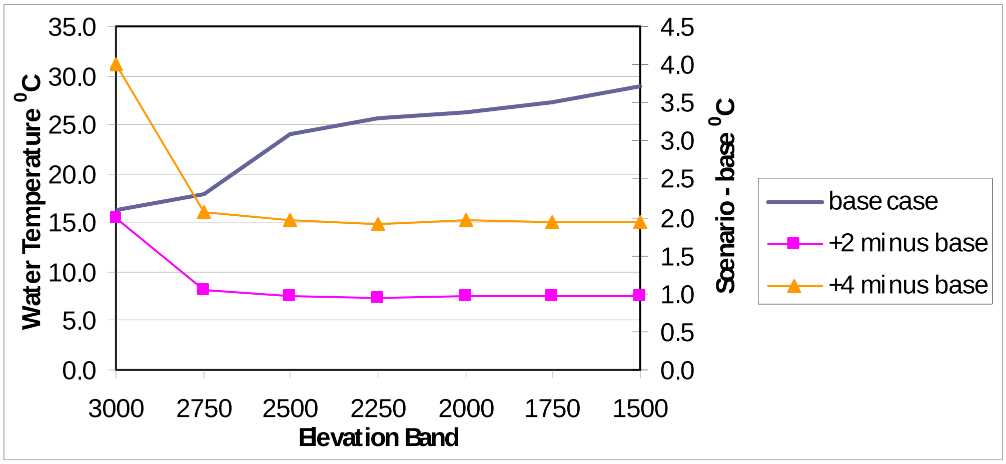

Figure 3. Longitudinal profile of base case and deviations from base case for the +2C and +4C cases during week 31 (July/August) in 1990

Time series plots were constructed showing the variation of water temperatures and other time varying results for the highest band 3,000m and the lowest band 1,500m. Resulting temperatures and the differences between base case and +2C and +4C cases are shown in Figure and Figure , respectively. Snowmelt runoff at the 3,000 m band clearly diminishes with increased climate heating (Figure), and is absent in both climate change scenarios at the 1,500 m band (Figure), suggesting domination by rainfall versus snowfall under the modeled assumption.

Examining results at the 3,000 m band under the base, +2C, and +4C conditions (Figure) suggests that the +2C case during winter months does not deviate considerably from base conditions. However, during summer months there is a notable positive excursion in water temperatures. The +4C case indicates considerable change in winter and summer. Although the snowmelt runoff is notably diminished in this case, the available snowmelt runoff nonetheless moderates conditions in spring when changes from baseline are at a minimum (in the vicinity of week 14). The sharp rise in temperature difference for the +4C scenario during winter is attributed to the increased groundwater flow from more precipitation in the form of rain. This groundwater flow under the +4C condition (see weeks 1-10 in Figure) results in appreciably different flow temperature contributions than would exist under a snow pack condition. Other graphs illustrating changes in runoff and temperature are included in the appendix.

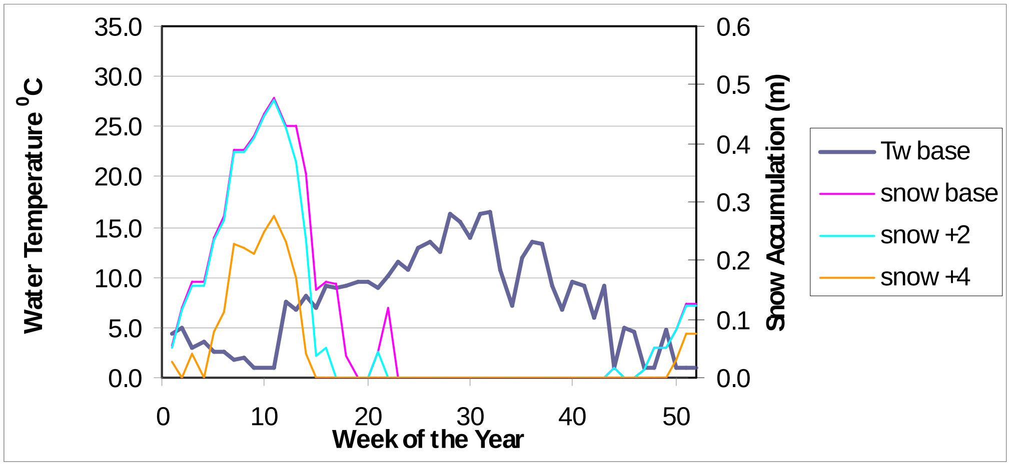

Figure 4. Time series of water temperature and snow melt flow for base, +2C, and +4C at band 3,000m

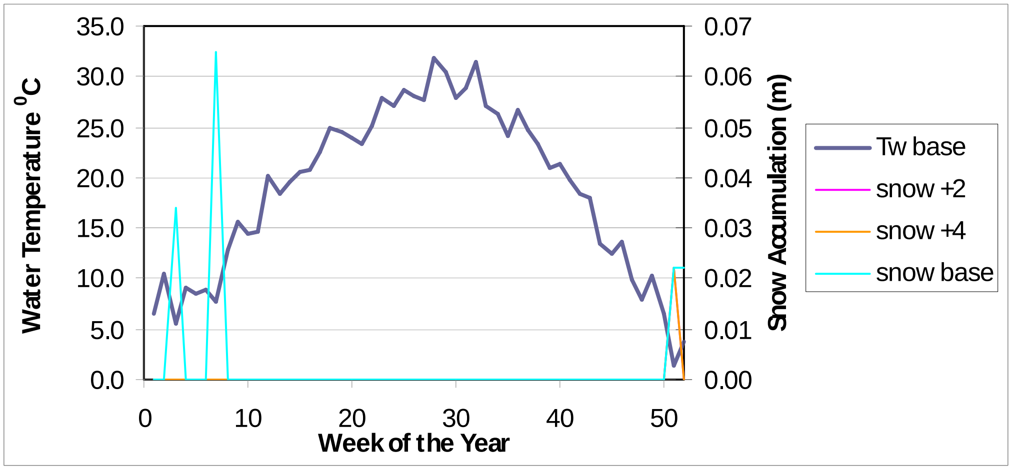

Figure 5. Time series of water temperature and snow melt flow for base, +2C, and +4C at band 1,500m

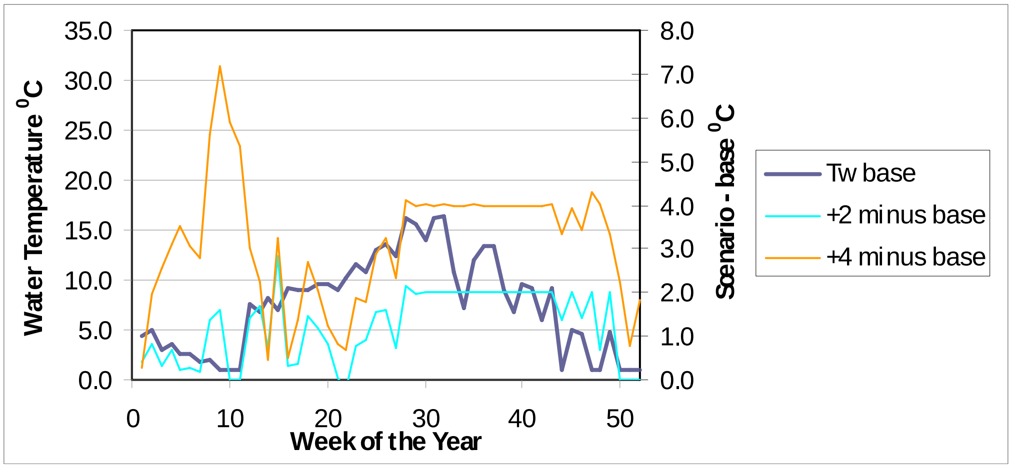

Figure 6. Time series of water temperature for the base case, and deviations from base case for the +2C and +4C cases at the 3,000m band

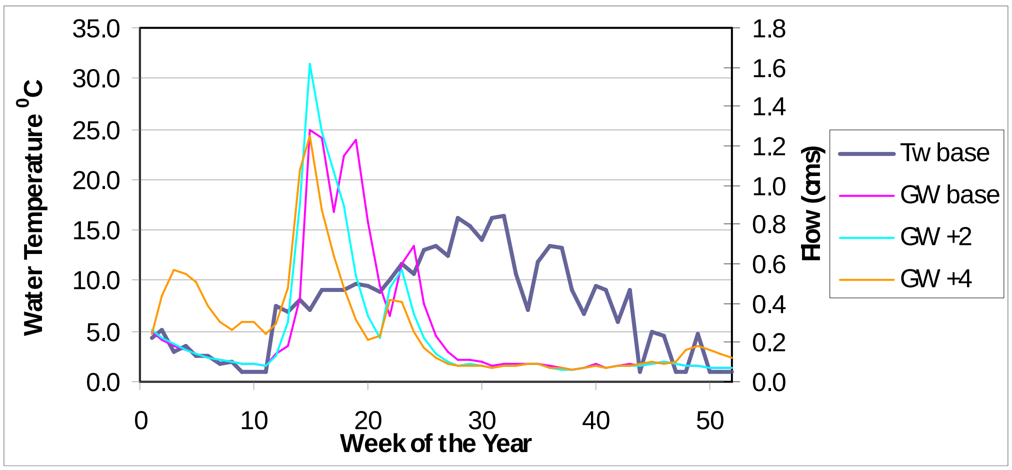

Figure 7. Time series of water temperature for the base case, and groundwater flow for the base, +2C, and +4C cases at the 3,000m band

Limitations

All models include assumptions and estimates that may limit the ability to predict physical processes. Further, one of the most important limitations is associated with data. Outlined herein are some of the more readily identifiable model limitations.

Meteorological Data

Data required to drive RTEMP includes meteorological data (air temperature, wet bulb temperature (or dew point temperature), solar radiation, cloud cover, wind speed, and barometric pressure). Historic records or calculated values for solar radiation, air temperature, and humidity/vapor pressure are available from DayMet. Challenged in meteorological data acquisition and estimation include cloud cover and wind. In future phases of work some potential data sources to fill data gaps include National weather service, Desert research Institute, Daymet, Federal resource agencies such as NPS, USFS, NRCS etc. Ideally, all the required meteorological data will be processed from different geographic locations and provided in a form similar to how air temperature is currently output from WEAP, i.e. DayMet type grid or similar format.

Water Temperature Data

Water temperature data is currently the primary limiting factor. Some data have been acquired and data sources have been identified. For a Sierra Nevada scale application, data from multiple basins are desired to calibrate the model to site-specific conditions.

Channel Length and Stream Order

Channel lengths were derived in a GIS process and were summarized based on stream order. The first order streams were given a minimum watershed area which resulted in some elevation bands containing no stream lengths yet flow was produced from WEAP. Future work could include the development of a band area and stream length relationship similar to that described by Leopold et al (1995). The relationship is in a power function form of $L = aA^b$ where known headwater band areas (represented by A) and stream lengths (L) are used. For this proof of concept version of RTEMP, an average stream length from all headwater bands was used.

Other study aspects associated with stream length and order which may be re-evaluated include the grouping of different order of stream for different flow type i.e. inter- and intra-band flows. The use average or total length of stream order in developing representative channels may be explored to determine an appropriate approximation.

Stream Velocity and Depth

Velocity is necessary in order to estimate a residence time for water being exposed to meteorological conditions as it moves through a band. Currently a constant value of 0.5 m/s was applied. Estimates for velocity can be made from gage rating data that would be in a power function form. Similarly, depth estimates are required to calculate the dynamic equilibrium temperature approach employed in RTEMP. Like velocity, a power function could be developed relating stage to flow using observed gage data. These refinements would be undertaken in a future phase of the project.

Snow Line Determination

Tracking the snowline is a critical attribute of both WEAP and RTEMP. In each band, there are three possible physical conditions for snow pack:

1. Complete coverage
2. Partial coverage
3. No coverage

Currently the model treats the band as either in condition 1 or 3. However, the physical condition may, for at least short periods of time, be best represented by condition 2 where the bands contain a patch work of snow cover. While determining the spatial distribution of snow pack is beyond the scope of this model, there may be an opportunity identify and track a snow line in the general context of elevation or percent coverage assuming the snow pack is evenly distributed with respect to elevation. The challenge for condition 2 is determining how the snow melt water will react in terms of temperature rise as it travels to the outlet of the band, i.e., a "time of concentration."

Automation

Currently tracking watershed and elevation band connectivity is a manual process. Automating the process of proper water flow connectivity remains a significant challenge and limits the application of the model to a large spatial domain, i.e., the entire Sierra Nevada. This will require advanced programming skills along with a working knowledge of hydrology. Developing this program logic would be accomplished in a future phase of the project.

Other

This model was developed in Excel with Visual Basic for applications, and can readily be ported to another platform. Integration of RTEMP with other global Sierra Nevada model elements is key to effective application of the model over large spatial domains. Determining where this temperature model will physically integrate e.g. as an ArcGIS macro or stand-alone program, will be evaluated early in any future phases of the project.

Refinement of the computational portion of the code can be explored as well to ensure numerical stability over a wide range of conditions. For example, a dynamic (on-the-fly) reduction of the time step of the Runge-Kutta approximation may be a useful attribute to include in a future version.

Conclusions

The conceptualization and construction of RTEMP demonstrates an equilibrium based temperature modeling approach to represent thermal conditions over large spatial regions and temporal periods. Further, given the size of the modeling domain and extended simulation periods, model output is produced at relatively fine time and space scales – weekly output at 250 meter elevation intervals. The application shows great promise in this initial representation of the Mokelumne River basin in the central Sierra Nevada. A baseline case, as well as two climate change scenarios with different levels of heating were simulated and compared. While the model is uncalibrated, the results are still useful for comparative analysis. The underlying assumptions did not change between simulations and the forcing data that were modified were within reasonably expected ranges of variation, i.e., plus 2^{o}C and 4^{o}C rise in air temperatures. Further, results were generally considered consistent with expectations on the impacts of changes in water temperatures. The lower elevation band of 1500m is considered to be producing temperatures that are slightly warmer than expected, but model refinement and calibration in future phases should allow for improved simulation results.

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Appendix

The charts in this appendix show the base case water temperature time series for the upper most (3,000m) and lowest (1,500m) elevation bands for sub-watershed 12 in the Mokelumne River watershed. The flows represented in these charts are intra-band flow components only i.e. flow generated from within the respective elevations bands.

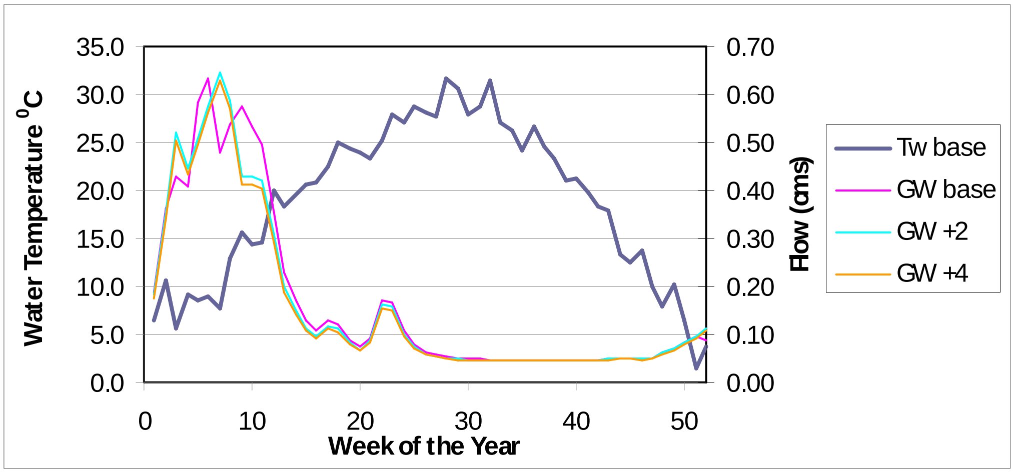

Figure A1. 1,500 m band base case water temperature and groundwater flow for base case and plus 2 and plus 4 scenarios. Note: 3,000m shown in body of report

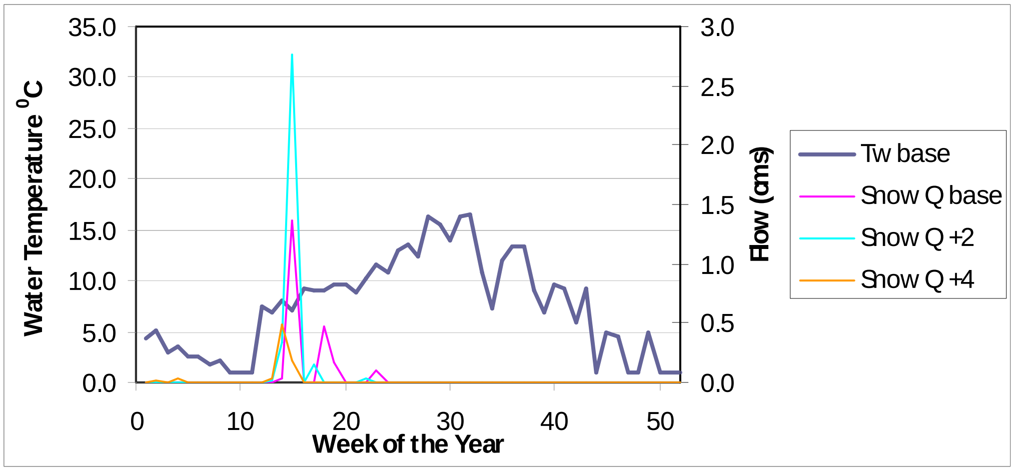

Figure A2. 3,000 m band base case water temperature and snow melt flow for base case and plus 2 and plus 4 scenarios.

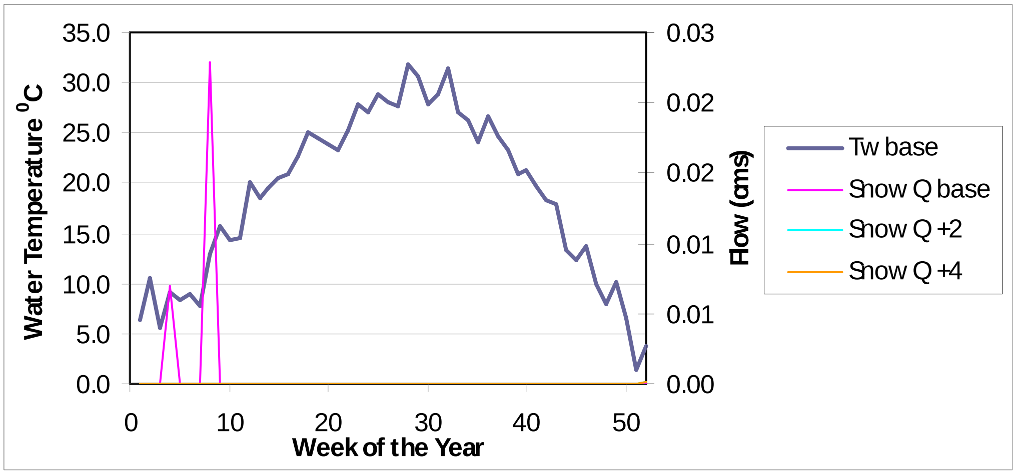

Figure A3. 1,500 m band base case water temperature and snow melt flow for base case and plus 2 and plus 4 scenarios.

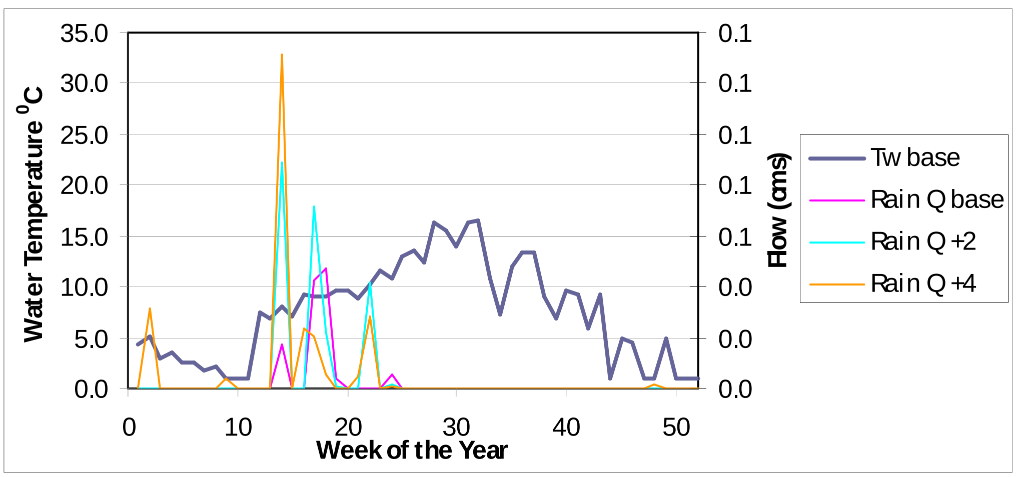

Figure A4. 3,000 m band base case water temperature and rain fall flow for base case and plus 2 and plus 4 scenarios.

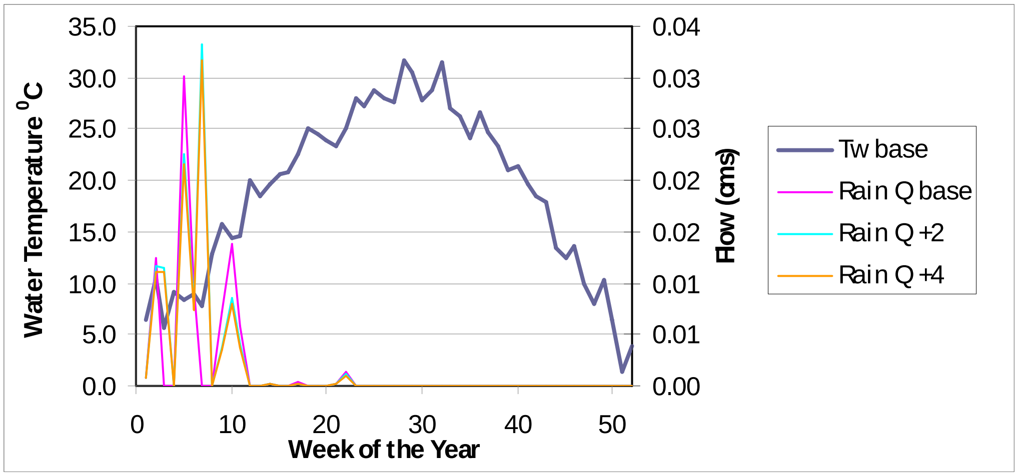

Figure A5. 1,500 m band base case water temperature and rain fall flow for base case and plus 2 and plus 4 scenarios.

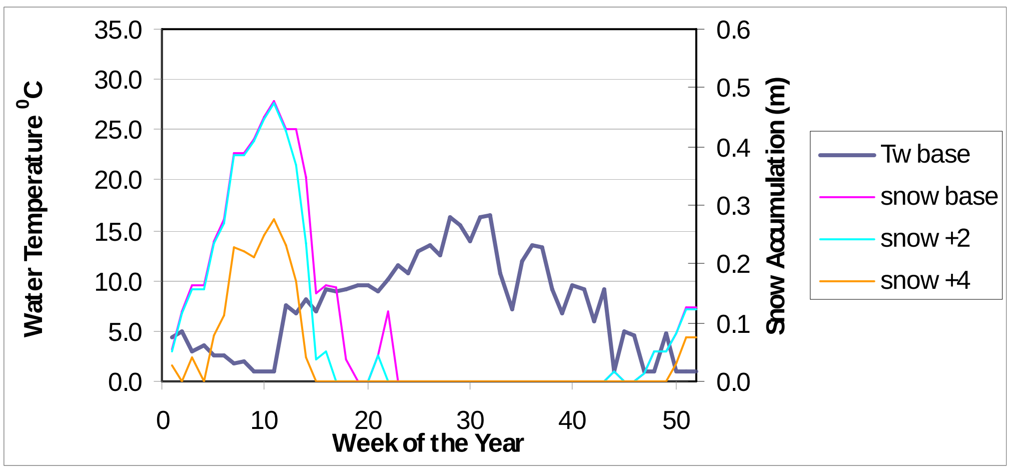

Figure A6. 3,000 m band base case water temperature and snow accumulation for base case and plus 2 and plus 4 scenarios.

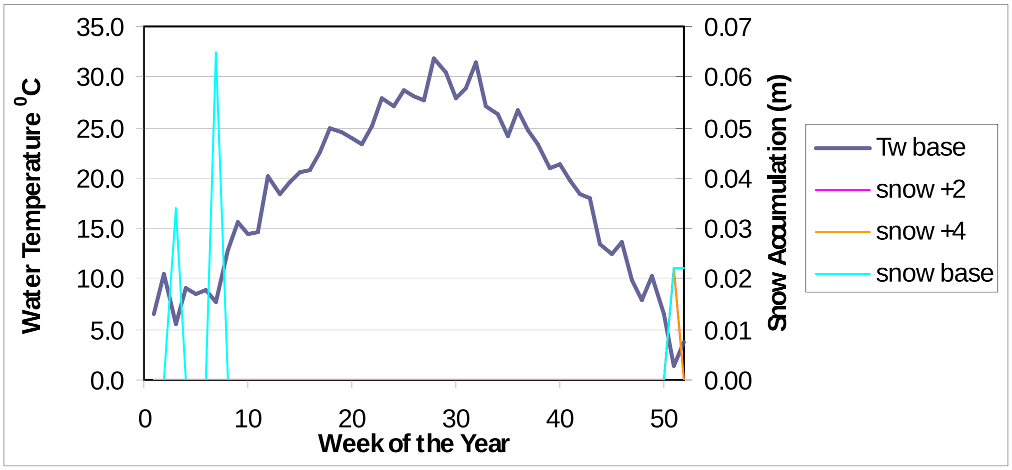

Figure A7. 1,500 m band base case water temperature and snow accumulation for base case and plus 2 and plus 4 scenarios.

ALTERATION AND SUSCEPTIBILITY OF STREAM PHYSICAL HABITAT TO CLIMATE CHANGE

PROJECT REPORT

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Abstract

Stream physical habitat where aquatic organisms perform ecological functions results from interactions among hydrologic, hydraulic, and geomorphic processes. Climate change affects hydrologic patterns that control hydraulics, geomorphology, and temperature conditions of the physical habitat. This report defines a series of hydrologic and temperature indicators derived from hydrologic and temperature models outputs to assess the effect of climate change on physical habitat. This report also proposes a simple approach to assess geomorphic impact by estimating the work performed on channels by diverse hydrologic patterns resulting from climate change scenarios. The conceptual framework proposed to assess alteration and susceptibility is based on comparing indicators from model outputs of different climate change scenarios to indicators from a reference scenario. A series of hypothesis to test alteration and susceptibly are suggested from the expected outcomes of applying the proposed conceptual framework. Finally, this report outlines future work first to incorporate indicators estimates and alteration and susceptibility results into GIS and statistical models, second to consider adaptation and vulnerability estimates, and third to calculate additional indicators from climate change hydrologic, temperature, and geomorphic models outputs for a more in depth study of the effects of climate change on stream physical habitat.

Keywords: stream physical habitat, climate change, hydrologic indicators, temperature indicators, geomorphic indicators, alteration of physical habitat, susceptibility of physical habitat.

Introduction

River ecosystem health depends on the condition of the physical habitat, defined as zones with characteristic physical attributes where organisms perform their ecological functions (Knighton 1998, Marcot and Heyden 2001, Moyle and Cech 2004). Physical habitat results from the interactions among hydrologic, hydraulic, and geomorphic processes (Poff et al. 1997, Brierley and Fryirs 2000, Wheaton 2003). Climate determines watershed hydrologic patterns, which, in turn, control hydraulics and geomorphology at geomorphic unit and reach scales (1-10 channel widths and > 100 channel widths, respectively). Hydrologic patterns are particularly susceptible to changes in atmospheric temperature (Stewart et al. 2005, Maurer 2007). In the western United States, data records show that increases in temperature increase the amount of precipitation falling as rain and cause an earlier onset of the snowmelt season (Maurer et al. 2007). Such changes in hydrologic patterns are expected to affect physical habitat by modifying flow regime, sediment inputs, and water temperature (Montgomery and Buffington 1997, Poff et al. 1997, Deas and Lowney 2000, Richards et al. 2002).

A key question is how to assess the alteration and susceptibility of physical habitat to climate change. Climate change scenarios of increased temperature can be incorporated into hydrologic and temperature models to produce outputs of hydrologic variables and temperature at different locations within a watershed (Strzepek et al. 1999, Deas and Lowney 2000, Yates et al. 2005). The effect of hydrologic alteration on geomorphic processes can be assessed using geomorphic models (Grant et al. 2003, Parker et al. 2003). Each model provides insight into understanding individual processes but they do not provide an integrated view of the multiple effects of climate change on physical habitats. The overall objective of this study is to develop a robust algorithm to assess the alteration and vulnerability of the physical habitat in river systems under predicted climate change conditions. The algorithm will be incorporated into a GIS environment to visualize the spatial distribution of physical habitat vulnerability, allowing the identification of the watersheds that are most vulnerable to the cascading effects of climate change on temperature, hydrology, geomorphology, and physical habitat. Output maps could be useful in the FERC relicensing processes by highlighting watersheds particularly susceptible to climate change.

This report presents a conceptual model for assembling physical habitat processes into a framework to assess overall physical integrity at any point along the mainstem of a river. First, the report defines hydrologic and temperature indicators to be obtained from hydrologic and temperature models outputs. Next, the report presents a geomorphic conceptual model of physical response to hydrologic forcing, and similarly defines geomorphic indicators. Then the report defines define metrics for assessment of the alteration of these indicators and the consequent susceptibility of the physical habitat as a whole, and confer hypothesis of expected results. Finally the report outlines the future course of this project by presenting the procedure to incorporate the indicators into the GIS environment, outlining a statistical model for physical and biological indicators correlations, describing graphical outputs, and proposing additional indicators of physical habitat assessment. The scheme presented in this report constitutes a tool to incorporate simple metrics within the GIS environment to visualize patterns of physical habitat alteration and susceptibility to climate change.

Objectives and Research Questions

The purpose of this study is to create a conceptual framework to assess the impact of climate change-induced hydrologic alteration on in-stream physical habitat and that can be used as a tool to prioritize investments in conservation activities. Specific research questions are: 1) what is the magnitude of physical habitat alteration and susceptibility under climate change scenarios, and 2) what is the potential for human adaptation to reduce the physical habitat vulnerability? In order to address the research questions, specific objectives of this report are to:

1. Identify indicators that represent relevant hydrologic and temperature processes and that are computable from hydrologic and temperature model outputs.
2. Propose a geomorphic model and indicators computable from the GIS database.
3. Propose a conceptual model and analytical model to assess physical habitat alteration and susceptibility of hydrology, temperature, and geomorphology for all the scenarios considered within the GIS environment.
4. Describe the procedure to calculate alteration and susceptibility along river lines and to produce maps of alteration and susceptibility for all the scenarios.

Individual Models and Scenarios

The upper Mokelumne River was selected as a test site to apply the models to assess climate change alteration. Models will be first applied, tested, and calibrated at this site, then applied to other watersheds in the Sierra Nevada. A set of models to characterize relevant physical elements and ecological aspects were used to assess functional integrity of the river system (Fig. 1) for a series of climate change scenarios. Scenario 0 (s_0) corresponds to the no dam condition; scenarios 0+2,4,6 ($s_{0+2,4,6}$) represent three alternatives that correspond to the no dam condition with temperature increases of 2,4 and 6 degrees Celsius (°C); scenario t (s_t) corresponds to the current conditions with dams for the record of water years 1984-2001, which represent a wide range of variability with very dry and very wet years; and scenarios t+2,4,6 ($s_{t+2,4,6}$) represent three alternatives that correspond to the current conditions with dams and the added effect of temperature increases of 2,4 and 6 °C.

At the end of Phase I of the project, hydrologic and temperature model outputs for s_0 and $s_{0+2,4,6}$ and ecologic model outputs for s_t were obtained (Table 1). The outputs of the hydraulic and temperature model are weekly average discharge values for a 17-year period. In addition, a GIS database including DEM, roads, dams, powerhouses, lakes, flow gauges, manmade hydraulic structures, vegetation, soils, and geology was assembled. Indices of biological integrity (IBIs) were developed for two specific groups of organisms, invertebrates and fish assemblages, and were incorporated into the GIS database. During Phase II of the project, the concepts presented in this report will be implemented, including the calculation of hydrologic, temperature, and geomorphic indicators that are relevant for the functional integrity of the system and the calculation of alteration, susceptibility, and vulnerability for hypothesis testing. Such results will be incorporated into the GIS and statistical models to obtain graphical outputs depicting zones with high, mid, and low susceptibility of the physical habitat to climate change (Fig. 1).

Physical Habitat Indicators

Climate conditions determine the quantity of water falling within a given watershed as rain and snow as well as the temperature of water bodies. In turn, watershed hydrologic processes determine the amount of rainfall turned into streamflow (Poff et al. 1997, Richter et al. 1997). Geomorphic processes at the basin scale such as landsliding, gullying, and sheetwash erode sediment off the land and into streams. In addition, bank and bed erosion contribute sediment to downstream reaches (Knighton 1998). These sources provide the river's sediment supply. The varied spectrum of streamflow transport and sediment supply capacities working in specific geological settings create a wide variety of channel and floodplain shapes (Rosgen 1994, Montgomery and Buffington 1997).

The dynamism of watershed processes cause hydrogeomorphic disturbances that act at different spatial and temporal scales (Table 2). Natural disturbances include floods, tributary confluences, mass wasting, and earthquakes; anthropogenic disturbances include watershed land use, engineered river projects, and climate change (Poff et al. 1997, Benda et al. 2004b, Petts and Gurnell 2005). Natural and anthropogenic disturbances have the capacity to create, rejuvenate, or destroy physical habitats (Petts 1984, Pasternack et al. 2004, Gregory 2006). Effects of climate change alterations superimpose with effects of other disturbances. For example, larger amounts of water falling as rain may create larger floods in the winter, may increase erosion and sediment inputs exaggerating the effect on local hydraulics caused by tributary confluences, and may increase the probability of mass wasting (Benda et al. 2004a, McBain & Trush 2006).

The combination of hydraulic conditions, sediment transport processes, morphological features, disturbances effects, and water temperature provide multiple physical habitat units that are used by organisms in different ways throughout their lifestages (Brierley and Fryirs 2000, Thorp et al. 2006). To assess how watershed processes affect physical habitat, a set of indicators derived from model outputs can be formulated. Such indicators will provide information about the status of individual elements of the physical habitat. The proposed indicators will vary along the river course, depending on upstream and local conditions (Fig. 2). Comparisons of indicator values among scenarios according to the framework proposed in Section 6 constitute measures of physical habitat alteration (See Section 6, Alteration and Susceptibility Model).

Hydrologic Indicators

Hydrologic variation over time yields a flow regime, defined as flow magnitude, frequency of occurrence of high and low flows, flow duration, flow timing, and rate of change between flow magnitudes (Poff et al. 1997). A river's flow regime is a primary control of physical habitat conditions, determining hydraulics, temperature, and sediment transport processes, and is the driving force of riverine ecosystems (Richter et al. 1997). Hydrologic alteration can be analyzed from a selection of indicators calculated from statistical measures of streamflow time series. A selection of indicators used in climate change and hydrograph management studies are proposed (Stewart et al. 2005, McBain & Trush 2006, Maurer et al. 2007):

The timing of the center of mass of the annual flow (CT)

$$CT = \frac{\sum(tiqi)}{\sum qi}$$

where ti is time in weeks (or months) from the beginning of the water year (October 1), and qi is the corresponding streamflow for the week i (or month i)

The fractional snowmelt season flow (FS)

$$FS = \frac{\sum qAMJJ}{\sum qi}$$

where qAMJJ is the streamflow that occurs between April and July.

Date of beginning of the spring or early summer snowmelt streamflow ("spring pulse onset") (St_o)

Date of peak spring snowmelt (St_{max})

Magnitude of highest snowmelt flow (QS_{max})

Duration of full snowmelt (DS)

$$DS = St_e - St_o$$

where St_e is the date of the end of the snowmelt

Duration of snowmelt recession limb (DS_r)

$$DS_r = St_e - St_{\max}$$

Slope of snowmelt hydrograph

$$SH = \frac{QS_{\max}}{DS}$$

Temperature Indicators

Temperature affects survival, growth rates, distribution, and developmental rates of organisms. It also influences disease incidence, predation, and long-term survival (Myrick and Cech). Threshold values for specific lifestages and species are summarized in Table 3. The temperature indicator proposed is the fraction of time that temperature values are within the specified ranges for each species:

$$FT = \frac{\sum t_{Trange}}{\sum t}$$

where the numerator is the summation of t_{Trange} or the number of weeks when temperature is within the optimal range for each lifestage timing, and the denominator is number of weeks in which the lifestage takes place in a year or period being analyzed (Fig.3).

Geomorphic Model and Indicators

To quantify the geomorphic response as a measure of physical habitat integrity this report proposes a simple approach to identify a streamflow threshold above which geomorphic work is done. Then we propose calculating the amount of work performed in the watershed by streamflow values larger than the threshold within a time period.

Two year return flood

The two year return flood (Q_2) is the streamflow magnitude that has about 50% probability of occurring in any given year. In California, the two year return flood is approximately equal to bankfull stage which is the water level above which the flow exceeds the channel capacity right before inundating the floodplain (Lisle et al. 2000). Bankfull flows produce enough momentum within the channel to cause sediment entrainment (Buffington and Montgomery 1997). Consequently, Q_2 provides a threshold to estimate geomorphically significant flows.

For a given time series of flow for a number of years, Q_2 can be obtained by calculating the recurrence interval (RI).

$$RI = \frac{N+1}{M}$$

where N is the number of years for which records exist, and M is the rank of the individual year whose RI is being calculated. RI is then calculated for each N to produce graphs and power correlations of Q *vs.* RI, from which Q_2 can be obtained. Since the hydrologic model will produce a flow time series for several years for each of the scenarios, Q_2 can be calculated for each scenario. Comparison of Q_2 values among scenarios is a first cut measure of geomorphic alteration.

Streampower

Streampower is an expression of the rate of potential energy expenditure per unit length of channel (Ω) (Knighton 1998).

$$\Omega = \gamma QS$$

where γ (=ρg) is the specific weight of water, Q is discharge, and s is slope. The units for Ω are Watts per meter length of channel (W/m). Streampower values above the hydrogeomorphic threshold Q_2 indicate the rate of work performed by the water on the channel surface. An indicator of the amount of geomorphic work for a period of time can be defined as the summation of streampower above Q_2,

$$\Omega year = \sum \Omega_{>Q2}$$

where Ωyear is the amount of streampower for a given year, and $\Omega_{>Q2}$ is the streampower value for discharge greater than Q_2. Ωyear will provide a first cut approximation of the amount of work done by the river system in a water year that can be compared to other water years within the same scenario and among other scenarios.

Alteration and Susceptibility Model

The model for alteration, susceptibility, and vulnerability is based on comparing hydrologic, temperature, and geomorphic indicators for each scenario to indicators calculated at the reference scenario (see summary of indicators in Table 4).

Alteration

Physical habitat alteration is defined as the ratio between the magnitudes of an indicator for any given scenario relative to the indicator for the reference scenario (s_0). This metric of the change in conditions indicates the proportion higher or lower of the present attribute with respect to the reference scenario as represented in the following Eq.

$$A_t = \frac{I_0, or, I_{0+2,4,6}, or, I_t, or I_{t+2,4,6}}{I_0}$$

where A_t is the alteration at any time, and I is any indicator representing physical habitat integrity for all the modeled scenarios. The definition of At can be applied to the set of indicators selected. If $I_t = I_0$, then $A_t = 1$ indicating no alteration; if $I_t > I_0$ or, $I_t < I_0$ then $A_t \neq 1$, indicating alteration (Fig. 4).

Susceptibility

Physical habitat susceptibility is defined as the lack of resistance of the system to endure alteration. A simple measure of susceptibility is the deviation of a given scenario (i.e. A_t) from the alteration of the reference scenario, which is 1 (i.e. $A_0 = I_0/I_0 = 1$), expressed as

$$S = A_t - A_0$$

where S is susceptibility. The definition of S can be applied to all the selected indicators, for all the scenarios, and for any point of the river lines within the GIS database. The spatial distribution of S can be fitted to a normal distribution to identify the mean ($\overline{S}$) and the standard deviation (σ) in order to classify sites according to their susceptibility. For instance, low susceptibility will be given to sites with S< $\overline{S} - \sigma$ and will be represented by green, intermediate susceptibility will be given to sites with $\overline{S} - \sigma < S < \overline{S} + \sigma$ and will be represented by yellow, and high susceptibility will be given to sites with S > $\overline{S} + \sigma > \overline{S + \sigma}$ and will be represented by red (Fig. 5).

Hypotheses

Hypotheses to be tested with the present framework are formulated based on expected outcomes.

Hydrologic indicators hypothesis

Climate change scenarios with higher temperature increase will present higher susceptibility to hydrologic parameters CT, FS, Sto, Stmax, Qsmax, DS, Dsr, and SH change.

Geomorphic indicators hypotheses

Climate change scenarios with greater temperature increases will present greater susceptibility to Q_2 change.

Climate change scenarios with greater temperature increases will present greater susceptibility to streampower change.

Spatial distribution hypotheses

Indicators from physical habitat units occurring midway between the dams and the low meandering valley will present greater susceptibility for any given climate change scenario.

Sections of the river with moderate high flows coinciding with fine sediment inputs into the stream that fill the interstitial space within larger particles, thus blocking the flow of oxygenated water, will present high susceptibility to climate change.

Temperature – hydrology hypotheses

Sites that present the lowest flows and the highest temperatures will present greater su

Lifestages specific hypothesis

Sites with the largest streampower values that scour the river bed will show the greatest susceptibility for lifestages that interact with or occupy the river bed, such as spawning and incubation.

Future Work

In this section we outline future work related to the incorporation of results into GIS models and the correlation of physical habitat indicators to biological indicators. We also propose additional hydrologic, temperature, and geomorphic indicators representing a higher level of detail that can be calculated from model outputs and that may provide additional information about the status of the physical habitat as function of climate change.

GIS and Statistical Models

Physical habitat indicator calculations from hydrologic and temperature models will be incorporated into a spatial database. Alteration and susceptibility will be calculated within the GIS environment according to the analytical procedure proposed in this report to visualize their spatial distribution (Fig. 1). Most altered and susceptible sections of the watershed for each scenario and each indicator will be classified using log or normal distributions and standard deviation statistical calculations. High, medium, and low alteration and susceptibility will be colored red, yellow, and green, respectively. A statistical procedure will be used to incorporate all the indicators into a unique metric (i.e. geometric mean) for each physical habitat component (hydrology, temperature, geomorphology) (Fig.6).

IBI values will be superimposed on the GIS model to identify ranges of values of each indicator that correlate to high IBI values. Statistical models, such as principal component calculations, will be used to identify physical habitats attributes that are more correlated to high IBIs (Fig. 1). Maps of susceptibility for the selected attributes colored green, yellow, and red will point out zones with the highest vulnerability to climate change and that are most significant for target species. Attention will be focused on the alteration and susceptibility of the physical habitat attributes identified in order to analyze in detail its spatial distribution and to help identify mitigation options to reduce susceptibility.

Adaptation and Vulnerability Estimates

Physical habitat vulnerability is defined as the capacity of the system to be distressed by climate change scenarios. In systems where dam operations can be modified to control hydrology, human adaptability can help achieve specific needs. Consequently, vulnerability is a function of physical habitat susceptibility and human adaptability. In addition, organisms present modes of biological adaptation to flow regime alteration (Lytle and Poff 2004). Conceptual and analytical models to estimate adaptability need to be explored in Phase II of the project.

Detailed Hydrologic and Temperature Indicators

In addition to the coarse indicators proposed for a first cut approximation of physical habitat characterization, detailed indicators can be defined for a more detailed assessment. Indicators are based on their relevance to biotic integrity. Invertebrates and fish assemblages require different physical habitat conditions. Consequently, specific definitions of the proposed parameters may need to be determined for the two groups. In addition, indicators need to be defined at different scales since the size of physical habitat units for invertebrates is microhabitat (<1 channel width), while for fish is geomorphic unit and reach scale (1-10 channel widths, > 100 channel widths respectively).

In order to assess the importance of hydrologic processes, additional non-redundant hydrologic indices that bear biological relevance and represent processes that induce geomorphic change can be formulated (Olden and Poff 2003). The selection of detailed hydrologic indicators represents flow regime attributes.

The hydrologic model outputs from Phase I have units of average weekly flow data. Weekly average data normalizes extreme values (i.e. snowmelt peak flows) but provides an approximate estimate of the trends in flow and temperature magnitude (Fig. 7). We propose the following set of indicators, which will be calculated from the hydrologic model output (Table 5):

- Magnitude of maximum weekly rainy season and maximum snowmelt season flows
- Minimum weekly summer flows

Timing of rainy season and snowmelt maximum, and timing of minimum summer flows

Rate of change between weekly flows

Magnitude of weekly flows in months preceding breeding seasons

Interannual variation of all the above indicators

Since temperature model outputs are weekly average values, a set of indicators that captures the effects of temperature on physical habitat and that is parallel to the flow regime indicators is proposed (Table 5):

Magnitude of minimum weekly rainy season and minimum snowmelt season temperature

Maximum weekly summer temperature

Timing of rainy season and snowmelt minimum, and timing of maximum summer temperature

Rate of change between weekly temperatures

Magnitude of weekly temperature in months preceding breeding seasons

Interannual variation of all the above indicators

Detailed Geomorphic Indicators

Geomorphic conceptual and analytical models are tools to examine watershed processes. Geomorphic indicators available from GIS data at any point in a river include slope, hillslope, tributaries presence and magnitude of watersheds, elevation, watershed area, and watershed geology and soil erodibility (Table 6 and Fig.8). Other geomorphic indicators such as channel type, grain size distribution, and sediment inputs are not available directly but can be estimated from GIS databases through analytical procedures with appropriate assumptions (Table 7). Next we outline some approaches to obtaining geomorphic information from DEMs and hydrologic models to identify physical habitat attributes. In addition to indicators representing geomorphic controls, natural and anthropogenic disturbances affecting flow regime and sediment inputs can be identified within a GIS environment. The degree of influence of geomorphic controls and disturbances varies depending on the position of the watershed and the magnitude of the disturbance events. We propose a set of approaches to estimate detailed geomorphic information using spatial information available from the GIS database.

Stream type classification

Channel reach morphology in mountain drainage basins has been categorized in several classification systems (Rosgen 1994, Montgomery and Buffington 1997, Brierley and Fryirs 2000). The Montgomery and Buffington (1997) classification system identifies seven channel types: cascade, step-pool, plane-bed, pool-riffle, dune-ripple, colluvial, and bed rock channels (Montgomery and Buffington 1997). The first five alluvial channel types have specific morphology and grain size distribution and present ranges of slopes with non-overlapping central tendencies (Buffington et al. 2004). Slope ranges of upper- and mid-altitude channels are: <1.5% for pool-riffle channels, >1.5%-3% for plane-bed channels, >3%-7.5% for step-pool channels and 7.5% for cascade channels. Slope can be used to develop a first cut classification of stream types associated with specific habitats. In addition to the classification of alluvial channels based on slope data, geologic databases can be used to identify bed rock sections of the channel.

Grain size prediction

Buffington et al (2004) proposed an approach to obtain grain size estimations using GIS based data. The median grain size (D_{50}) that can be mobilized by a discharge that produces a critical shear stress can be estimated from the Shields equation

$$\tau_{c50}* = \frac{\tau_{c50}}{g(\rho_s - \rho)D_{50}}, \text{ then}$$

$$D_{50} = \frac{\tau_{c50}}{g(\rho_s - \rho)\tau_{c50}*} = \frac{\rho hS}{(\rho_s - \rho)\tau_{c50*}}$$

where $\tau_{c50}*$ is the critical Shields stress for movement of D_{50}, τ_{c50} is the threshold shear stress for significant sediment transport defined as the stage for D_{50} entrainment from the depth-slope product (ρghS), and ρs and ρ are sediment and fluid densities, respectively.

Bankfull depth is a common approximation for critical discharge stage for significant sediment transport, and it can be expressed as a power function of drainage area:

$$h = \alpha A^{\beta}$$

where A is drainage area, and α and β are empirical values that represent geology, topography, climate, basin hydrology, and sediment supply. Approximations of this function for the Sierra Nevada can be obtained with correlations between area obtained from DEMs and discharge obtained from the hydrologic model. Bankfull shear stress can be expressed as a function of mean bankfull shear stress:

$$\tau_{bf}* = k\tau^n = k(\rho ghS)^n$$

where k and n are empirical coefficients that vary with channel type and can be obtained from the literature (Buffington et al. 2004).

Rearranging the previous equations, a new formula is obtained

$$D_{50} = \frac{(\rho\alpha A^{\beta} S)^{1-n}}{(\rho_s - \rho)kg^n}$$

which indicates that for given values of α, β, n, and k, surface grain size can be predicted as a function of drainage area and slope, which are readily available from GIS DEMs.

Sediment budget

Sediment budgets are mass balance calculations of input, output, and storage within a river system (Trush et al. 2000). Sediment inputs vary as function of watershed position, tributary confluences, channel characteristics, and road density, among other parameters Within a DEM environment, soil erosion is commonly estimated by the universal soil loss equation (USLE) and sediment supply is modeled using lumped sediment delivery ratios (SDR) (Verstraeten 2006). Several models are available in the literature such as the WATEM/SEDEM model, which has been calibrated against field data for several countries (Verstraeten 2006). A review of literature will be performed in order to select a proper sediment budget model that applies to the region and to the data available from the GIS database.

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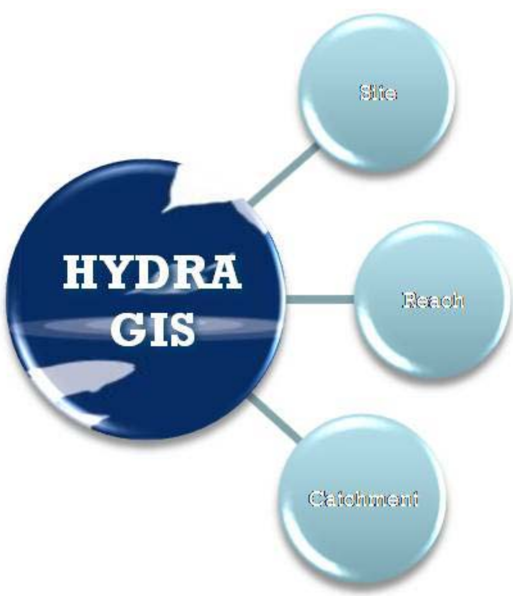
HYDRA: A GEOGRAPHICAL INFORMATION SYSTEM FOR SIERRA NEVADA WATERSHEDS



Project Report

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Abstract

We describe Hydra, a geographical information system (GIS) of tabular and spatial data for 18 major basins of the Sierra Nevada, California. We created Hydra for the purpose of characterizing the current status of Sierra Nevada watersheds and to serve as the basis for future analyses. The Hydra GIS allows us to assemble, analyze, and provide access to spatial physical, ecological, jurisdictional, hydrological, and meteorological data for the entire study region in an integrated framework. We created Hydra using the ESRI ArcGIS environment and a number of extensions, such as ArcHydro, which was used to create a standard hydrographic datum for each basin. Hydra contains a number of data storage formats, such as ESRI GRID and Personal Geodatabase, as well as Shapefiles that were used for certain analytical processes. The Hydra allows us to not only create project-wide and basin-specific maps, but also and more importantly it creates a standardized and centralized repository of information to be used in analyses of physical habitat parameters, relevant historical information, hydrologic alteration, and specific ecological data describing stream and watershed condition. The Hydra GIS provides a robust and dynamic data store to be used in project evaluation, cross-basin comparative analyses, and scenario modeling of future conditions.

Keywords: California, Sierra Nevada, watershed, GIS, geodatabase

Introduction

HYDRA is a geographical information system implemented using ArcGIS 9.2 (ESRI, Redlands, CA). In principle, a geographical information system (GIS) is defined as "A set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world for a particular set of purposes " Burroughs (1986)[1]. Our compilation of georeferenced data for the Sierra Nevada, as cataloged by major watershed, is fundamentally based on the inherent terrain of the mountain range, its rivers, and thus its watersheds. The working definition for watershed in our case is from Black (1996)[2], which states "The watershed is defined as a unit of land on which all the water that falls collects by gravity and fails to evaporate and runs off via a common outlet. The watershed is the basic unit of water supply." Watersheds when used as the bases for GIS development, create a robust organizing framework from which to conduct geospatial analyses. Thus, a watershed-based GIS is inherently a set of tools for the collection and manipulation of hydrodynamic information; moreover, it is inherently organized to optimize analysis of landscapes at the watershed scale. In the context of evaluation of impacts of dams and the possibilities for restoration and mitigation of those impacts, the watershed scale of analysis is particularly important.

Scope

Our intention with the creation of Hydra was to create a spatial and temporal base from which to create, manipulate, update, and extract information within a referenced context. Our contextual references include sites (e.g., biological inventories or dams), reach segments (i.e., a tributary to tributary stream reach, also called a link) sub-catchments (i.e., discrete, localized catchments draining to a segment), basins (i.e., cumulative catchments capturing all surfaces draining to a segment), and watersheds (i.e., major drainage basins), among many. By capturing and housing pertinent geospatial data for the breadth of the Sierra Nevada mountain range of California, and by developing a robust and dynamic data store within a GIS, present and subsequent analyses are made possible in a fashion that is both encompassing -- by housing disparate data types from a variety of disciplines Hydra GIS creates a central data storage and processing repository -- and responsive -- the Hydra GIS data framework inherently allows for reasonable scenario building that can be applied to each watershed in an automated fashion.

Project Phase 1

Our scope for phase 1 includes the 18 major watersheds of the west slope of the Sierra Nevada mountain range in California (watersheds are listed in Appendix B; see Figure 3 for watershed locations). In addition, we have focused on more detailed data development for the Mokelumne River watershed. Some of this analysis is described

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[1] P.A. Burrough, 1986.*Principles of Geographical Information Systems for Land Resources Assessment*

[2] P. E. Black, 1996, *Watershed Hydrology*, Second Edition

below. As this analysis is currently in progress, this document does not describe all of the data or analysis performed thus far.

Methodological Approach

Our methodological approach to create HYDRA GIS was to maintain a systematic data capture, creation, and manipulation for each major watershed. The data included in the GIS was geographically constrained to each watershed through a step-wise process of manipulating a continuous 10m Digital Elevation Model obtained from United States Geological Survey (http://seamless.usgs.gov/). To maintain consistency, we created a separate workspace that houses each step of the raster and vector data processing. Raster data are stored in the ESRI GRID format, principally, with occasional use of the GeoTIFF image file format. Vector data are housed in two primary data formats: shapefile and personal geodatabase. Shapefiles are used as intermediaries for analysis, conflation, and further data development. The personal geodatabase format was used as a final repository as it is a single wrapper technology, facilitating ease of distribution, and later database manipulation through Microsoft Access. Example data structures for each watershed workspace can be seen in Figure 1, which shows data cataloged for the American River watershed (code AMR); consistent naming conventions are used for all watersheds.

Data Development

Digital elevation models (DEMs) are digital raster representations of elevation, which can be manipulated to depict topography, calculate drainage area, or derive slope. We are using 1/3 arc second DEMs created by the United States Geological Survey (USGS) as the primary data for all terrain related analyses. These data have a nominal ground resolution of 10m when projected into the Teale Albers Equal Area projection (North American Datum 1983) – the best standard practice when working with California state agencies. The standard methodology we used for creating each analysis drainage basin was as follows:

- Obtain native DEMs from USGS (http://seamless.usgs.gov/)
- Merge as appropriate to create continuous digital coverage for drainage basin
- Fill anomalous elevational sinks in data
- Determine flow direction for each cell in entire drainage basin
- Determine flow accumulation for each cell in entire drainage basin
- Manipulate position of terminal outlet to correspond with flow accumulation path, most typically a major jurisdictional dam
- Generate a corresponding raster representation of the drainage basin for the outlet
- Convert the raster data to vector
- Reset the bounding extent of the raster analysis framework to the vector extent
- Set an analysis mask to the watershed
- Bring the clipped elevations raster into the ArcHydro environment.
- Run ArcHydro analyses on the clipped raster in a separate project in order to maintain file structure integrity.

    - Re-calculate flow direction and flow accumulation rasters
    - Threshold flow accumulation to a minimum drainage area of 50 ha to create a drainage network
    - Calculate unique identifiers for each series of contiguous cells (each link) on a tributary to tributary basis
    - Vectorize stream networks based on flow direction, this produces a unique ID for each link; each link is attributed with a LinkIDand a NextDownID to identify the next downstream link.
    - Delineate local and cumulative watersheds (drainage areas) for each link
    - Generate local and cumulative watershed polygons based on points of interest (eg, the Index of Biological Integrity sites, dam locations; see figures)
    - Generate an ARC Network with directional attributes for further analyses
- Perform other stream and watershed level analyses in a separate project
- Obtain and parameterize other ancillary data within basin boundary

Subsequent routines, coupled with those algorithms discussed above, were used to create data which include, but are not limited to:
Standard Raster Data Created for HYDRA (grids) --

- DEM, Flow Direction, Flow Accumulation, Total Curvature, Planform Curvature, Profile Curvature, Percent Slope, Degree Slope, Flow Length to Divide, Flow Length to Outlet, Hillshade, True Area, Rugosity

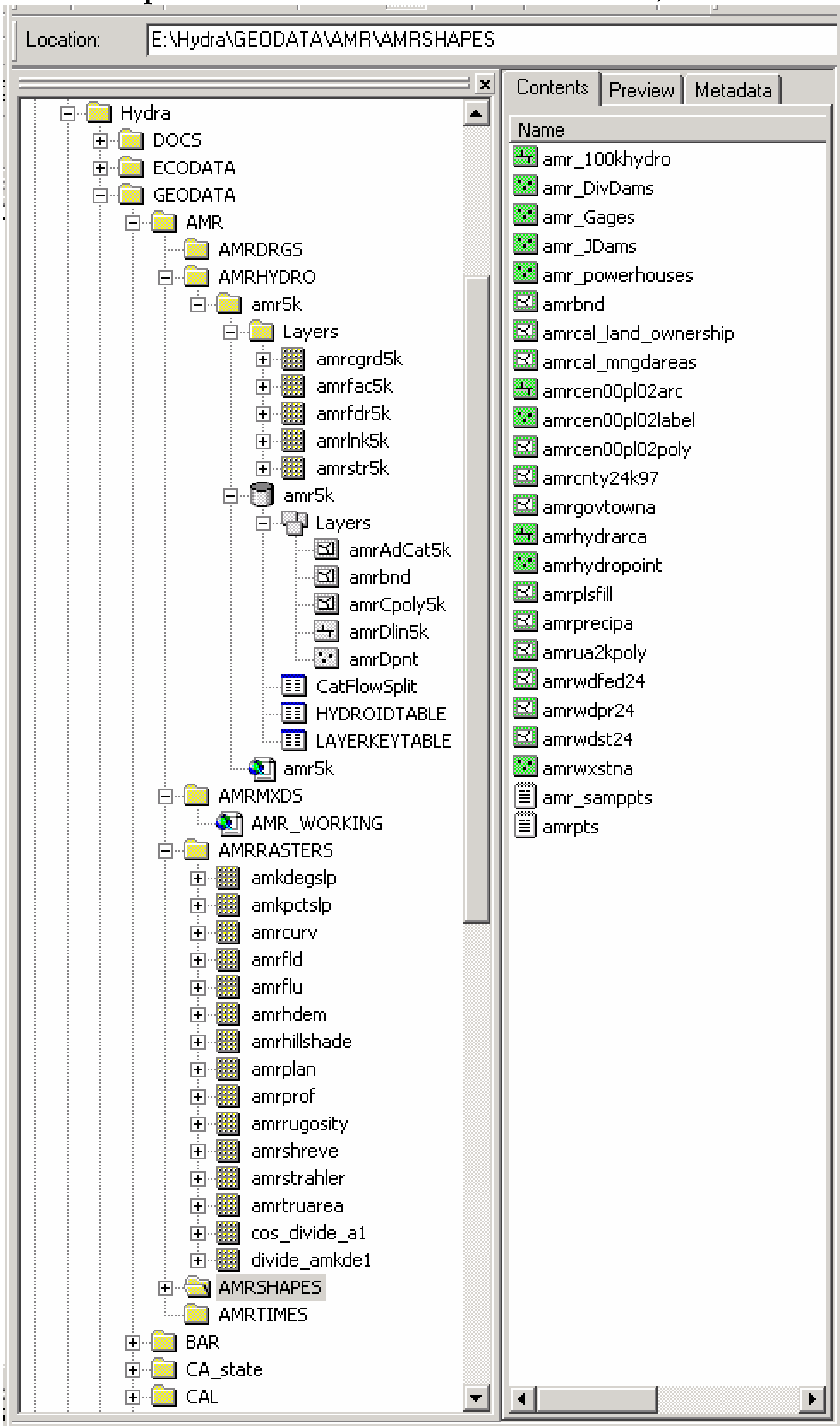
Standard Vector Data Created for HYDRA (shapefiles) --

- Watershed Boundary, Natural hydrography, Tributary Pour Points, Confluences, Catchment Polygons, Cumulative Drainage Area Polygons, Stream Link Routes

Standard Data Captured for each Watershed in HYDRA --

- Water District Boundaries, Hydrography, Dam locations, other Hydromodifications, Transportation Infrastructure, Stream Gauges, Weather Stations, Powerhouses, Population, Soil Depth, Geologic Formation, Land Cover, PLSS, Isohyets (1900-1960 mean), Land Ownership, Management Areas

Figure 1. GIS Workspace for the American River Watershed, Shown in ARC Catalog



Preliminary Findings

Our analysis for the current report is limited to large-scale attributes across the entire project study area and some higher-resolution analyses of the Mokelumne River watershed. The Mokelumne River was chosen for more detailed analysis as a demostration of the types and quality of analyses that are possible within HYDRA.

Project-wide Findings

The 18 basins of the current project are briefly characterized in Table 1 below.

Table 1. Watershed Information for Project Basins

Basin Name	Basin Area (km^2)	% Study Area	Ann. Avg. (1960-1990) Precip (in)	Area X Precip (af)	Reservoir Cap. Total (af)
American	4821.50	7.6	54.52	5,413,007	785,150
Bear	730.35	1.2	47.03	707,308	182,385
Calaveras	936.99	1.5	33.01	636,914	321,494
Cosumnes	1385.00	2.2	41.23	1,175,884	42,906
Feather	9411.51	14.9	45.75	8,866,480	1,859,037
Kaweah	1450.97	2.3	36.10	1,078,612	143,943
Kings	3997.80	6.3	37.12	3,055,835	1,245,693
Kern	5983.38	9.5	19.88	2,449,422	568,000
McCloud	1571.27	2.5	59.96	1,940,056	35,300
Merced	2685.43	4.3	45.21	2,500,049	835
Mokelumne	1497.54	2.4	50.53	1,558,224	220,734
Pit	12823.79	20.3	27.04	7,140,422	357,089
Sacramento	1107.72	1.8	58.72	1,339,416	26,000
San Joaquin	4315.41	6.8	41.71	3,706,493	1,145,945
Stanislaus	2341.03	3.7	49.71	2,396,362	376,944
Tule	1015.11	1.6	29.81	623,124	325
Tuolumne	3970.62	6.3	44.92	3,672,815	692,175
Yuba	3113.72	4.9	63.37	4,063,156	1,380,911

Table 2: Hydropower Information by Watershed

Basin Name	HydroPower Facilities	Jurisdictional Dams	Earliest Hydromod	Latest Hydromod	First FERC Expire
American	16	57	1862	1990	2007
Bear	10	10	1928	1968	2011
Calaveras	0	8	1850	1970	
Cosumnes	0	10	?	1989	
Feather	16	38	?	1979	2009
Kaweah	3	4	1903	1962	2021
Kings	5	7	1888	1958	2026
Kern	4	1	1953	1953	2026
McCloud	0	1	1965	1965	
Merced	0	3	1956	1957	
Mokelumne	6	14	1900	1973	2013
Pit	11	84	?	1991	2011
Sacramento	0	1	1969	1969	
San Joaquin	17	21	1896	1986	2007
Stanislaus	8	28	1895	1990	2032
Tule	2	1	1963	1963	2033
Tuolumne	5	28	?	1991	2022
Yuba	9	55	1850	1989	2011

At least eleven of the 18 study basins have FERC-licensed hydropower facilities that will require relicensing within 20 years (see Table 2). Of the 112 hydropower facilities we have identified in the study area, we have information about sediment accumulation for about 75. Of these reservoirs, some 55 are indicated to have sediment accumulation problems in one or more associated reservoirs (see Table 3).

Table 3. Reservoirs Known to have Sediment Accumulation Problems

Reservoir	Storage (AF)	Reservoir	Storage (AF)
L. Almanor	1101251	Pit 4	1382
Salt Springs	125873	Lake Tabeaud	1246
Courtright & Wishon	123300	Pit 1 Forebay	1159
Wishon	118254	Kerckhoff	1084
Mammoth Pool	117462	Tiger Creek Afterbay	1007
Lake Spaulding	74773	Cresta	915
Lake Spaulding/Fordyce Lake	74773	Belden	695
Englebright	34000	Grizzly Forebay	512
Bass Lake	27443	Poe	426
Butt Valley	25177	Pit 5	407
Mountain Meadows	23942	Edison & Florence	325
Iron Canyon & Lake McCloud	20541	Baum Lake	290
Strawberry/Pinecrest	18266	Angels	100
Lake Britton	14443	Corrine Lake	66
Pit 7	10377	Tiger Creek Regulator	22
Phoenix Forebay	6224	Deer Creek	13
Pit 6	5821	Cassal Pond	13
Rock Creek	4342	San Joaquine 3 Forebay	10
Belden	2254	Manzanita Lake	10
Chili Bar	1550		

Mokelumne River Basin

We performed extensive analysis on the Mokelumne River watershed as a template for the rest of the study region. Analysis begins with the National Elevation Dataset 1/3 Arc Second Digital Elevation Model. Hydrography is developed from the DEM with a flow accumulation threshold of 5000 cells (equivalent to 1/2 of a square kilometer). At this threshold, the hydrography is very similar to the USGS 7.5 minute quadrangle map blue lines. This hydrography produces a distribution of Strahler ordered streams in the Mokelumne basin as shown in Table 4, below.

Table 4. Distribution of Stream Order in the Mokelumne River Watershed at 0.5km² Stream Definition Threshold

Strahler Order	Total Length (km)	Length Fraction
1	741.99	0.518948
2	301.11	0.210601
3	199.24	0.139349
4	107.76	0.075369
5	49.90	0.034903
6	29.79	0.020834

The outlet for the Mokelumne watershed is defined for the purposes of this study to be at the outlet of Pardee Reservoir. The elevation at this point is approximately 72 meters above sea level. The elevation maxima in the watershed is the peak of Round Top Mountain, on the north-eastern edge of the watershed, at approximately 3165 meters above sea level. The longest flow path from headwaters to the outlet is 136.64 km along the North Fork Mokelumne River. The watershed is 67% forested, 25% shrublands, 5% grasslands, 2% barren, and less than 1% urban and agriculture. Private land owners control 43% of the watershed, 29% is part of the El Dorado National Forest, 24% is part of the Stanislaus National Forest, and 4% is owned by the Bureau of Land Management.

Future Directions and Considerations

Hydropower Infrastructure & Hydrologic Alteration Data Needs

Our current dataset describing jurisdictional dams, diversion dams, transfer facilities, and powerhouses has significant gaps that must be addressed in order to perform larger-scale analyses in the future. Filling in the blanks in our dataset will involve interfacing with the California Department of Water Resources, the Army Corps of Engineers, the Federal Bureau of Reclamation, and the Federal Energy Regulatory Commission. Specifically, we need better data on expiration of FERC licenses, storage capacities, generation capacities, throughflow capacities, and structural status (eg. sedimentation of reservoirs, canal and aqueduct sizes, reservoir expansion potential).

Other Data Needs

In addition to hydro-infrastructure data, additional ecological data will be required in development of models of ecological impairment, sensitivity, and adaptability. Higher resolution landuse data may also be required, as our current dataset does not distinguish between types of agriculture or urban land uses. Data describing bridges, culverts and other crossings may be important in model development as it has been shown these nodes play an important role in stream ecology (Blakely et al 2006, Lane and Sheridan 2002, Schaefer et al 2003). Likewise, more detailed information about road surfaces may be very valuable.

Expansion of Detailed Watershed Analyses

Currently, our datasets for the 18 major basins consists of only the basic data described above, except in the case of the Mokelumne River basin. For the Mokelumne, we have developed a much more detailed analysis and have related this spatial data to ecological data collected by other investigators. In an expanded project, we would collect more ecological data in all basins, and develop models of ecological integrity based on spatial data. In the process of expanding the datasets for each basin, we would develop automated techniques for analysis based on the handwork done in the Mokelumne, but tailored to fit the unique parameters of each basin. In addition to expansion of this type of meta-analysis, further investigation into spatio-temporal changes related to hydropower operations may require new field studies and data collection (monitoring) efforts.

Contextualization of the GIS

This GIS describes the 18 basins in their current state. This can be expanded and refined in terms of the analytic methodology, the resolution of data, the number of data types, the scope of the data (include more watersheds, move farther downstream), and other elements. In order to maintain relevance over time, however, it must be designed to allow integration of temporal change, and, specifically, climate change scenarios, into the analytic regime. A number of potential integrative applications have been identified to utilize the push-pull capability of the Hydra GIS (Appendix B).

Integration of Datasets from Earlier Investigations

Currently, the GIS includes two ecological datasets: the Index of Biological Integrity sites described elsewhere, and a set of several dozen sites compiled from Dr. Peter Moyle's investigations in fisheries biology and stream ecology over the last several decades (see Figure 4). This dataset should be expanded to include as many datasets from other investigations as possible. Ideally, the GIS could become a repository for watershed ecological data for the Sierra Nevada. This will require an interface that allows evaluation of the quality of data, determination of the appropriate data vessel (point, line, polygon, grid), and integration with previously acquired data. A system for acquisition and integration of data can be implemented with minimal modification of the current data structure.

The project study area includes many dams that are facing relicensing, sedimentation problems, and which have highly impacted watersheds. The Hydra GIS can be used to analyze the impacts of dams, and, more importantly, to analyze the various options for reoperation or mitigation of these dams - as well as other impacts on ecosystem health in the Sierra Nevada. The Hydra GIS will provide a framework for integration of data describing the ecological status of the Sierra Nevada at multiple scales, and from disparate sources. This framework can be expanded to accommodate many types of spatial and temporal data.

Schematic Representation of Sierra Nevada Waterbodies and Hydropower Infrastructure

Data visualization is a basic challenge to complex problem sets. Our project is inherently complex and of wide scope; thus, it is essential to simplify system networks and relative properties to effectively visualize large amounts of data and discern pattern and process. Such visualization requires multiple representations of data, at different scales and in different forms to adequately assess the efficacy of proposed analyses and potential outcomes.

Recognizing the need to understand the complex inter-relationships of hydropower facilities, off-stream water withdrawal, and natural stream pathways in the Sierra Nevada, we have constructed a preliminary schematic of natural and artificial flowpaths of water in the Mokelume River watershed. This schematic represents the waterways in the pilot study area, characterized as either natural and anthropogenic, and as related to hydropower infrastructure. The outcome of this exercise will allow future graphical representations of large data arrays in a variety of forms, but most notably in regards to network conectivity, rather than geographic location. The schematic representation facilitates our understanding of the interconnection of the hydropower systems, both within and among watersheds, and of potential impacts on natural waterways. This approach is consistent with other objectives and is fully integrated with the Hydra GIS, aiding our ability to understand regional hydropower needs, as well as local resource needs. For example, the schematic representation can be plotted against elevation, as opposed to a horizontal planar coordinate system, so that infrastucture and natural features are easily indexed against climatic variables, such as snow line.

Schematic Methodology

By using the built-in algorithms of the ESRI arcgis Schematic Extension, we build a schematic diagram based on geometric networks housed within the Hydra GIS. These geometric networks are in turn based on the previously described DEM-derived hydrographic networks, which were similarly used by Stockholm Environment Institute to construct the WEAP hydrologic model (see Fernandes et al. this report). The hydrographic network serves as the basis for the initial geometric relationship; features and topology are constructed to form a series of schematic-specific elements wherein topological relationships are generated to insure referential integrity. Once all unique schematic elements are indexed, the network is shaped to create "main line tree" type hierarchical groupings. The resulting schematic diagram effectively illustrates the organizational structure of the river systems and the accompanying hydropower-related infrastructure.

Our pilot schematic (Appendix D) is arranged with elevation in the vertical direction. Subsequent basins will be added sequentially from north at the left to south at the right. Junctions preserve flow direction (e.g., a tributary joins the main stem from either left or right). Absolute distances between locations are not preserved. Reservoirs and powerhouses are represented by icons, with capacity relative to icon size. Waterways are colored to represent type, such as river, tunnel, or canal. Peak elevations within major subwatersheds are also depicted.

Appendix A. Maps

Figure 2. California Hydropower Facilities

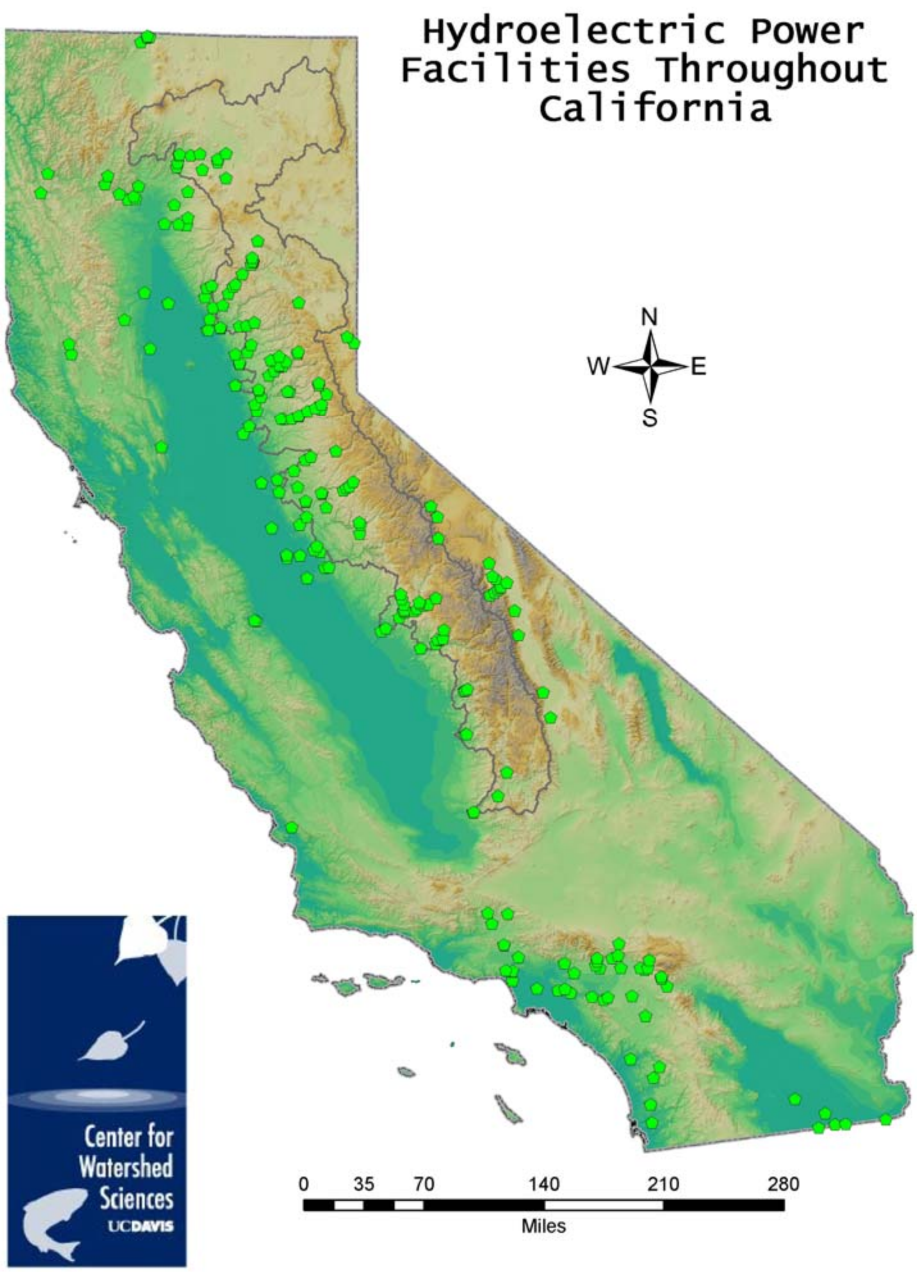


Figure 3. Project Watershed Locations

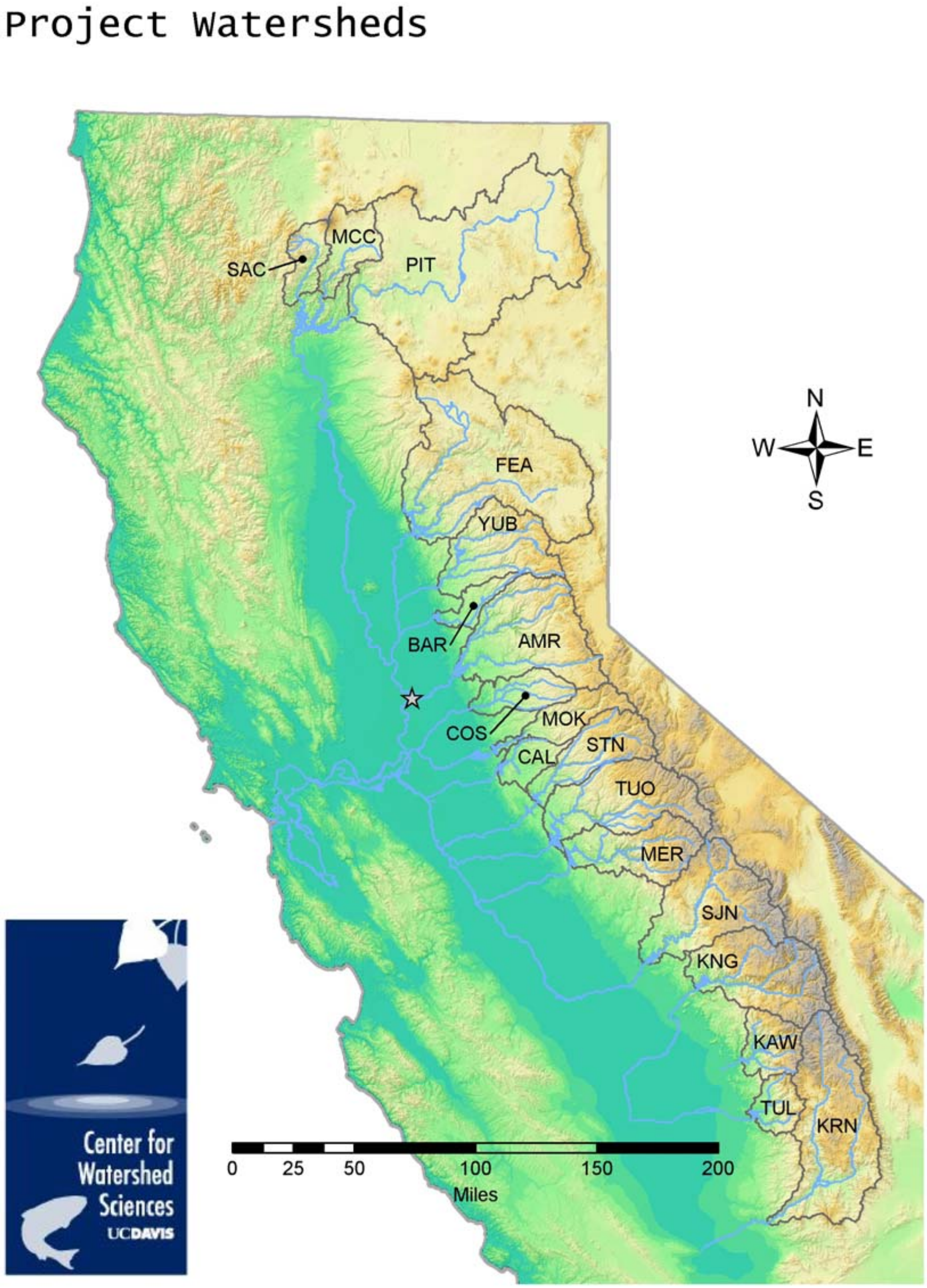


Figure 4. Moyle Sites in Project Study Basins

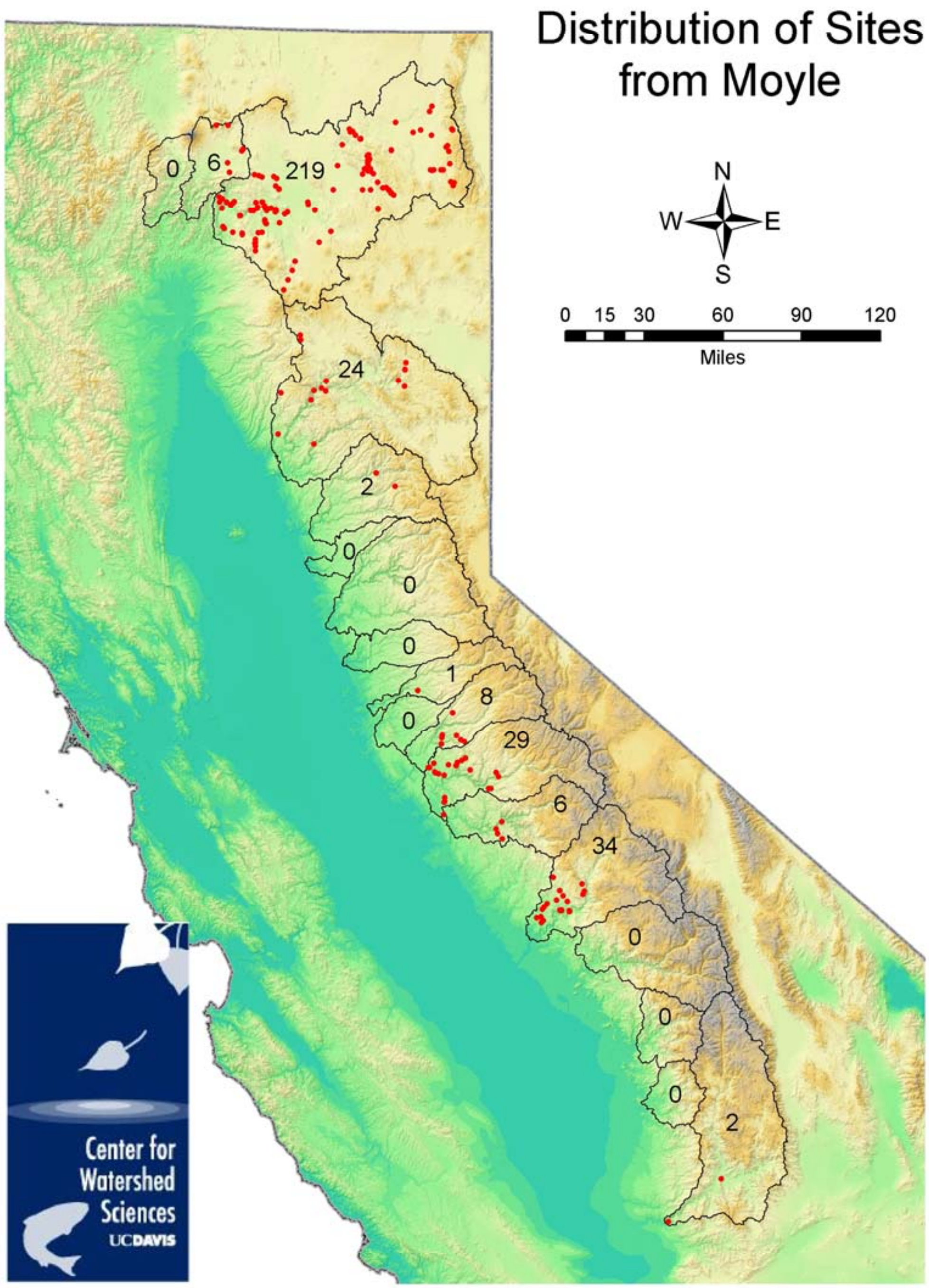


Figure 5. FERC Licenses

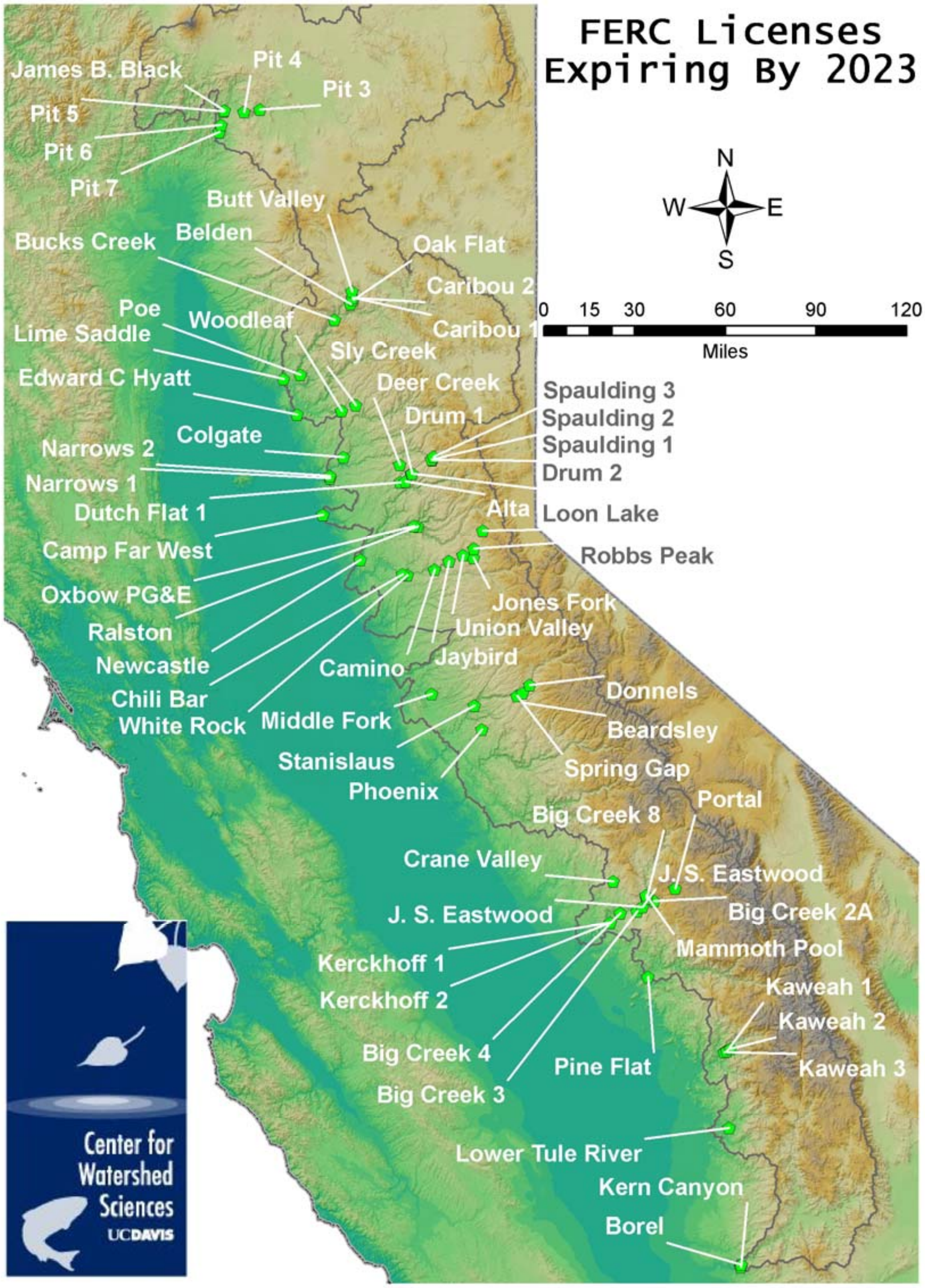


Figure 6. Storage Capacity

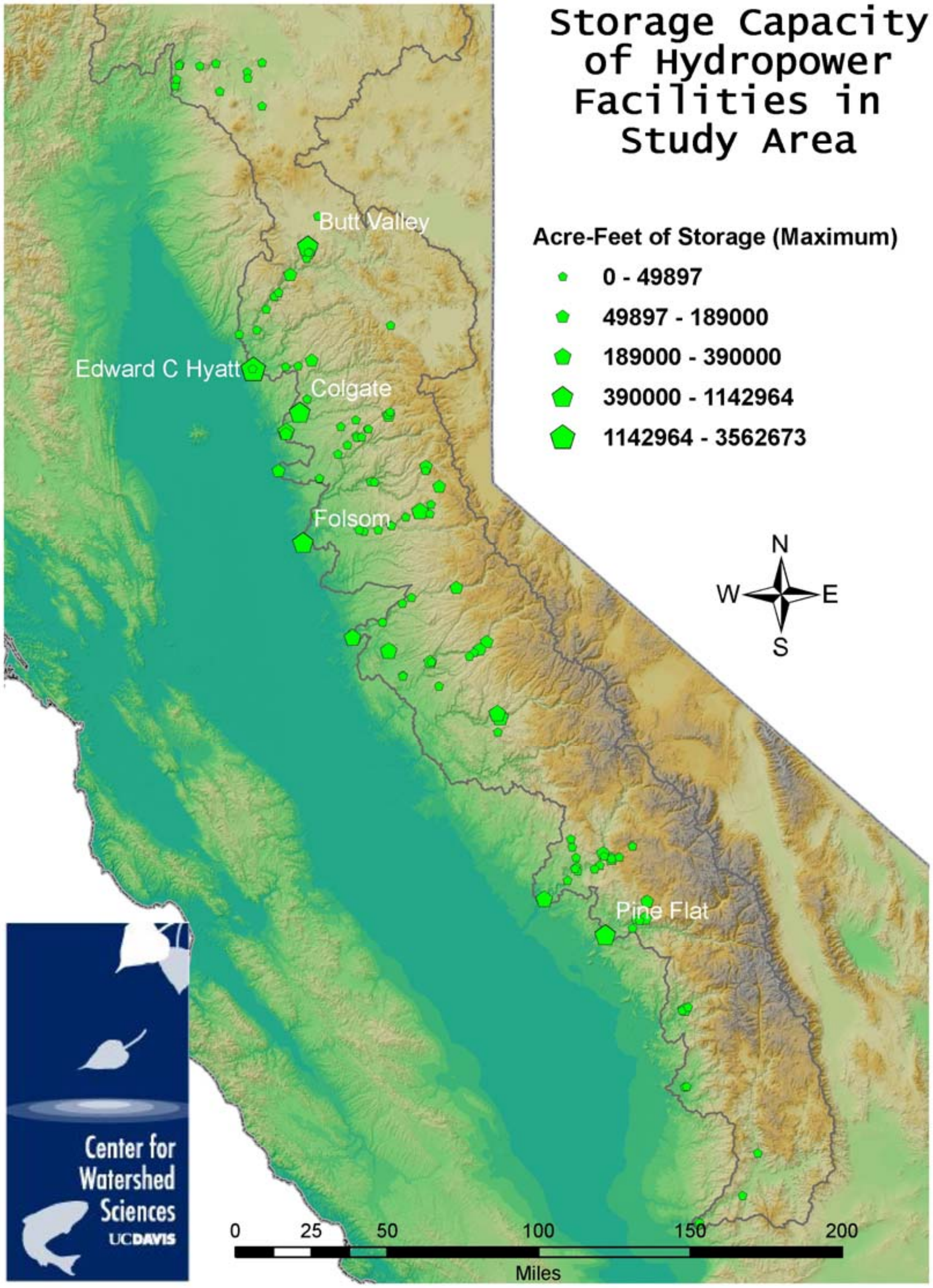


Figure 7. Average Historical Annual Rainfall (1960-1990)

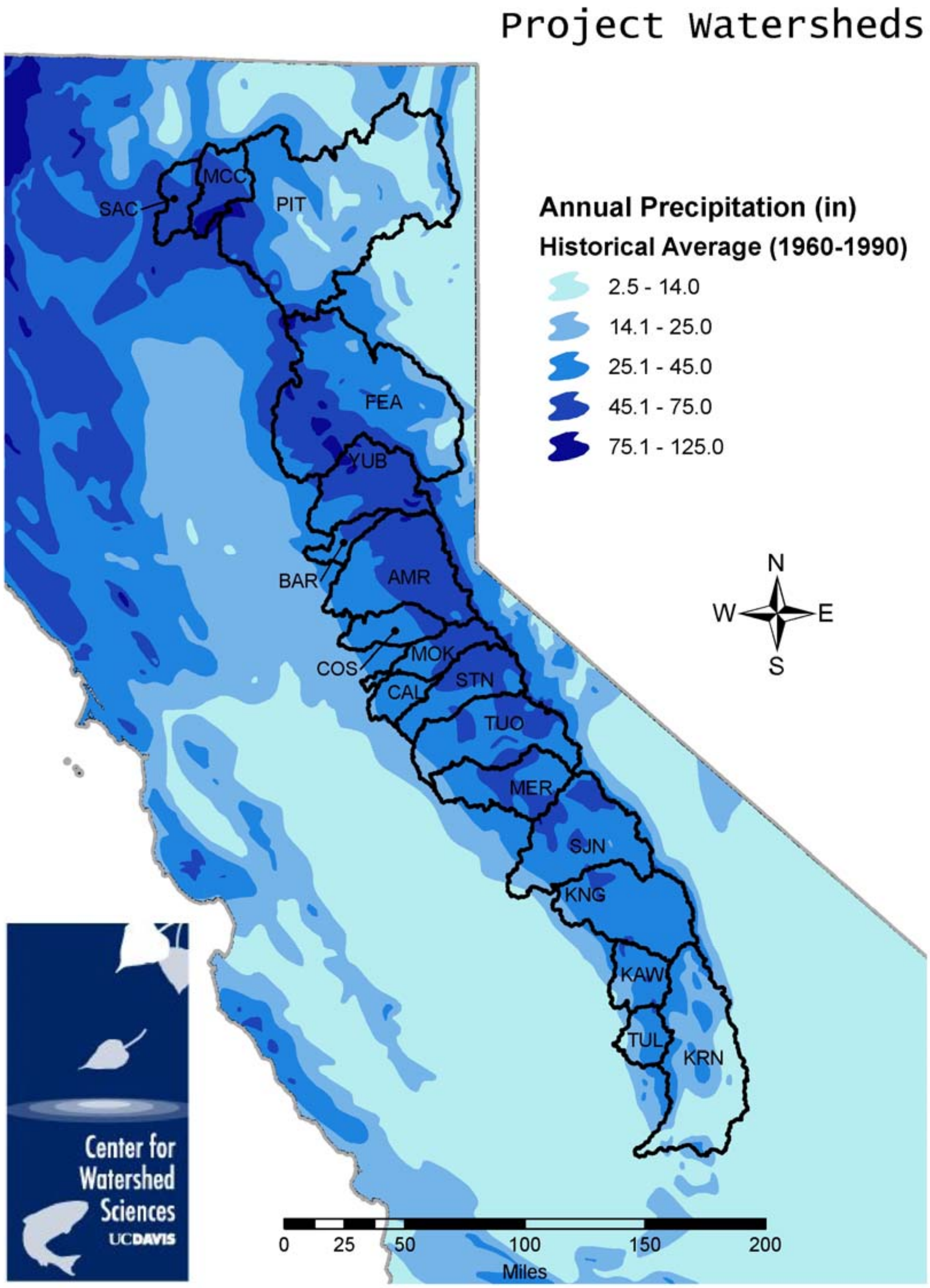


Figure 8. Sediment Accumulators

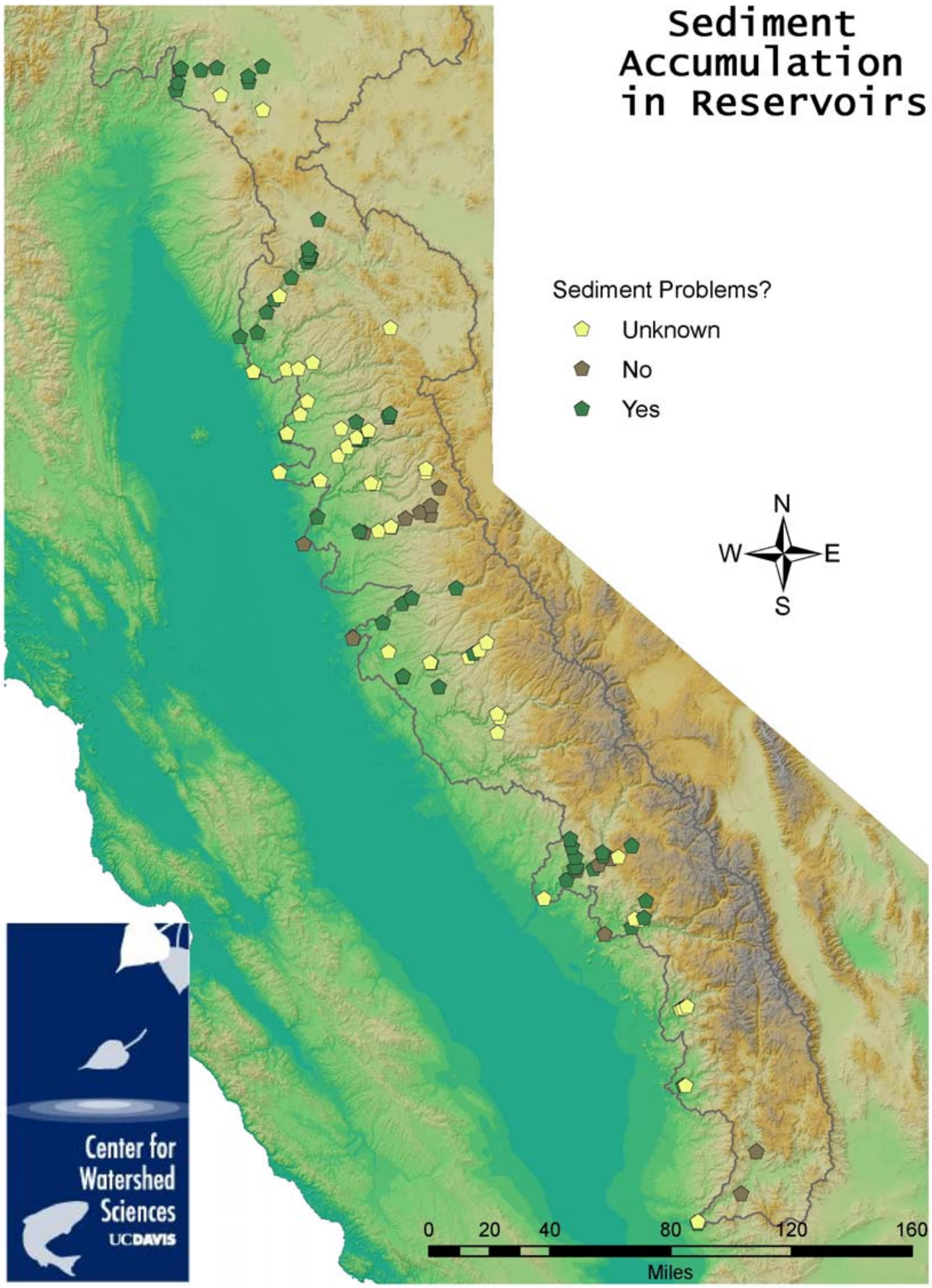


Figure 9. Mokelumne Watershed Geology

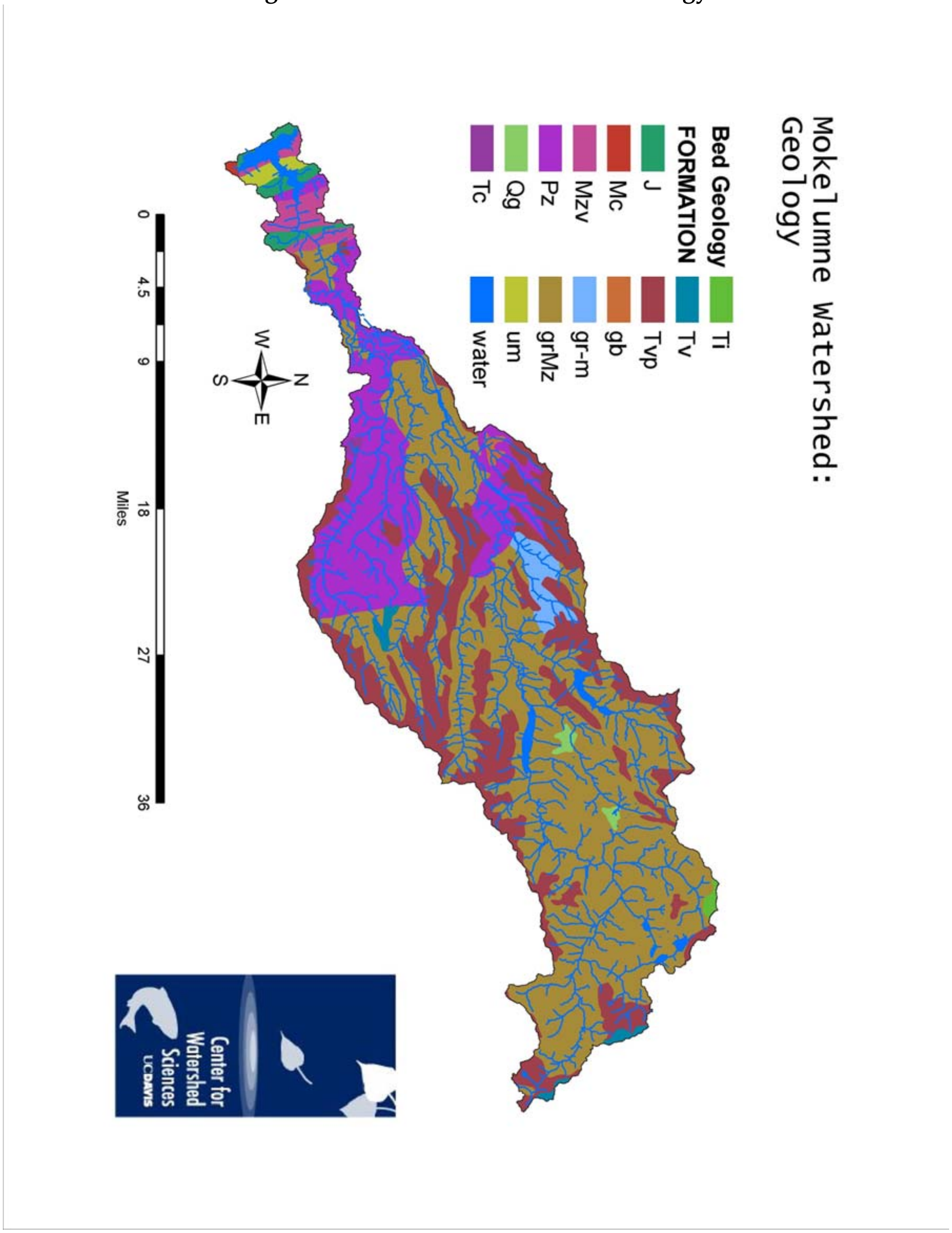


Table 5. Geology formation types.

FORMATION	DESCRIPTION	ROCKTYPE
J	Jurassic marine	Mesezoic-Palezoic-Precambrian Sedimentary and Metasedimentary
grMz	Mesozoic Granitic rocks	Cenozoic-Precambrian Plutonic, Metavolcanic, and Mixed Rocks
um	Ultramafic rocks, cheifly Mesozoic	Cenozoic-Precambrian Plutonic, Metavolcanic, and Mixed Rocks
Qg	Glacial deposits	Cenozoic Sedimentary Rocks
Tvp	Tertiary pyroclastic rocks and volcanic mudflow deposits	Cenozoic Volcanic Rocks
Mzv	Mesozoic volcanic and metavolcanic rocks; Franciscan volcanic rocks	Cenozoic-Precambrian Plutonic, Metavolcanic, and Mixed Rocks
gb	Mesozoic gabbroic rocks	Cenozoic-Precambrian Plutonic, Metavolcanic, and Mixed Rocks
Pz	Paleozoic marine, undivided	Mesezoic-Palezoic-Precambrian Sedimentary and Metasedimentary
Ti	Tertiary intrusive rocks	Cenozoic Volcanic Rocks
Tc	Tertiary nonmarine, undivided	Cenozoic Sedimentary Rocks
gr-m	Granitic and metamorphic rocks, undivided, of pre-Cenzoic age	Cenozoic-Precambrian Plutonic, Metavolcanic, and Mixed Rocks
Tv	Tertiary volcanic flow rocks (or predominantly flow rocks)	Cenozoic Volcanic Rocks
Mc	Miocene nonmarine	Cenozoic Sedimentary Rocks
water	Water	water

Figure 10. Mokelumne Jurisdictional Dams

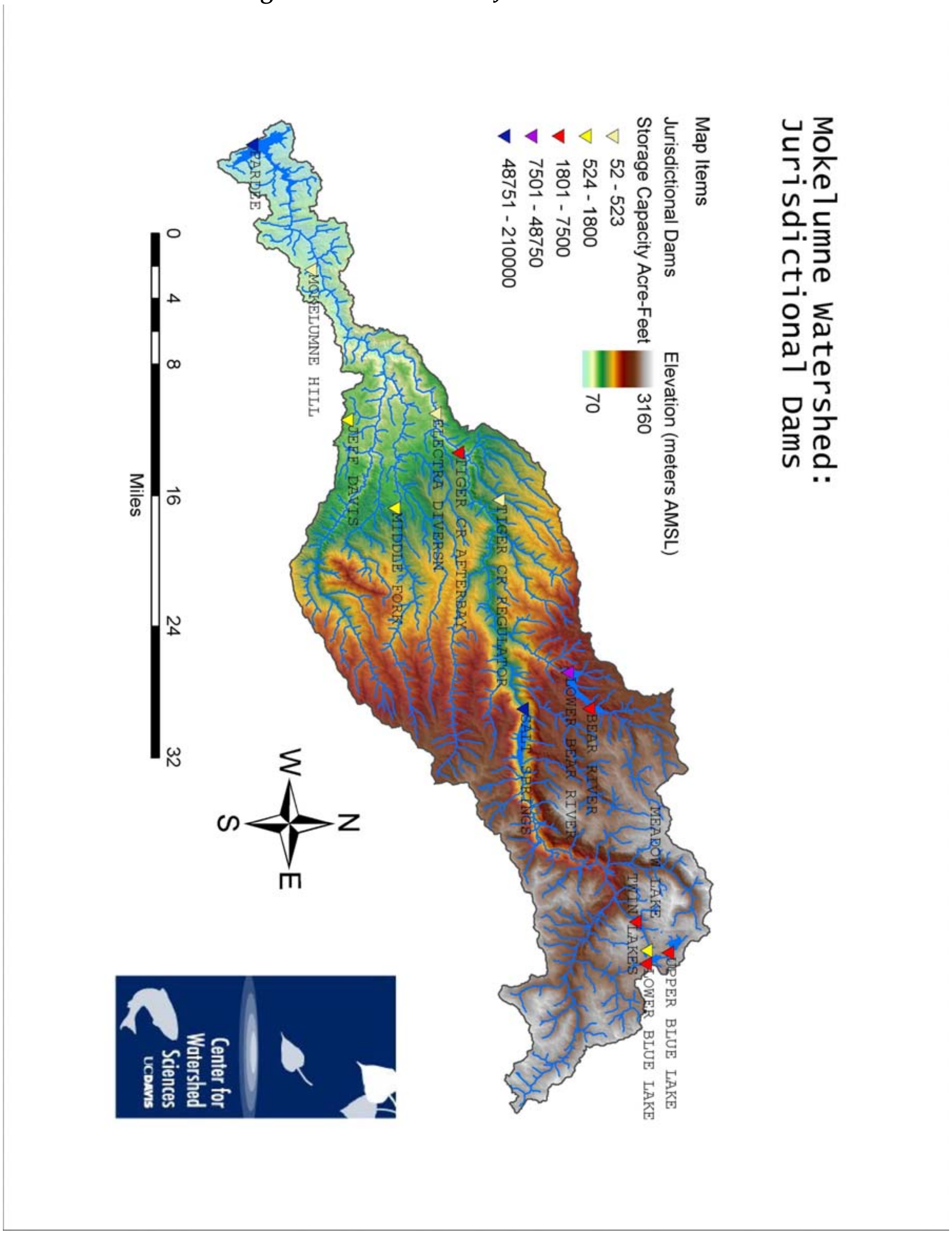


Figure 11. Land Cover

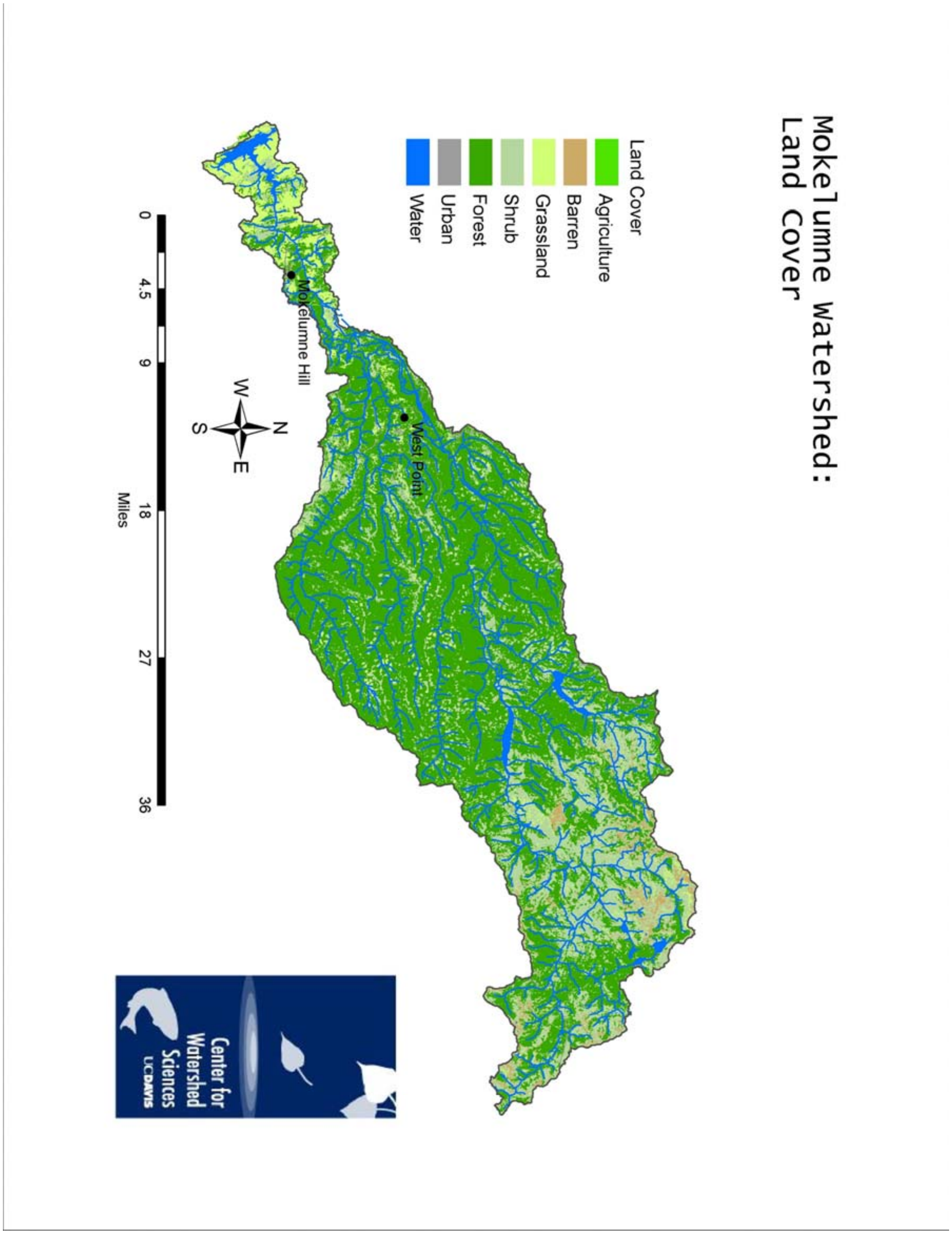


Figure 12. Topsoil Depth

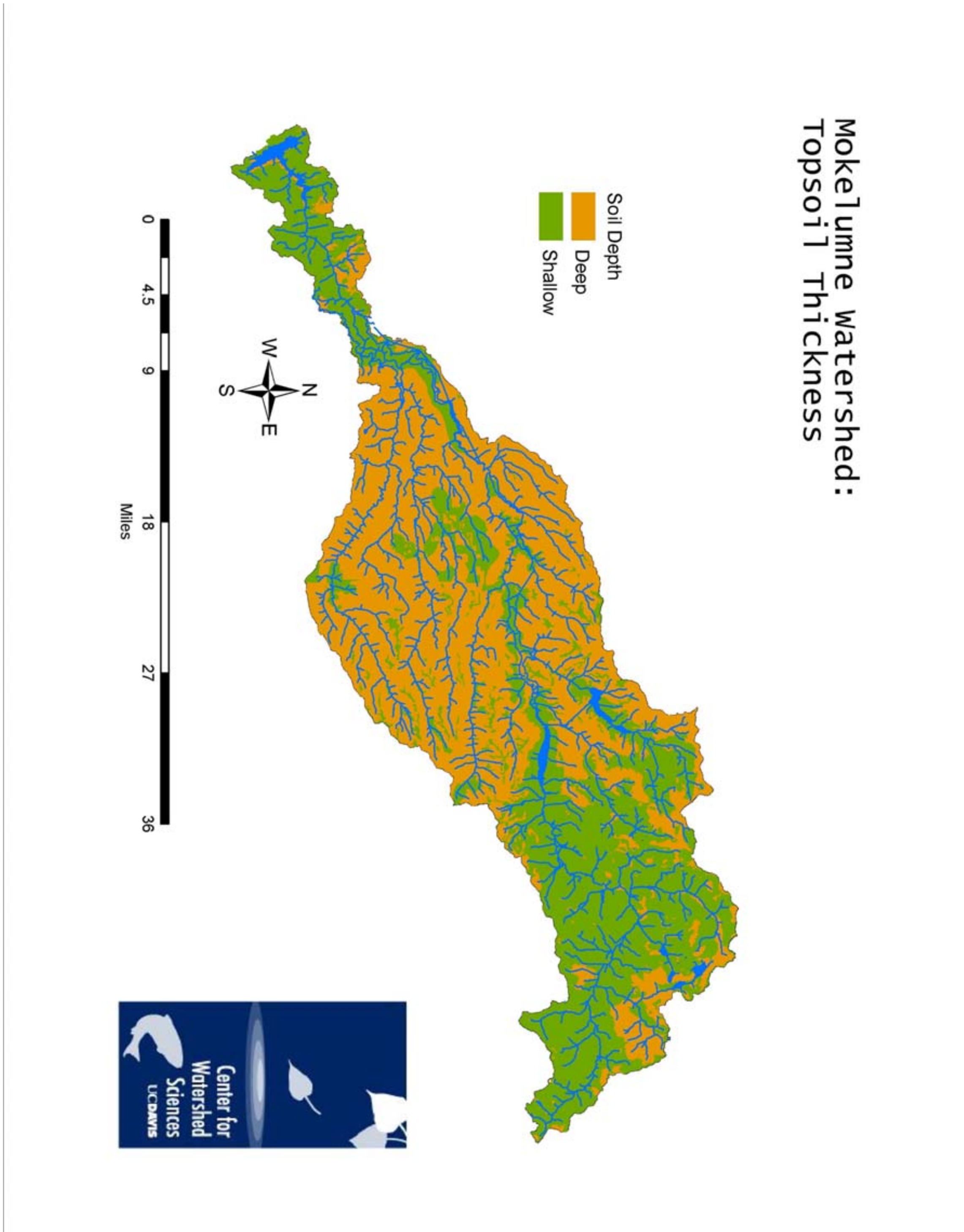


Figure 13. Hydropower facilities

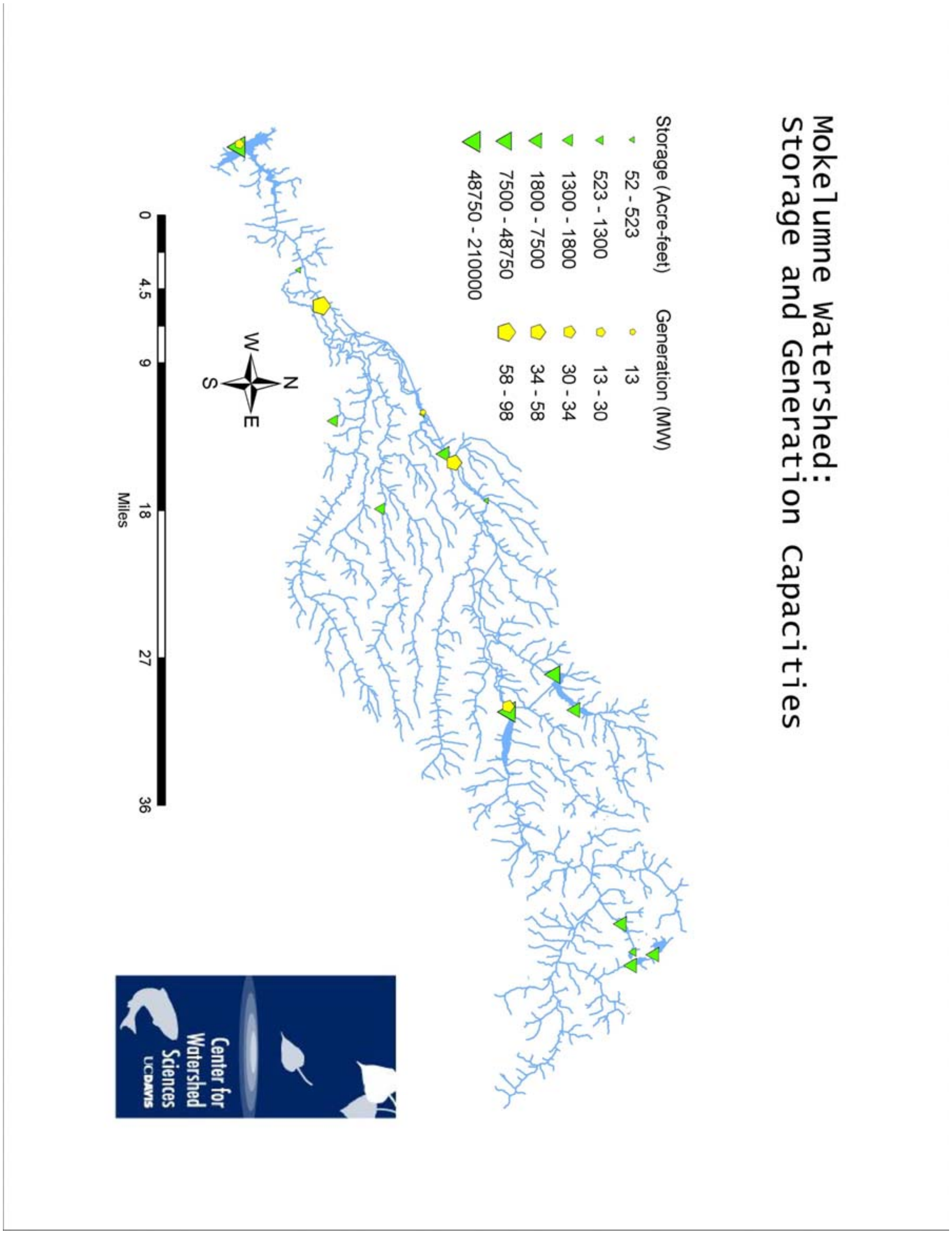


Figure 14. Triburary Basin Area Ratios

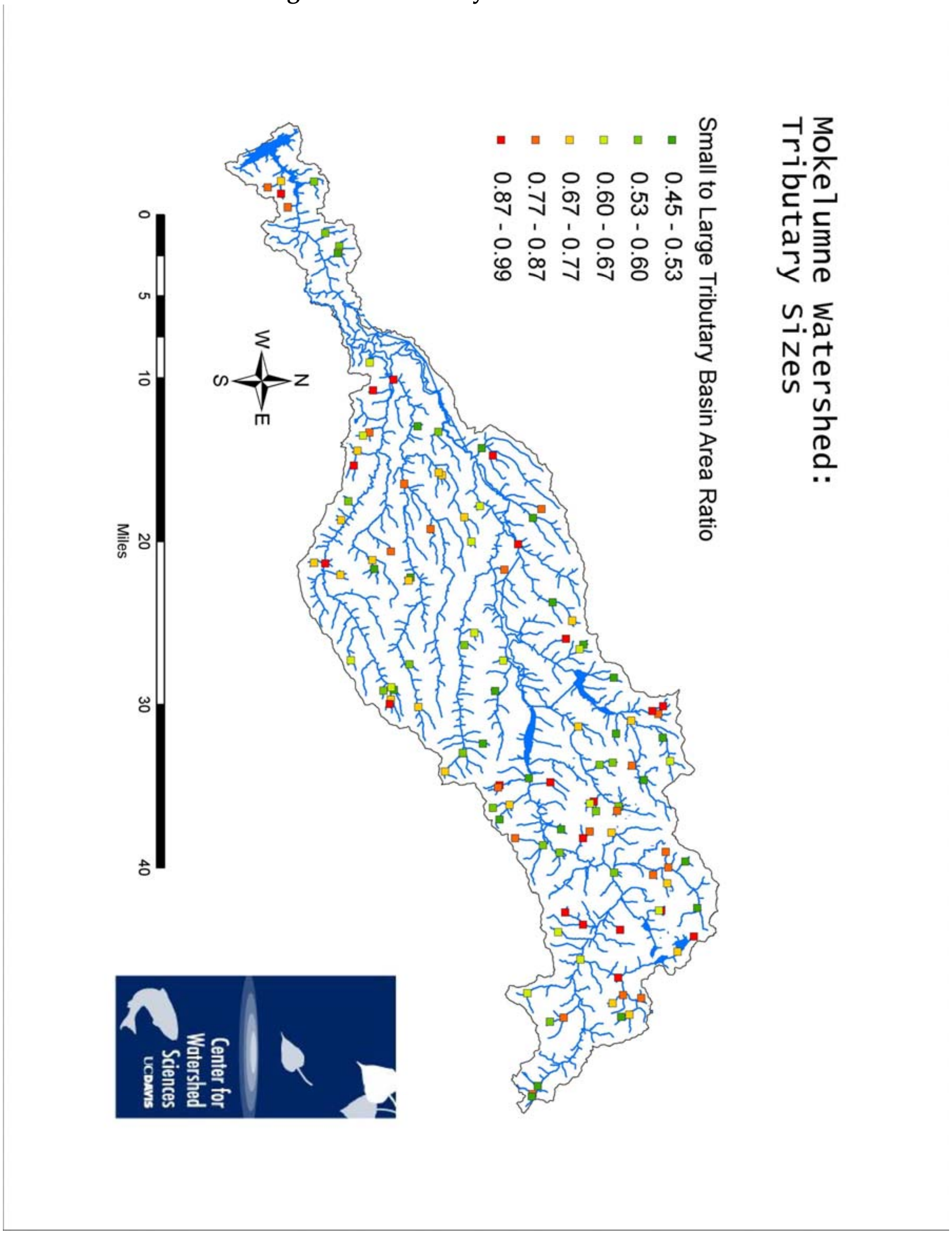


Figure 15. Strahler Stream Order

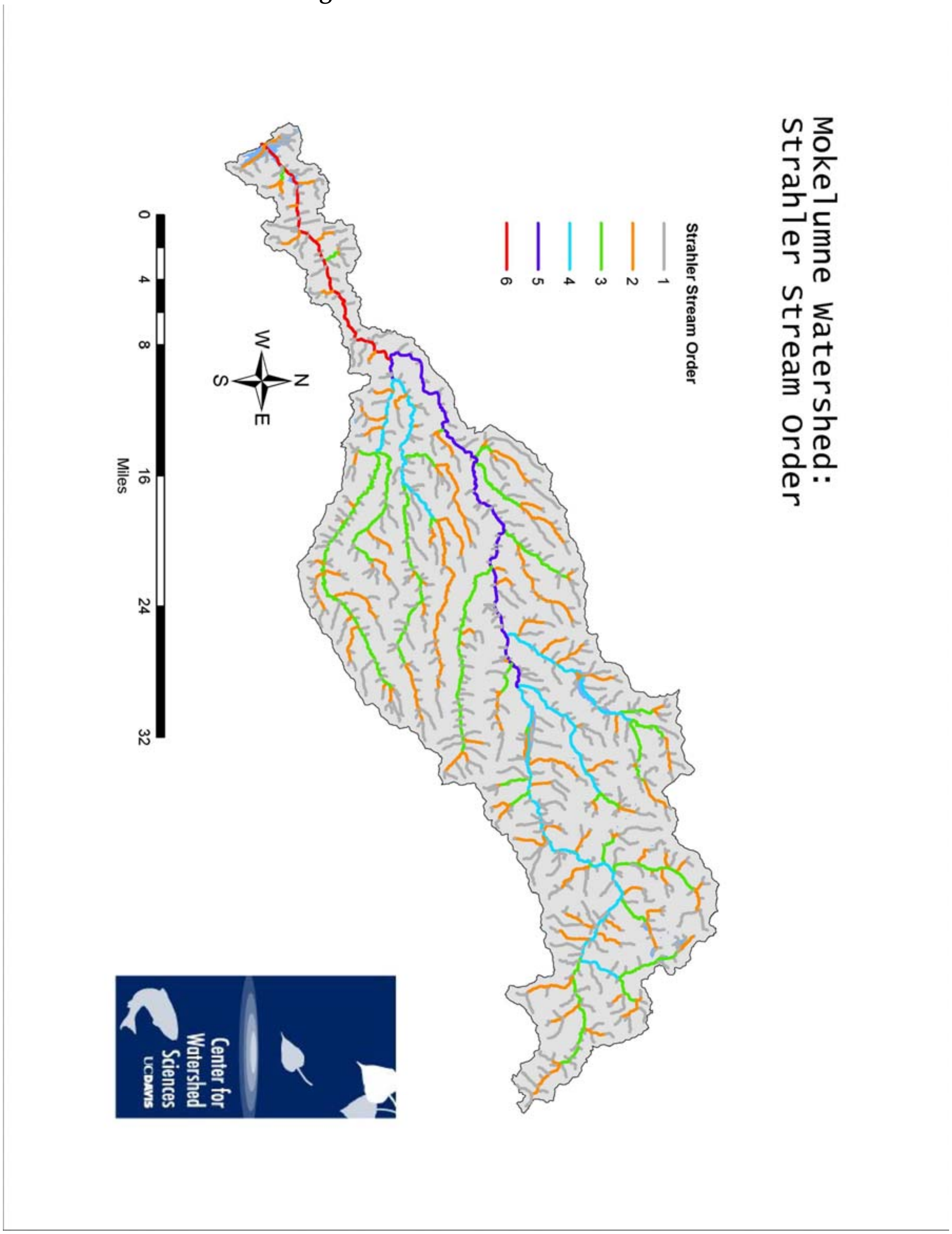


Figure 16. Subwatersheds and Elevational Bands

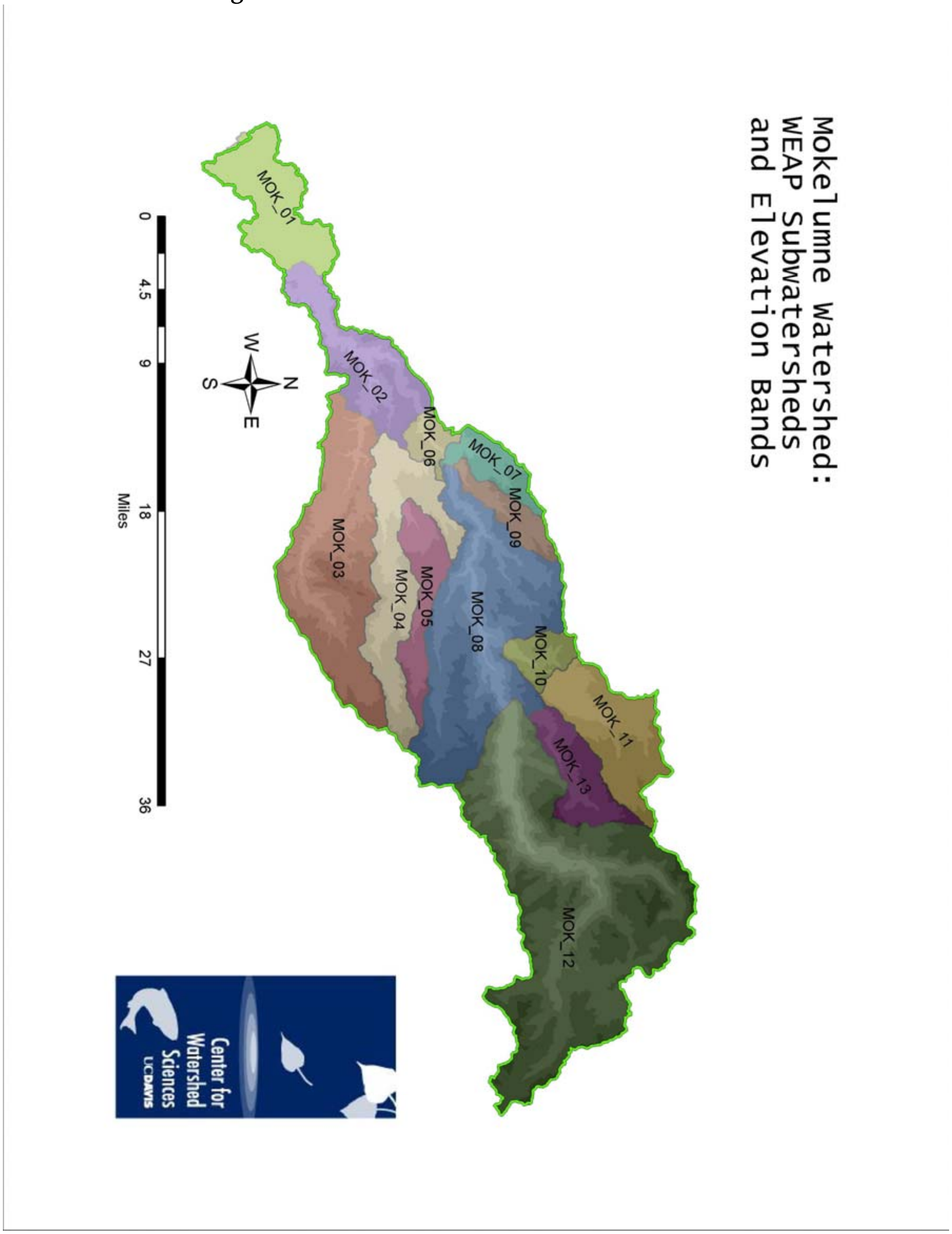


Figure 17. IBI Scores (Viers et al. this report)

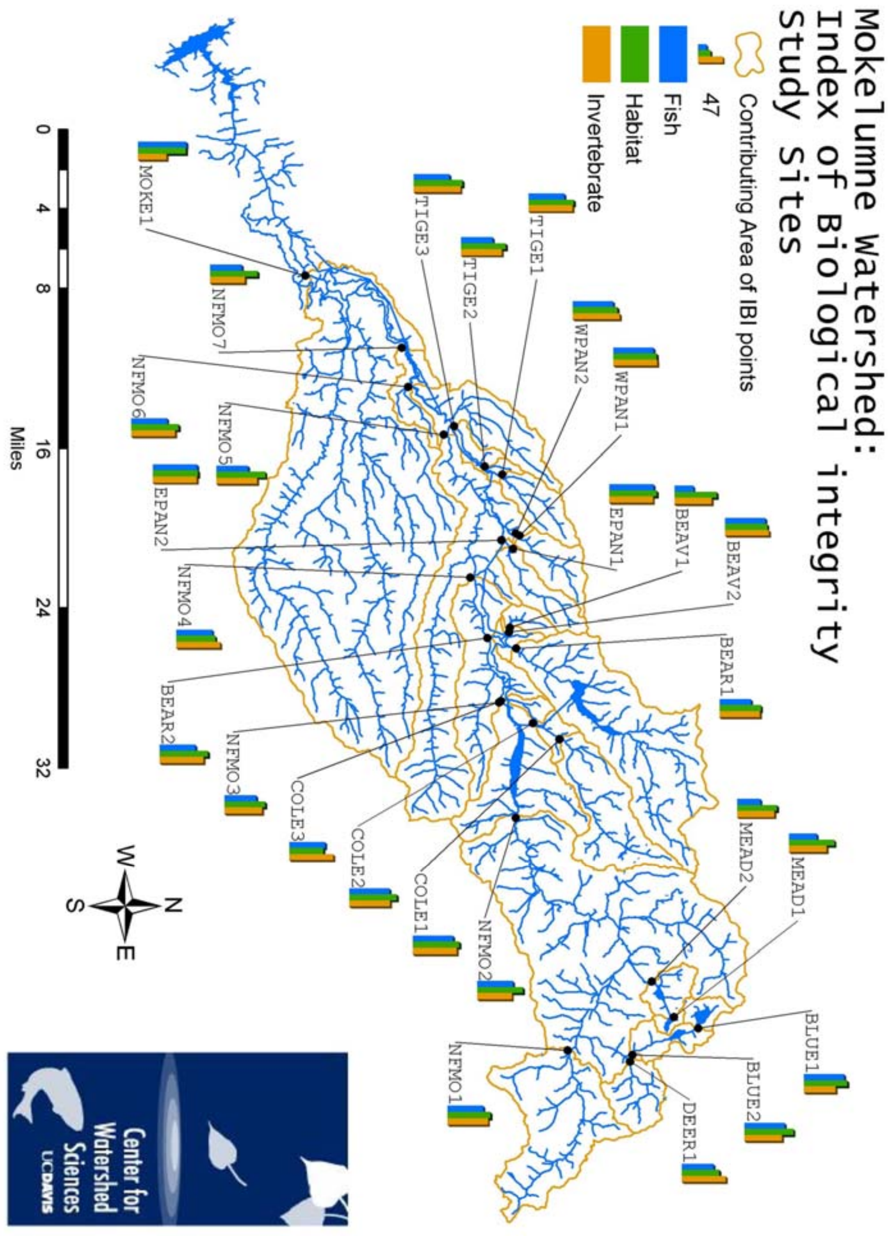
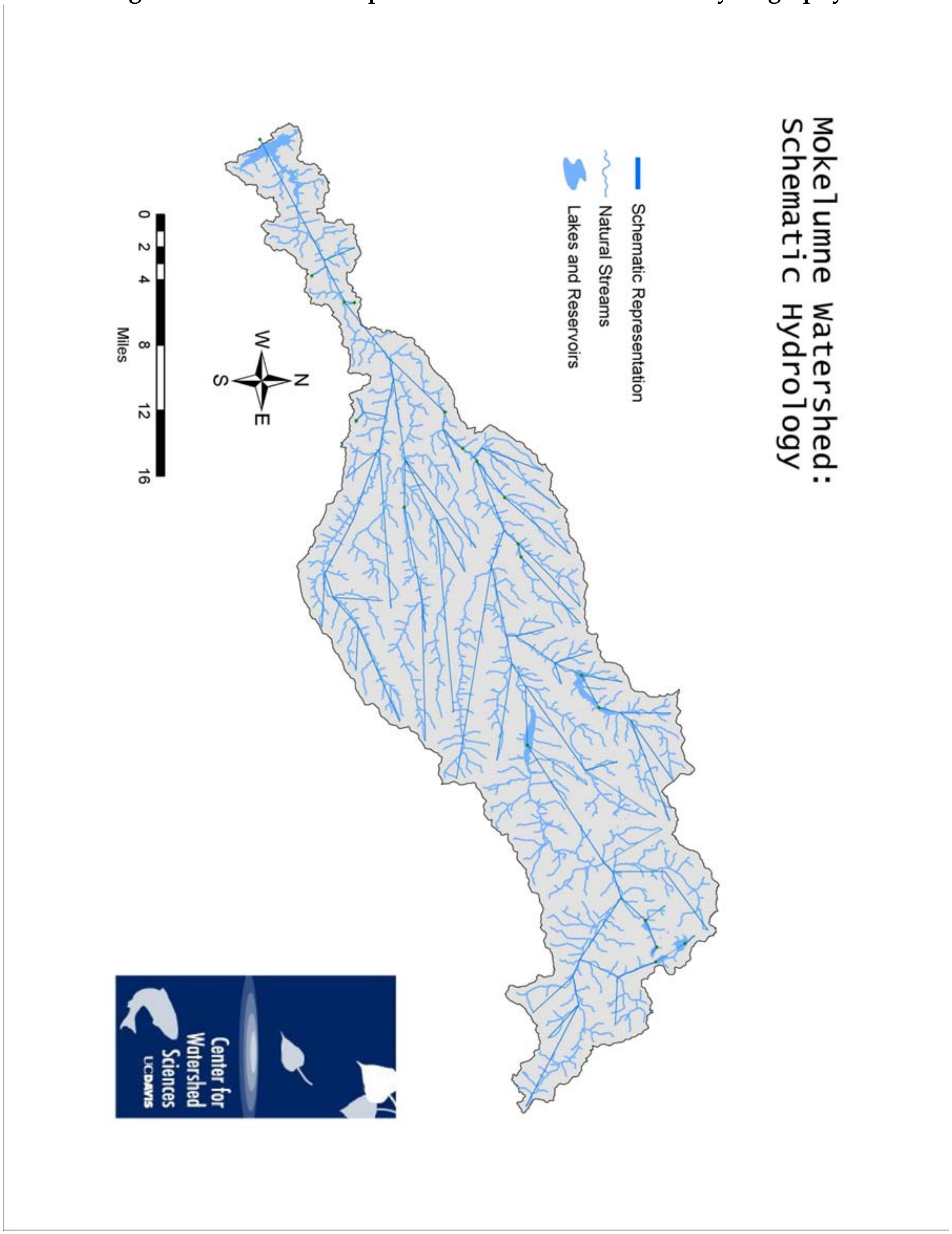


Figure 18. Schematic Representation Built on Natural Hydrography



Appendix B: Major Sierra Nevada Watersheds

First Phase Base GIS Data are created for the following major Sierra Nevada watersheds prefaced by standard 3-character code:

Table 6. Watershed Codes

Watershed	Watershed Code
American	AMR
Bear	BAR
Calaveras	CAL
Cosumnes	COS
Feather	FEA
Kaweah	KAW
Kings	KNG
Kern	KRN
McCloud	MCC
Merced	MER
Mokelumne	MOK
Pit	PIT
Sacramento	SAC
San Joaquin	SJN
Stanislaus	STN
Tule	TUL
Tuolumne	TUO
Yuba	YUB

Appendix C: HYDRA Database Structure

Figure 19. Each Watershed Directory Contains Multiple Geodatabases for Analysis

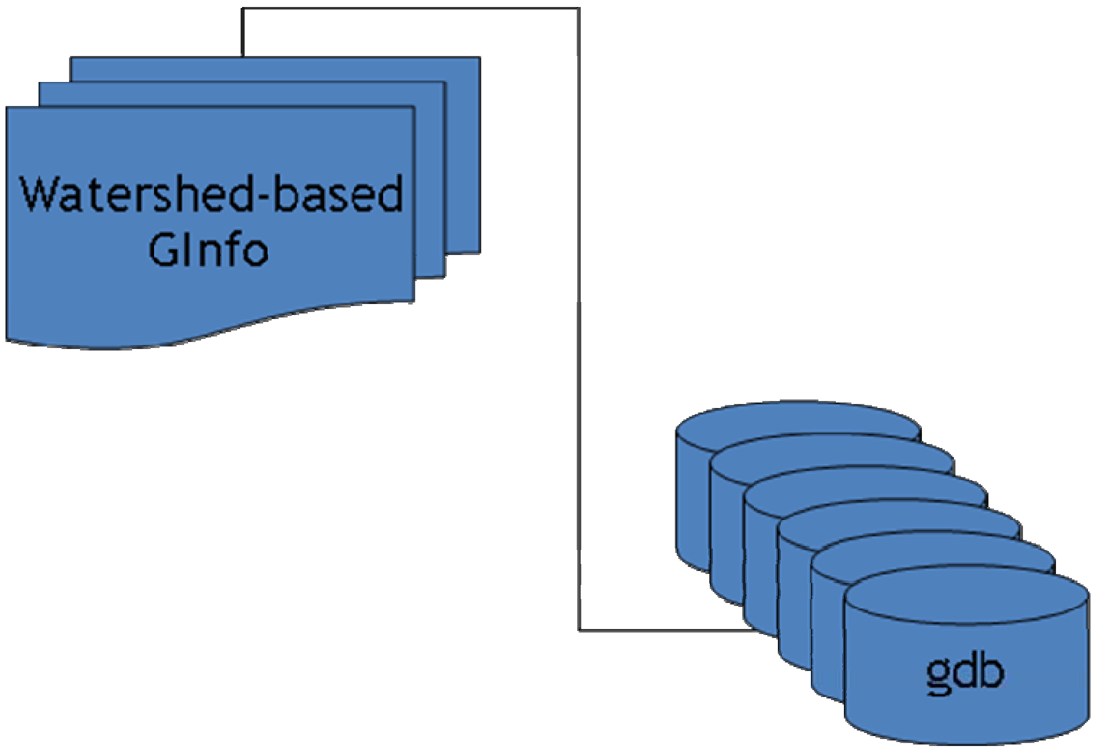


Figure 20. The Geodatabase Provides a Powerful Setting for Data Compilation, Analysis, and Extraction

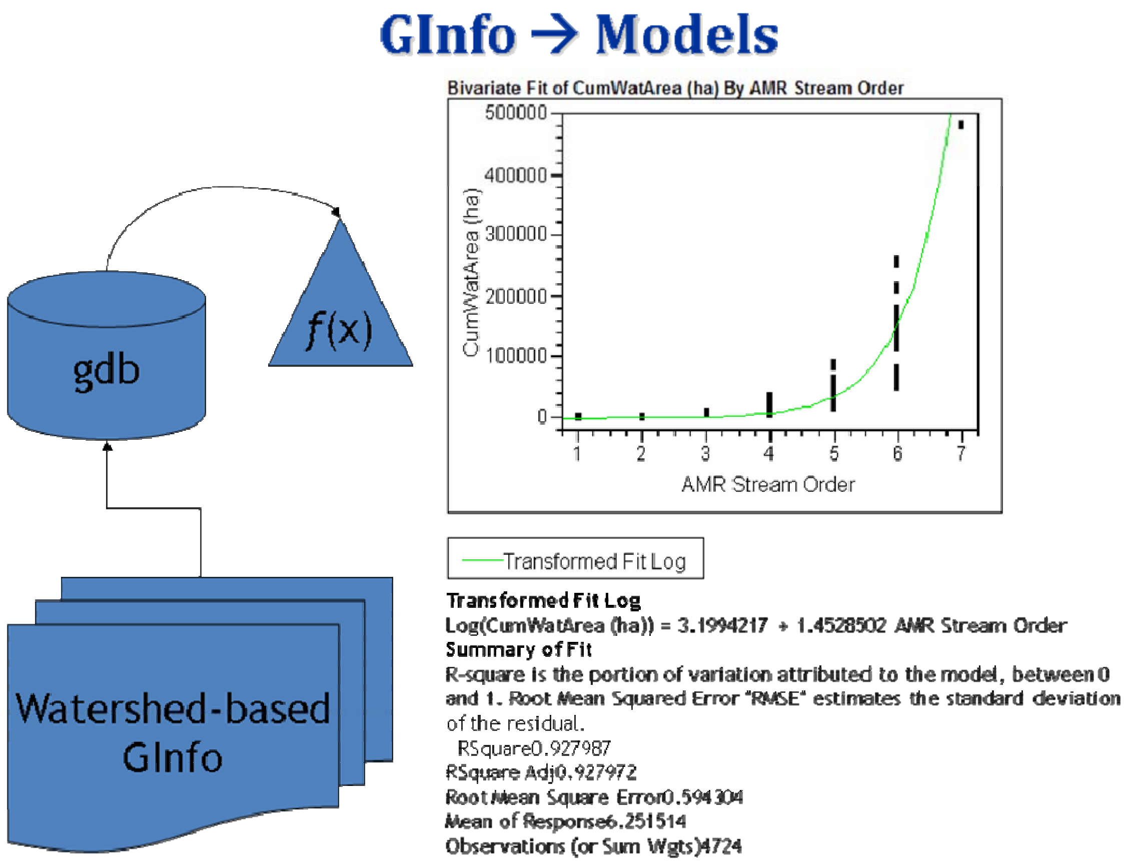


Figure 21. HYDRA Database Is Designed To Interface Efficiently With Other Analytical Frameworks

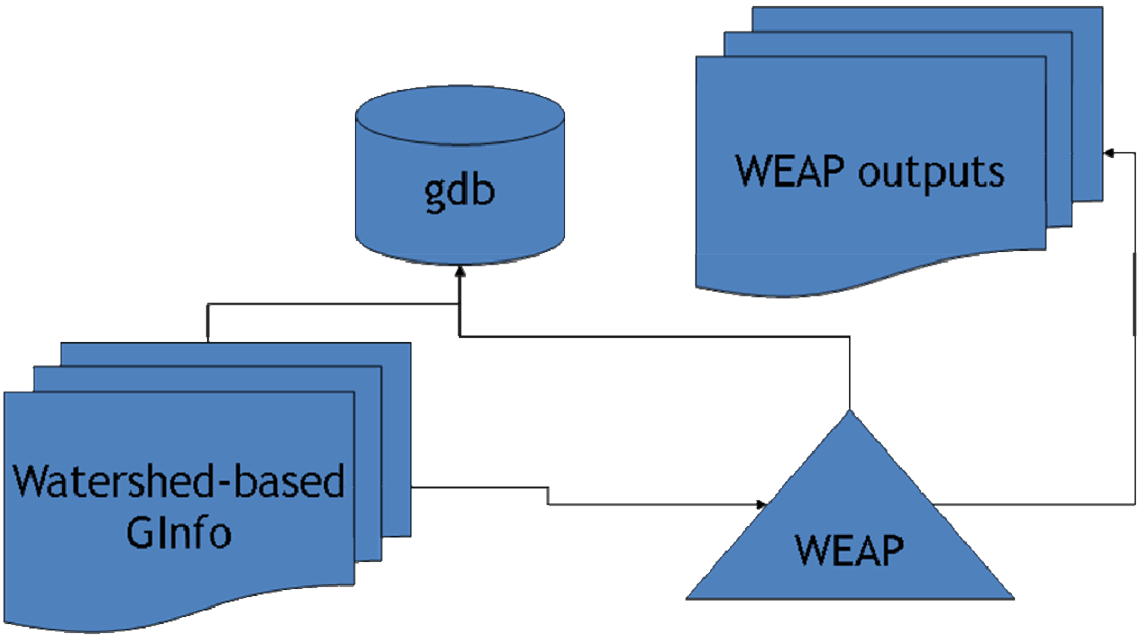
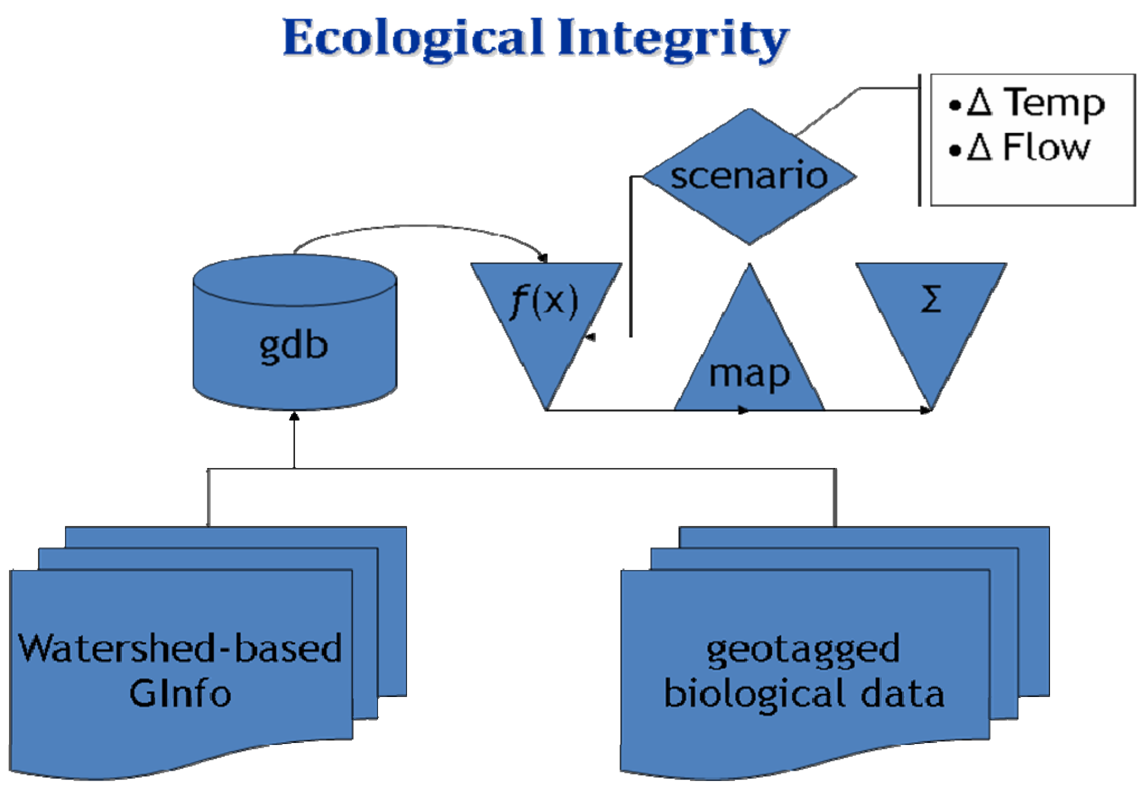
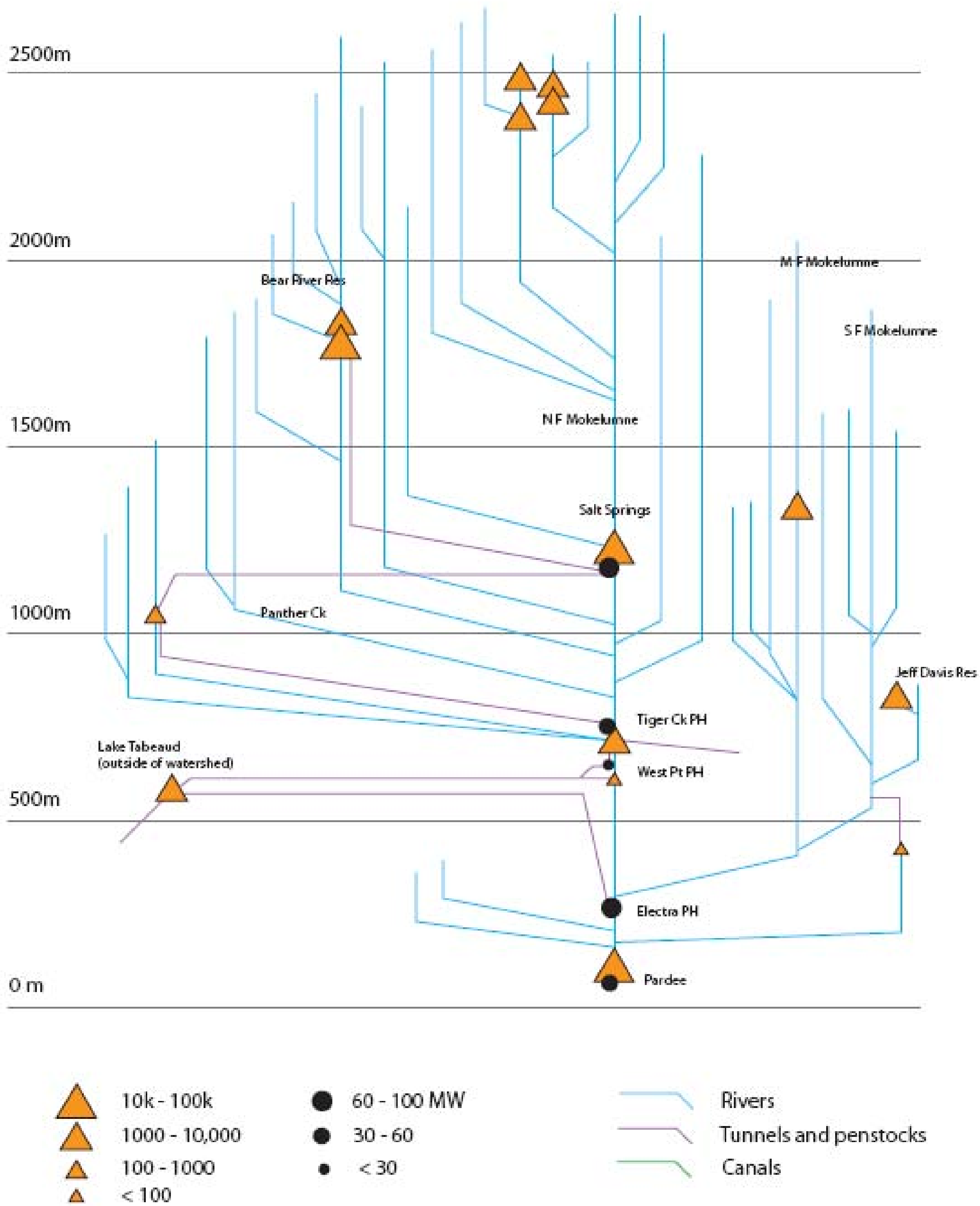


Figure 22. Ultimately, modelling of ecological scenarios will enhance understanding of management options



Appendix D: Schematic

Figure 23. Schematic of Mokelumne Stream Network



Appendix E: Detailed HYDRA GIS Data Listing for Mokelumne River Watershed

Data available on request.

COMPARATIVE ANALYSES OF ECOLOGICAL INTEGRITY INDICES AS APPLIED TO WATERS OF THE MOKELUMNE RIVER WATERSHED

PROJECT REPORT

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Abstract

Freshwater resources and ecosystems are globally impaired by human activities and acutely stressed throughout California, including the rivers and streams of the Sierra Nevada. We assessed the condition of the Mokelumne River, a representative watershed located in the central Sierra Nevada, at multiple scales to meet three explicit objectives. One, we developed indices of biotic integrity to represent the conditions of fishes, benthic macroinvertebrates, and habitat found in representative locations at the site-specific scale. Two, we developed a watershed-scale index of riverine integrity to characterize the ecological state of all streams within the basin. Three, we performed the first explicit comparison of integrity indices to assess how well traditional instream-based methods correspond to those developed at the watershed scale. Our results indicate that hydrologic alteration from hydroelectric power operations has a significant negative influence on the integrity of streams as measured by both fish and benthic macroinvertebrate integrity indices. We found no significant relationship between habitat integrity and hydrologic alteration, suggesting that studies using only measures of instream habitat condition may not be able to detect impairment. Our explicit comparison across scales suggests that future studies can use GIS-based, watershed-scale indices of integrity to evaluate riverine integrity widely across basins.

Keywords: California, Sierra Nevada, watershed, river, stream, integrity, index

Introduction

Globally, freshwater resources are imperilled (Revenga et al. 2000) and aquatic ecosystems continue to be severely threatened by human activities (Moyle and Williams 1990). Hydrologic alteration in the form of dam building, channelization, diversions, and infrastructural development has significantly, and negatively, affected freshwater resources worldwide. Pacific Rivers Council (2007) recently stated, "there is simply no substitute for clean water," nor the numerous ecosystem services provided by freshwater habitats such as rivers, lakes, and wetlands (Wilson and Carpenter 1999). Despite these observations, freshwater ecosystems remain largely ignored in most habitat conservation plans (Higgins et al. 2005). In California, dams (Moyle and Williams 1990), habitat alteration (Mount 1995), and invasive species (Moyle and Marchetti 2006) are among many human mediated activities that directly impact the integrity of aquatic ecosystems. Hydrological alteration is especially problematical to freshwater ecosystems in the semi-arid western United States (Richter et al. 1996), and California's Sierra Nevada in particular (Moyle et al. 1996).

Current methods for assessing human mediated impacts on freshwater habitats have not kept pace with those developed for terrestrial ecosystems. A primary reason for this disconnect, above and beyond the lack of focus (Abell et al. 2007), is the dearth of integrated and multiscalar techniques for rapid assessment of the ecological integrity of freshwater ecosystems (Amis et al. 2007). Assessments of ecological integrity are often resource intensive and based on limited data thus hindering the scale and scope of their application. Moreover, the very definition of freshwater integrity (sometimes referred to as river health), and its methods of evaluation are contentious and elusive (Wicklum and Davies 1995, Norris and Norris 1995, Norris and Thoms 1999).

For this study, we ask the question to what degree can contemporary instream-based indices of ecological integrity correspond with indices developed at the riverscape or watershed scale? Rather than focusing on the definition of integrity at a single scale, we address the applicability of bridging scales to broaden the assessment framework. The main advantage of this approach is that it provides a means to gauge ecological integrity for the many waterbodies where empirical biological and physical (biophysical) survey data do not exist, thus increasing the spatial scope of assessments and the rapidity in which the assessments can be made. The use of an index or numeric qualifier to describe the condition of a resource is not new; however, no study to date has explicitly aimed to compare indices developed at different ecological scales for freshwater systems. The importance of this study is to establish through a pilot programmatic approach the comparability of multiple methods for indexing the ecological integrity of waterbodies, where the methods differ not only in their input parameters, but also in the spatial scale from which they were derived. If the different scales can be bridged, we can apply the broad scale indexing approach to all waterbodies, alleviating the need for resource intensive biophysical field surveys. Such an approach also expands the veracity of scenario modeling in which watersheds undergo any number of changes in future condition, such as changes in hydrologic condition or land use impacts.

Indices of Biotic Integrity

Groups of freshwater organisms (e.g., amphibians, fish, macroinvertebrates, and periphyton) are frequently used to evaluate the ecological condition of streams, lakes, and wetlands. Unlike chemical and physical measures of water quality that provide a snapshot of environmental conditions, aquatic organisms integrate all of the biogeochemical influences to which they are exposed throughout their lifetimes (Karr 1991, Barbour et al. 1999, Karr and Chu 2000). Hence, stream communities are often responsive to forms of environmental impairment (e.g., altered flow regimes, increased water temperatures, or increased sediment deposition) that would generally remain undetected by traditional chemical or toxicological sampling (Karr and Chu 1999, Barbour et al. 1999). When used in concert, biological, chemical and physical assessments reflect the effects of water quality over time, are sensitive to an array of environmental stressors, and yield very robust evaluations of local stream condition (Yoder and Rankin 1998, Barbour et al. 1999, Ode et al. 2005).

Biological assessments have been a fundamental component of water quality monitoring programs since the passage of the Clean Water Act in 1972. Early attempts to apply biological criteria to water quality standards often relied on a single measurement of community structure such as taxonomic richness, biomass, or the presence/absence of one or more indicator species. However, single-variable approaches often failed to adequately explain the responses of biotic communities to various impairments (Yoder and Rankin 1998) and yielded little information to guide water resource managers. In response to these shortcomings, integrative approaches that examined and quantified multiple attributes (or metrics) of the biological community were subsequently developed.

The most widely employed multimetric approach, the index of biotic integrity (IBI), was first introduced by Karr (1981) as a measure of stream condition based on fish assemblages. Developed for use in small warmwater streams in central Illinois and Indiana, Karr's IBI consisted of 12 metrics that reflected fish community composition, number and abundance of indicator species, trophic structure and function, reproductive function, and condition of individual fish. Each metric was selected for inclusion in the index because it was a readily quantifiable attribute of the biological assemblage that changed in a predictable way with different levels of impairment (Karr 1981, Chirhart 2003). Waters with high biological integrity are defined as those that possess "a balanced, integrated, adaptive community of organisms having a species composition, diversity and functional organization comparable to that of the natural habitats of the region" (Frey 1977, Karr and Dudley 1981, Karr 1991). Variations of this definition have since been adopted by most federal and state agencies charged with water quality management (Angermeier and Karr 1994).

Indices of biotic integrity seek to condense multiple biological and/or physical parameters at a specific site (generally a stream reach) into a single numerical score. Scores may then be used to assess a site's deviation from locally calibrated reference conditions (i.e., reference sites with little environmental degradation) or compare multiple sites across a geographic area. Since the initial development of the IBI, it has been modified for a variety of regions, ecosystems, and organisms (Miller et al. 1988, Fausch et al. 1990, Simon and Lyons 1995, Hughes and Oberdorff

1999) and has proven to be a reliable and defensible means of assessing the effect of human disturbance on streams and watersheds (Karr and Chu 1999).

Although fish-based IBIs have been developed and applied in many regions of North America (Miller et al. 1988, Simon and Lyons 1995) their application has been limited in the Pacific Northwest and California (Miller et al. 1988, Fore et al. 1996, Moyle and Marchetti 1999). A number of ecological issues restrict the use of fish based IBIs in California watersheds (reviewed in Moyle and Marchetti 1999), but two are especially relevant to Sierra Nevada drainages: the small number of native fishes in most streams and the homogenization of fish assemblages through historic trout stocking programs. Both issues undermine the robustness of traditional multimetric IBIs because the behavior of integrity models is strongly influenced by diversity related metrics (Miller et al. 1988, Moyle and Randall 1996).

In contrast to native fishes, California streams and rivers often contain several hundred identifiable taxa of aquatic macroinvertebrates. This has resulted in the development of numerous aquatic biological assessment programs that utilize macroinvertebrates to assess ecological condition. Extensive benthic macroinvertebrate data sets have been collected by numerous agencies including the California Department of Fish and Game, the US Forest Service, and State and Regional Water Quality Control Boards (Herbst and Silldorff 2006). These efforts, in turn, have led to the development of multimetric B-IBI (Benthic-Index of Biotic Integrity) models for wadeable streams in specific watersheds (e.g., Russian River watershed; CDFG 1999), for broad geographic areas such as the southern California coastal region (Ode et al. 2005), and eastern slopes of the Sierra Nevada mountains (Herbst and Silldorff 2006). However, no B-IBIs have been published to date for watersheds draining the west side of the Sierra Nevada range.

Indices of Watershed Integrity

It has been long recognized that a more holistic view of watershed processes is required to effectively ascertain the threats, vulnerabilities, and ecological capacity of streams and rivers (Frissell et al. 1986). A growing body of theoretical work has resulted in the emerging discipline of riverscape ecology which seeks to bridge observations from stream ecologists with the insights and tools of landscape ecologists (Fausch et al. 2002). This has led to a profusion of published studies which attempt to identify and quantify ecological processes and anthropogenic disturbances at the riverscape scale. The Sierra Nevada has received some of this effort, with early identification and cataloging of discrete freshwater habitats by Moyle and Ellison (1991). Their observations, coupled with numerous other synoptic studies in the Sierra Nevada Ecosystem Report (see SNEP 1996a, 1996b, 1996c), have led to a number of qualitative and quantitative attempts to capture rarity, vulnerability, and the importance of aquatic ecosystems in the Sierra Nevada (e.g., Moyle 1996, Moyle and Randall 1996).

In a seminal study, Moyle and Randall (1998) developed a unique biotic index intended to assess the health of individual Sierra Nevada watersheds and identify those drainages with high conservation potential. Unlike previous IBI models that characterized site-specific conditions, Moyle and Randall's (1998) Watershed Index of Biotic Integrity (W-IBI) utilized broad, watershed-scale measurements of biotic information such as the presence and abundance of native fish, ranid frogs, and anadromous fishes. Once W-IBI scores were derived for each basin, they were compared to landscape-scale variables that served as measures of disturbance in each watershed (e.g., number of dams, reservoir capacities, and road densities). Only seven of the 100 watersheds examined by Moyle and Randall (1998) scored in the excellent condition category (i.e., W-IBI scores >80). In general, watersheds that scored poorly were either at lower elevations and highly modified by dams, agriculture, or urbanization, or at high-elevation where introduced trout were present in historically fishless areas.

Although few published studies have been as explicit in describing an index of biological integrity at the watershed scale as were Moyle and Randall (1998), a number of contemporary studies have used a geographical information system (GIS) to capture, catalog, and assess catchment-scale impacts of human activities on freshwater ecosystems. Four recent studies are particularly relevant to our efforts, as their methods influenced the approach used in our study. Each of the methodological approaches described in the studies below pursued two central objectives: 1) to characterize the integrity of freshwater ecosystems using coarse scale data at the riverscape or watershed scale, and 2) to develop a robust indicator index from multimetric data that was repeatable and potentially applicable to watersheds outside the immediate study.

In a study of South Africa's major watersheds, Nel et al. (2007) described ecological integrity as a function of flow, inundation, water quality, stream bed condition, introduced instream biota, and riparian or stream bank condition. Similarly, Amis et al. (2007) identified twelve factors that impact freshwater ecosystems, which included measures of human activity such as dams, roads, and land use. In his study of the Navarro River watershed in California, Viers (2007) identified two broad measures of human activities (beyond hydrologic modification) on freshwater ecosystems that can be measured within a GIS: road impacts and riparian alteration. Viers (2007) also described a GIS-based algorithmic solution to establishing ecological integrity for stream segments in an automated fashion. A similar algorithmic approach was used by Linke et al. (2007) who created a GIS-based model of watershed impairment by estimating freshwater ecosystem stressors as two broad gradients: 1) disturbance, as measured by a combination of biophysical parameters, and 2) land use, which included measures of forestry, agriculture, and urban uses. A number of other studies have also attempted to capture and index the ecological integrity of waterbodies at the watershed scale (e.g., Allan et al. 1997, Mattson and Angermeier 2007), and each has relied on readily available data over broad areas. It should be noted, however, that there are at least two limitations to the approaches utilized in these studies. First, readily available data rarely represent the best parameter collected in its latest condition with the finest resolution, which is to say that these data are inherently error-prone. Second, the spatial scope of any given study is inherently limited; therefore, the methods and results used in one specific region are not always applicable to others. Despite these limitations, the development of watershed-scale approaches to assess ecological integrity represents a critical step in assessing hydrologic alteration and informing freshwater conservation.

Methods

Pilot Study

We focused our pilot effort on the Mokelumne River watershed, located in the central Sierra Nevada. The Mokelumne River watershed is an ideal location to compare ecological integrity indices across scales because it is relatively small (1497.55 km^2), has both free flowing and dammed rivers, and has robust biological and physical survey data available for multiple locations. The three main objectives of our pilot study were as follows:

- To evaluate the site-specific ecological integrity of the Mokelumne River using preexisting data to represent stream condition at the reach scale.
- To develop a new method to characterize ecological integrity at the watershed scale that is robust, repeatable, and widely applicable.
- To compare the results of the ecological assessments from different scales and determine thresholds of influence that are evident across scales.

Instream Indices

We developed three conventional indices of integrity in support of this pilot study using previously collected biophysical information: 1) a fish-based index (F-IBI), 2) a benthic macroinvertebrate index (B-IBI), and 3) a physical habitat index (P-IBI). Our comparative approach (see objective 3 above) used the mean of these three biotic indices to represent a composite score for each site in the study.

Data collection for the instream indices of biological integrity was conducted by Garcia and Associates (2000), who surveyed 27 locations in the Mokelumne River watershed in September and October of 1999 for a variety of biophysical attributes. Survey sites were located throughout the watershed, including the headwaters at Blue Lakes in El Dorado County, to the mainstem near Electra Dam (Figure 1). The primary site selection criterion was the representative nature of each survey site in relation to the larger riverine segment. Sites were also chosen relative to physical hydropower structures so that comparisons could be made between regulated and unregulated reaches (Garcia and Associates 2000). At each survey site, data were collected on fish, benthic macroinvertebrates, physical habitat, and water quality in accordance with standard methods (e.g., California Stream Bioassessment Procedure[3], see Harrington and Born 1999). A detailed description of field and laboratory methods can be found in Garcia and Associates (2000).

Fish IBI

A variety of human activities may impair fish community integrity, such as fish stocking, hydropower operations, road construction, and urbanization. Anthropogenic disturbances that result in altered flow regimes can be especially detrimental to fish populations. Negative effects may include streambed scouring due to ramping, changes in temperature and turbidity, loss of

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[3] California Department of Fish and Game's publication available online: http://www.dfg.ca.gov/cabw/csbp_2003.pdf

invertebrate prey production, and loss or alteration of critical habitat. Our fish IBI (F-IBI) included five component metrics that are responsive to various types of environmental impairment. The metrics included: 1) fish biomass in grams/m^2, 2) species richness, 3) total fish abundance, 4) presence of native trout, and 5) percent native species. The rationale behind each metric is as follows:

Fish biomass: This metric accounts for the amount of fish production per unit area of streambed. The greater the biomass supported, the higher the function of a reach. Adult fish are fairly resilient to hydropower operations, but over time, biomass can decrease in impaired reaches if operations cause high mortality during one or more life stages (e.g., eggs or juveniles). We expect this metric to decrease with impairment.

Species richness: High species richness indicates stable and productive habitat that can support a diverse assemblage of fishes. Greater diversity indicates good overall condition in a reach (though diversity is naturally curtailed with increased elevation). We expect decreased diversity in impaired reaches. Headwater streams are often an exception to this, however, as many reaches that would have historically been fishless now support populations of introduced trout.

Total fish abundance: Total abundance is similar to biomass, however it measures the number of individuals rather than the weight of the collected fishes. This is useful when comparing large and small reaches because small streams limit the size fish can grow to, but not necessarily the numbers of fish present.

Presence of native trout: Stocking of hatchery bred and non-native trout significantly impact species composition in streams throughout the Sierra Nevada. Therefore, higher numbers of native trout[4] indicate less human alteration of the system.

Percent native species: The percentage of native species in a reach is indicative of relatively stable communities and lack of human alteration. This metric shows the impacts of non-native fishes to the system. We expect this metric to decrease with active stocking or major hydrologic alteration.

Each metric was scored by examining the distribution of values and determining natural breaks in the data. We then divided the data into three categories representing low, moderate, and high values. If a metric was classified into the low value category it was assigned a score of 1, the moderate value group a score of 3, and the high value group a score of 5. All five individual metric scores were then summed to create an overall site score, divided by the total number of metrics used to construct the IBI, and multiplied by a normalizing value (20 in this case) to scale the IBI to a maximum value of 100 points (Table 1). The resultant index score provided a broad, qualitative assessment of the overall integrity of a specific site. An integrity index score ranging

[4] Rainbow trout (*Oncorhynchus mykiss*) are the only trout native to the Mokelumne River, however it is impossible to tell whether current rainbow trout populations are of wild or hatchery origin due to widespread stocking programs.

from 0-25 indicated a site of “poor” biotic integrity, 26-50 as “fair”, 51- 75 as “good”, and 76-100 as “natural.”

Table 1. Metrics and distribution of scores used in our Mokelumne River fish IBI (F-IBI).

Metric	1 Score (Low)	3 Score (Moderate)	5 Score (High)
Fish Biomass (g/m^2)	< 2.0	2.1-5.0	>5.0
Species Richness (n)	0-1	2-3	4+
Fish Abundance (n)	< 10	10-50	50+
Native Trout Presence	Non-native species only	Native and non-native species mixed	Native species only
Native Species (%)	< 25	25-75	>75

Benthic Macroinvertebrate IBI

Benthic macroinvertebrates are good indicators of stream condition and water quality because of their variable tolerances to water quality impairments. Furthermore, macroinvertebrates often respond to smaller scale perturbations than do fishes, and can thusly provide information not evident in the highly mobile fish community. Scores for our B-IBI were based on seven metrics: 1) taxonomic richness, 2) number of EPT[5] taxa, 3) sensitive EPT index, 4) percent dominant taxa, 5) tolerance value index, 6) Shannon diversity index, and 7) percent Hydropsychidae (Table 2).

Taxonomic richness: The number of unique taxa is a measure of the diversity at a site. An impaired site will have a reduced invertebrate community in which more tolerant taxa dominate and sensitive taxa disappear. The greater the diversity at a site, the less likely it is to suffer from impairment.

Number of EPT taxa: EPT taxa refers to the number of distinct taxa in the orders Ephemeroptera, Plecoptera, and Trichoptera, which are generally thought to be among the most sensitive to water quality impairment. EPT taxa often decline below hydropower operations and are replaced by more tolerant taxa, though overall abundance of all taxa may be low. Higher proportions of EPT in a community indicate good stream health with good overall production.

Sensitive EPT index: The sensitive EPT index measures the percent of EPT species in the sample with published tolerance values of 3 or lower. These species are particularly sensitive to any kind of water quality impairment and are thus good indicators of stream condition. This metric is expected to decrease with impairment.

[5] Organisms in the aquatic insect orders Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies).

Percent dominant taxa: This metric is a measure of taxonomic evenness in the invertebrate community. At equilibrium, community composition is fairly even, but under impairment, there is often a shift in the community and certain taxa will dominate. We expect an increase in percent dominant taxa at impaired sites.

Tolerance value index: The tolerance value index (TVI) is a measure of taxa pollution tolerance values weighted against the relative abundance of each taxa in the sample. Laboratory-derived tolerance values reflect an organism's ability to withstand pollution, sedimentation, and other water quality impairments. The more intolerant the organism, the lower its tolerance value index. We expect higher TVI scores at impaired locations.

Shannon diversity index: The Shannon diversity index is commonly used to characterize species diversity in ecological communities. Shannon's index is a compound measure that accounts for both abundance and evenness of the species present. The higher the score, the more diverse and heterogeneous a community is.

Percent Hydropsychidae: Whereas most caddisfies are considered to be pollution intolerant, those belonging to the family Hydropsychidae have been found to be fairly robust indicators of impairment, particularly altered flow regimes (Harrington and Born 1999). As such, a high proportion of Hydropsychids in a given sample is indicative of environmental degradation.

Table 2. Metrics and distribution of scores used in our Mokelumne River benthic macroinvertebrate index of biotic integrity (B-IBI).

Metric	1 score (Low)	3 score (Moderate)	5 score (High)
Taxonomic Richness (n)	0-26	26-36	> 36
EPT Taxa (n)	0-11	12-19	>19
Sensitive EPT Index (%)	0-16	17-53	> 53
Percent Dominant Taxa	40-100	16-39	<15
Tolerance Index	>12	4.6-12	< 4.6
Shannon Diversity	< 2.2	2.2-2.9	> 2.9
Percent Hydropsychidae	>22	11-22	<11

Like the F-IBI, all metric values were categorized as low medium or high values and assigned scores of 1, 3, or 5, respectively (Table 2). Scores were subsequently summed, averaged, and normalized to a 100-point scale.

Physical Habitat IBI

The P-IBI represents a physical habitat index for high gradient streams initially developed by the USEPA (see Barbour et al. 1999) and subsequently adopted for use in California. The P-IBI is based on 10 metrics that score physical and biotic habitat conditions in a discrete stream reach. The metrics that comprise the P-IBI are: 1) epifaunal habitat, 2) embededness, 3) velocity/depth regime, 4) sediment deposition, 5) channel flow status, 6) channel alteration, 7) frequency of riffles, 8) bank stability, 9) vegetation protection, and 10) riparian zone width (Appendix A). Each habitat metric is scored to represent conditions from very poor (score = 0) to optimal (score = 20).

Watershed Index of Riverine Integrity (WIRI)

We created a watershed index of riverine integrity (WIRI) from a multimetric composite of GIS-derived parameters depicting watershed condition. These WIRI parameters cover four broad areas: hydrologic alteration, intentional fish stocking, road impacts, and riparian impairment. Our choice of watershed parameters was guided by three complementary tenets: 1) the metrics needed to be indicative of habitat condition and well supported by scientific literature, 2) each component needed to be largely independent of the others and readily calculated within a GIS, and 3) the resulting choices needed to be applicable to Sierran watersheds outside the Mokelumne pilot project. We believe that each WIRI parameter discussed below reflects thi rationale and is robust in itsformulation. The data sources, metrics, and thresholds for each parameter are included in Table 3. All GIS analyses were conducted in ArcGIS 9.2 (ESRI, Redlands, CA) and all statistical analyses were conducted in JmpIn 5.1 (SAS Institute, Cary, NC).

Hydropower and Hydrologic Alteration

We used two separate measures of hydropower induced alteration to hydrologic conditions for our study sites. First, we calculated the distance between each study site and the closest upstream dam, including both jurisdictional and diversional types. Second, for each site we summarized the upstream cumulative total capacity for reservoirs behind jurisdictional dams. Jurisdictional dams are defined as "artificial barriers, together with appurtenant works, which are 25 feet or more in height or have an impounding capacity of 50 acre-feet (af) or more. Any artificial barrier not in excess of 6 feet in height, regardless of storage capacity, or that has a storage capacity not in excess of 15 af, regardless of height, is not considered jurisdictional."[6] Distance to closest upstream dam gives a relative measure of the effect of hydrologic alteration, as sites closer to dams do not have tributary inputs to dampen effects of hydropower operations. The cumulative capacity of upstream reservoirs behind jurisdictional dams gives a regional measure of impactedness, detailing the volume of flow presumably altered in its timing, duration, and magnitude.

[6] California Department of Water Resources Bulletin 17-93

Table 3. Breakdown of watershed IRI metrics and associated data sources.

Parameter	Data Source	Metric	Poor (Score: 0)	Moderate (Score: 2)	Good (Score: 4)
Hydrologic Alteration (HydroModCapScore) *Eq. 1: Hydro$_C$*	California Dept. of Water Resources	Sum of Jurisdictional Dam Reservoir Capacity within Cumulative Watershed	Dam Capacity Upstream > 3000 acre-feet	Dam Capacity Upstream < 3000 acre-feet	No Dams Upstream
Hydrologic Alteration (HydroModDamDistScore) *Eq. 1: Hydro$_D$*	California Dept. of Water Resources	Distance from IBI Site to Closest Upstream Jurisdictional or Diversion Dam	Closest Dam Upstream < 2000 m	Closest Dam Upstream > 2000 m	No Dams Upstream
Fish Stocking (StockScore) *Eq. 1: Stocking*	California Dept. of Fish & Game	Stocking Activity (2002 - 2006)	Active Fish Stocking	Upstream or Downstream of Active Fish Stocking 1000m	No Active Stocking
Roads (LocalRdDensityScore) *Eq. 1: Roads$_L$*	Geographic Data Technology, Inc.	Density of Local Roads within 100m Buffer of Cumulative Streams	High Density > 1.28 km/km^2	Moderate Density 1.28 > x > 1.1 km/km^2	Low Density < 1.1 km/km^2
Roads (RdXingDensityScore) *Eq. 1: Roads$_X$*	Geographic Data Technology, Inc.	Density of All Road Crossings within Cumulative Watershed	High Density > 1.4 Xing / km^2	Moderate Density 1.4 > x > 1.25 Xing / km^2	Low Density < 1.25 Xing / km^2
Riparian (RipCovScore) *Eq. 1: Riparian*	National Landuse Classification Database (USGS NLCD)	Percent Tree cover within 100m of IBI Site	Riparian Tree Cover within 100m of Site < 50%	Riparian Tree Cover within 100m of Site > 50% <= 85%	Riparian Tree Cover within 100m of Site > 85%

Fish Stocking

We chose to include fish stocking as a measure of riverine integrity for two distinct reasons. First, stocked fishes are a well documented contributor to the decline of native amphibians in the Sierra Nevada (e.g., Knapp and Matthews 2000, Knapp 2005). Fish stocking not only alters the aquatic community through manipulation of the composition and abundance of fishes, but also through direct and indirect ecological interactions such as predation and competition. Second, the principal intent of fish stocking is to improve recreational opportunities for anglers. Unfortunately, several detrimental activities are associated with recreational fishing, including habitat alteration (e.g., bank erosion) and the introduction of non-native species as bait (e.g., signal crayfish). Using CDFG stocking records for the period 2002-2006, we classified all sample sites as being either 1) actively stocked, 2) within 1 km of a stocking location, or 3) beyond 1 km of a stocking location.

Road Impacts

The impacts of roads on freshwater habitats are well documented (reviewed in Jones et al. 2000). Roads typically lead to an imbalance in geomorphic fluxes within rivers through confinement, bank instability, aggradation, et cetera. Other impacts include changes in runoff conditions, increases in impervious surfaces, disconnection of waterbodies due to road crossings and culverts, removal of riparian cover, the introduction of non-native species, and increased opportunities for human encroachment. We measured the impacts of roads on riverine ecosystems in two ways: 1) we calculated the cumulative density of local roads (excluding highways and four wheel drive roads) within 100m of all streams above each site, and 2) we calculated the density of all road crossings above a site regardless of road type. While these metrics are moderately positively correlated (R= 0.58), each provides a complementary measure of impactedness.

Riparian Cover

We used a single metric to describe the influences of terrestrial land uses on riverine ecosystems and riparian condition. Specifically, we calculated the percent of tree cover within 100m of a sample site. Since riparian trees are known to provide numerous physical and ecological benefits to riverine ecosystems (e.g., stream shading, allochthonous inputs, streambank stability, and habitat forming debris), we emphasized the significance of this variable by doubling its influence on the WIRI composite score.

WIRI Composite Score

For each watershed metric, we assigned an integrity score to reflect one of three conditions: poor, moderate, or good with scores of 0, 2, or 4, respectively. Scores were summed, weighed, and normalized to produce composite scores that ranged from 0 to 100. The WIRI can be defined by equation 1 (see table 3 for a description of input variables). In this equation, β_2 takes on a value of 2 (see 34.3.4 above), whereas β_1 remains 1.

$$\frac{\sum\left(\beta_1(Hydro_D, Hydro_C)\middle|\beta_1(Stocking)\middle|\beta_1(Roads_L, Roads_X)\middle|\beta_2(Riparian)\right)}{\sum_i^n metric\ score_{\max}}\times(100) \qquad \text{Eq. 1}$$

We compared the WIRI scores to the composite IBI which was derived from the average of the three instream IBIs (i.e., the mean of F-IBI, B-IBI, and P-IBI scores for a given site).

Results

Results from Instream Indexing

The results from the 27 Mokelumne River sites indicate that nearly all of the sites in the watershed fall within the range of good to natural condition for all instream IBIs constructed.

Fish

The F-IBI generated the greatest overall range of scores with a low of 36 (BEAV1) and a high of 92 (MOKE1). The low index score for BEAV1 was largely the result of low species richness, low total abundance, and the absence of native species at the site (Table 4). In fact, only one fish species was present at BEAV1 (non-native brown trout, *Salmo trutta*) and only 20 individuals were discovered in the entire 100 m study reach. Conversely, MOKE1 contained six fish species and had extremely high total abundance (1279 fishes). Native rainbow trout were the only salmonid species present, and all fish species at MOKE1 were native to the watershed. It should

Table 4. Comparison of raw data, metric scores, and F-IBI scores for the highest and lowest scoring sites in the study.

Site Name	MOKE 1		EPAN1		BEAV1	
Metric	Raw Score	Metric Score	Raw Score	Metric Score	Raw Score	Metric Score
Biomass (g/m²)	2.57	3	8.25	5	2.27	3
Species Richness (n)	6	5	2	3	1	1
Total Abundance (n)	1279	5	225	5	20	3
Trout Community	Native only (rainbow trout)	5	Native and Non-native (rainbow and brown trout)	3	Non-native only (brown trout)	1
% Natives	100%	5	82.7%	5	0%	1
F-IBI Score	**92**		**84**		**36**	

be noted, however, that MOKE1 had a very unique fish assemblage relative to all other sites included in the study. Specifically, the fish assemblage at MOKE1 was characteristic of those typically found in larger Central Valley waterbodies rather than smaller salmonid-dominated Sierran streams. By way of comparison, the next highest scoring site, EPAN1 (F-IBI = 84), only contained two species (83% native rainbow trout and 17% non-native brown trout) but the index score was heavily influenced by remarkably high biomass ($8.25g \cdot m^{-2}$) and total abundance (N=225). The overall mean F-IBI score for the Mokelumne watershed (all sample sites combined) was 67.7 ± 12.0 (mean ± 1SD) suggesting that the watershed is in "good" condition overall (Table 5).

Table 5. Site condition categories for instream IBIs. Note that P-IBI has a different nomenclature because it is a preexisting, national index we adopted for use in this study (Barbour et al. 1999). In this study, Natural/Optimal = No or negligible modification from a natural state, Good/Sub-optimal = Biodiversity largely intact with some past or current impacts, Fair/Marginal = Native assemblages altered, some past or current impairment observed, and Poor = Considerable current impairment, loss of native assemblage, mostly tolerant species.

Scoring Categories	76-100	51-75	26-50	0-25
F-IBI	Natural	Good	Fair	Poor
B-IBI	Natural	Good	Fair	Poor
P-IBI	Optimal	Sub-Optimal	Marginal	Poor

Benthic macroinvertebrate IBI

Overall, the benthic macroinvertebrate IBI scores were quite good with all Mokelumne River sample sites being classified as "good" to "natural" condition (Table 5). The two highest scoring B-IBI sites were TIGE3 and WPAN2, each scoring 89 out of 100 possible points (Table 6). Despite receiving identical scores, there were marked differences in the component B-IBI metrics that suggest perceptibly different water quality conditions at TIGE3 and WPAN2. For example, TIGE3 scored better with respect to tolerance value index, percent dominant taxa, and percent Hydropsychidae, while WPAN2 had higher taxa richness, EPT taxa, Shannon diversity index, and sensitive EPT index (Table 5).

The lowest B-IBI score was generated for MOKE1 which scored 54 out of 100 possible points. Although MOKE1 scored similar to high integrity sites (e.g., TIGE3 and WPAN2) for metrics such as percent dominant taxa and Shannon diversity index, the overall index score suffered from low taxonomic richness (*N*=34), sensitive EPT index, fewer EPT taxa (*N*=18), and especially percent Hydropsychidae (37% of the assemblage was comprised of Hydropsychid caddisflies).

Table 6. Comparison of raw data, metric scores, and B-IBI scores for the highest and lowest scoring sites in the study.

Site Name	WPAN2		TIGE3		MOKE1	
Metric	Raw Score	Metric Score	Raw Score	Metric Score	Raw Score	Metric Score
Taxa Richness	41	5	37	5	34.33	3
%Dominant Taxa	31.76	3	26.96	3	20.16	3
EPT Taxa	24.67	5	20	5	18	3
Sensitive EPT Index	62.42	5	58.23	5	43.46	3
Shannon Diversity	2.82	3	2.79	3	2.76	3
% Hydropsychidae	3.78	5	1.78	5	37.35	1
Tolerance Value	2.89	5	2.44	5	3.06	3
B-IBI Score	**89**		**89**		**54**	

Physical Habitat IBI

The P-IBI consistently yielded the highest scores of the three indices examined. Results of the P-IBI suggest "optimal" physical habitat conditions throughout the Mokelumne watershed, with only 3 sites (COLE3, DEER1, and NFMO4) scoring in the "sub-optimal" category (Table 5). The scores ranged from a high of 93 (BLUE2, NFMO5, and TIGE3) to a low of 64 (COLE3). The overall mean P-IBI score for the Mokelumne watershed (all sample sites combined) was 84.1 ± 7.3 (mean ± 1SD) suggesting that the habitat in the watershed is in "optimal" condition overall (Table 5).

Table 7. Mokelumne River sample sites and associated index of biotic integrity (IBI) scores. The mean composite IBI score represents the average value of the fish, benthic macroinvertebrate, and habitat IBIs.

Sample Site	Fish IBI	Benthic Macro-invertebrate IBI	Physical Habitat IBI	Mean Composite IBI score
BEAR1	60	77	79	72.0
BEAR2	68	83	92	81.0
BEAV1†	36	71	80	62.3
BEAV2	76	83	80	79.7
BLUE1	76	60	82	72.7
BLUE2	76	71	93	80.0
COLE1	76	83	88	82.3
COLE2	76	77	90	81.0
COLE3	68	83	64	71.7
DEER1	60	83	71	71.3
EPAN1	84	83	90	85.7
EPAN2	84	83	86	84.3
MEAD1	52	71	86	69.7
MEAD2	44	71	76	63.7
MOKE1	92	54	91	79.0
NFMO1	68	77	82	75.7
NFMO2	68	66	87	73.7
NFMO3	60	71	77	69.3
NFMO4	68	83	74	75.0
NFMO5	60	77	93	76.7
NFMO6	68	83	90	80.3
NFMO7	60	66	90	72.0
TIGE1	68	83	86	79.0
TIGE2	60	77	85	74.0
TIGE3	68	89	93	83.3
WPAN1	76	83	82	80.3
WPAN2	76	89	85	83.3
Overall Mean	67.7	76.9	84.1	76.3
Std. Deviation	12.0	8.6	7.3	6.1

†Site was excluded from all watershed-scale analyses.

Results from Watershed Indexing

The Watershed Index of Riverine Integrity is a compound score of watershed condition based on GIS-derived parameters indicative of human alteration to freshwater ecosystems. We derived WIRI to assess the ecological integrity of the Mokelumne River watershed and determine the comparability of condition indices derived at different spatial scales and with different metrics. As applied to the Mokelumne River watershed, WIRI scores were generated for 26 of 27 sites used in our instream IBI evaluation. We excluded site BEAV1 from all analyses as it was a statistical outlier.

WIRI scores ranged from 29 to 93, with a median score of 50 and mean score of 60 (± 18, 1SD) (see Map Figure 2). Scores were normally distributed, as determined by the Shapiro-Wilk goodness-of-fit test. Moreover an evaluation of environmental factors revealed that there was no bias in WIRI scores as a function of elevation ($p = 0.65$), watershed area ($p = 0.22$), drainage density ($p = 0.46$), distance to watershed divide ($p = 0.34$), distance to watershed outlet ($p = 0.89$), length of reach ($p = 0.34$), reach slope ($p = 0.68$), latitude ($p = 0.81$), or longitude ($p = 0.90$). From these diagnostic statistics, we determined that there was no inherent bias to WIRI scores in regards to either environmental correlates or spatial pattern.

The site with the highest WIRI score was COLE1, which scored 93 out of 100 points. The COLE1 site represented a 4th order stream 1869 m above sea level, draining 500 ha of watershed, and a 3.7% stream gradient. COLE1 scored high in each WIRI category except distance to dam (Table 8). The lowest scoring site was MEAD2, which scored 29 out of 100 points. The MEAD2 site represented a 3rd order stream 2313 m above sea level, draining 1510 ha of watershed, and an 8.2% stream gradient. The MEAD2 site scored the lowest possible value in three of the parameter classes: upstream jurisdictional dam capacity (6460 af), distance to upstream dam (1.1 km), and riparian cover (22%). MEAD2 had moderate scores for fish stocking (< 1 km) and road density within 100m of streams (0.1 km/km^2), and scored high for low road crossing density (0.2 Xing / km^2). Comparatively, the MEAD2 site had the second lowest composite instream IBI score (63.7; Table 7).

Table 8. Mokelumne River watershed sample sites, component watershed index of riverine integrity (WIRI) metrics and overall WIRI scores.

SampleSite	$Hydro_C$	$Hydro_D$	Stocking	$Road_L$	$Road_X$	Riparian	WIRI
BEAR1	0	2	4	2	4	2	57
BEAR2	0	2	4	2	2	2	50
BEAV1	4	4	4	2	4	4	93
BEAV2	4	0	4	0	2	4	64
BLUE1	0	0	2	0	4	2	36
BLUE2	0	2	4	2	2	2	50
COLE1	4	2	4	4	4	4	93
COLE2	4	0	4	2	0	4	64
COLE3	4	0	4	2	0	0	36
DEER1	4	4	4	4	2	2	79
EPAN1	4	2	4	2	0	4	71
EPAN2	4	0	4	2	2	4	71
MEAD1	2	0	2	0	0	4	43
MEAD2	0	0	2	2	4	0	29
MOKE1	0	2	4	2	0	2	43
NFMO1	4	2	4	4	4	2	79
NFMO2	0	2	4	4	4	0	50
NFMO3	0	2	4	4	4	0	50
NFMO4	0	2	4	2	4	2	57
NFMO5	0	2	2	2	2	2	43
NFMO6	0	2	4	2	2	2	50
NFMO7	0	0	4	2	2	2	43
TIGE1	4	4	4	0	0	4	71
TIGE2	2	0	4	0	0	4	50
TIGE3	2	2	2	0	0	4	50
WPAN1	4	4	4	0	0	4	71
WPAN2	4	4	4	0	0	4	71

Comparative Analysis

We compared the instream versus watershed indexing methods in two ways: 1) we analyzed individual WIRI parameters against instream biotic indices (i.e., F-IBI, B-IBI, and P-IBI independently); and 2) we regressed the composite IBI values against WIRI scores. For the initial comparison, we used non-parametric Wilcoxon tests of rank sums to determine if WIRI parameter classes had discriminatory power against the respective IBIs. For the second comparison, we used ordinary least squares linear regression with ~10% sites excluded as outliers (BEAV1, DEER1, and TIGE3).

Statistical analyses revealed that both F-IBI and B-IBI scores reflected watershed GIS derived measures, including hydrologic alteration, riparian impairment, and fish stocking. For example, in regards to fish stocking, there was a marginally significant difference between sites less than

1 km from an active stocking location versus sites greater than 1 km; low F-IBI scores corresponded to closer proximity ($p = 0.08$, $X^2 = 3.2$). Similarly, percent riparian cover within 100m of a site was significantly reflected in B-IBI scores ($p = 0.04$; $X^2 = 6.2$); sites with greater than 85% cover (high) possessed higher B-IBI values than sites with less than 85% cover (moderate) and less than 50% cover (low). Most strikingly, both F-IBI and B-IBI performed well when compared to the two WIRI metrics used to describe hydrologic alteration. In particular, B-IBI scores were significantly different when assessed by distance to upstream dam (< 2 km, > 2 km, or no upstream dam). Sites without an upstream dam scored highest, followed by sites further than 2 km from an upstream dam and sites within 2 km of an upstream dam, respectively ($p = 0.01$; $X^2 = 10.1$). The F-IBI followed the same trend for distance to dams ($p = 0.02$; $X^2 = 7.4$).

The WIRI metric addressing cumulative capacity of upstream storage behind jurisdictional dams resulted in two distinctly different outcomes for IBI types. Both F-IBI and B-IBI scores were comparatively higher for sites without upstream dams. Further, B-IBI scores were higher for sites with less than 3000 acre-feet of water storage upstream than those site with more capacity ($p = 0.01$; $X^2 = 8.9$). However, F-IBI scores were opposite in their response, in that sites with more than 3000 acre-feet of upstream storage capacity scored higher than those sites with less capacity ($p = 0.04$; $X^2 = 6.5$). Lastly, there were no statistical differences between sites in regards to P-IBI scores and underlying classes of impairment for hydrologic alteration, such as upstream dam capacity ($p = 0.45$) or distance to dam ($p = 0.21$).

We regressed mean composite IBI values against the broad scale, GIS-derived WIRI values to compare indexing methods and determine the applicability of assigning ecological integrity scores to river reaches without extensive site surveys. The ordinary least squares linear regression was significant ($F = 20.5$; $p < 0.0002$) and explained nearly half the variance ($r^2_{adj} = 0.46$). The slope and intercept from the linear fit and was indicative of the numeric range from the different scoring systems (composite IBI mean = 63.205803 + 0.240524*WIRI). A multiple, forward stepwise linear regression that included environmental correlates such as elevation, drainage area, stream gradient, and distance to watershed outlet, suggested that the mean composite IBI reflected some bias toward high order streams. A final model ($r^2_{adj} = 0.52$) included distance to watershed outlet as a significant co-predictor ($p = 0.059$).

Discussion

IBI Considerations

Fish IBI

The relatively low watershed-wide F-IBI scores in our study were a result of the large numbers of non-native species that occur within the watershed and their high relative abundance at numerous sites. Large scale indiscriminate stocking of non-native fishes throughout California has occurred for more than a century (Moyle 2002) and many of the "native" rainbow trout in the Mokelumne River may have had hatchery origins. The site that scored highest in the F-IBI (MOKE1; Table 7) had the highest diversity of native fishes as well as remarkably high biomass. It should be noted, however, that high F-IBI scores may not always reflect superior water quality. The fish assemblage at MOKE1 was largely comprised of Central Valley fishes such as Sacramento pikeminnow (*Ptychocheilus grandis*), Sacramento sucker (*Catostomus occidentalis*), California roach (*Lavinia symmetricus*), and sculpin species (*Cottus* spp.). These fish are typically less sensitive to water quality problems such as low dissolved oxygen, increased temperature, alkalinity, and turbidity than the trout that dominate the upper portions of the watershed. Furthermore, the mobility of fishes and their potential connection to larger metapopulations greatly reduces their sensitivity to localized impairments.

Benthic macroinvertebrate IBI

Benthic macroinvertebrates are probably the most responsive to localized changes in environmental conditions due to their small size and limited mobility. It should also be noted that microhabitats are generally more important to macroinvertebrates than to fishes, and markedly different community assemblages can often be found within the same reach. Macroinvertebrates are especially sensitive to changes in flow and substrate, with cobble or boulder substrate being the most amenable to colonization by EPT taxa, and slower warmer waters with emergent vegetation supporting a more tolerant assemblage. In general, sandy, silty, or muddy substrates support mostly non-insect taxa and often have reduced biomass. In contrast to invertebrates, fishes often prefer pooled habitats because of the cover they provide and the abundance of hiding places. Fish generally venture into riffles to feed, but favor lower gradients to save energy and hide from potential predators. Because fish have no aerial stage, like most aquatic invertebrates, all migration must be by swimming and they are especially hindered by physical barriers and stream discontinuity.

Physical Habitat IBI

The USEPA physical habitat index that our P-IBI was based on measures and combines very coarse habitat parameters. It is qualitative rather than quantitative in nature and relies on subjective interpretations on the part of field researchers. Hence, it is not surprising that the P-IBI generally yielded high scores for all sites (Table 7), and did not exhibit sensitivity to the WIRI hydropower metrics. The USEPA physical habitat scoring scheme was designed to be applicable to all of the potential stream conditions that occur within the United States and provide generalized habitat categories rather than numerical distinctions between sites.

Therefore, it is unrealistic to expect such an index to have the power to detect subtle differences between proximate sites. The development of a robust habitat index that is more sensitive to the range of conditions found throughout the Sierra Nevada would be tremendously useful to both natural resource and water quality managers.

WIRI and Comparability of Indices

We compared two methods of indexing the ecological integrity of freshwater ecosystems derived at two different scales (i.e., site-specific and whole watershed). To assess complementarity between the two methods, we tested IBI scores as a function of WIRI metrics and regressed mean IBI values against WIRI. The results from this comparative analysis indicated that WIRI was a robust indicator of ecological condition and riverine integrity. Most prominent in this finding was that GIS-derived watershed-scale metrics of hydrologic alteration definitively indicated instream conditions at the site scale. Any discussion of site response to hydrologic alteration due to hydropower operations must emphasize that sites without dams have higher ecological integrity. Further, sites farther downstream from dams have higher integrity than those that are closer to upstream facilities, likely due in part to the influence of tributaries between sites and facilities increasing drainage area and thus flow.

When compared to the two WIRI metrics depicting hydropower operations (i.e., cumulative capacity of upstream jurisdictional dams and distance to closest dam, jurisdictional or otherwise) our B-IBI accurately reflected hydrologic alteration. In general, sites with the highest B-IBI scores had no dam upstream, while sites with dams upstream had similar responses to our measures of alteration. By examining distance to upstream facility, our analysis showed that sites greater than 2 km from a dam possessed a higher B-IBI score than closer sites. Furthermore, sites with less than 3000 af of cumulative upstream reservoir (presumably less altered), scored higher than sites with more than 3000 af of upstream reservoir capacity. Collectively, these results indicate that our two WIRI measures of hydrologic alteration are complementary to our B-IBI and indicative of the ecological integrity of Mokelumne watershed rivers and streams.

The F-IBI, on the other hand, had a mixed response to the two WIRI hydrologic alteration metrics. Unsurprisingly, sites without upstream dams yielded the highest F-IBI scores while sites closer to upstream dams were ranked lower suggesting a higher level of impairment due to hydropower operations. However, sites with higher cumulative upstream reservoir capacity ranked higher on average for their F-IBI than sites with less capacity. Although this result represents a different response than observed in B-IBI scores and might be counter intuitive in assessing hydrologic alteration, it is plausible that F-IBI scores actually reflect flow releases from hydropower operations. All things being equal, a one percent release of total annual capacity for example, results in much less water to aquatic ecosystems downstream from small facilities. This observation also reflects the possibility that more upstream capacity might dampen or regionalize hydropower effects, as opposed to local effects from less capacity.

In general, the WIRI methodology and resulting scores suggest that we met our aforementioned objectives: 1) to characterize the integrity of freshwater ecosystems using coarse scale data at extents broader than sites; and 2) to develop a robust indicator index from multimetric data that is repeatable, applicable, and readily generated.

Climatic Change and Stream Warming

Climate-related changes to stream flow will play a major role in determining the future integrity of many Sierra Nevada watersheds. Nearly all climate change models for California predict that less wintertime precipitation will fall as snow and more will fall as rain, resulting in increased winter flows and decreased spring and summer flows (Cayan et al. 2001, Mote et al. 2005). This fundamental change in flow regime, and the interrelated changes in water temperature, will significantly influence aquatic biodiversity and the many critical ecosystem services provided by Sierran stream and rivers.

Of all the aquatic assemblages, trout communities will likely be most impacted by climate change scenarios. We expect that a warming trend in the watershed would result in trout moving higher into the watershed where maximum weekly average temperatures (MWAT) remain below 20° C. Similarly, the Central Valley fish assemblage would be expected to move up in elevation as far as gradient and migration barriers allow. This up-basin movement by trout, coupled with migration barriers to the warm water fish assemblage advancing from the lower elevations, may result in the loss of fishes in those reaches that are affected by warming but cannot be colonized from below.

It is also likely that we will see a shift in macroinvertebrate community structure with less environmentally sensitive species dominating community composition. Moreover, we expect EPT taxa to decrease, particularly Plecopterans (stoneflies), which are the most sensitive to loss of dissolved oxygen because they rely on rudimentary gills for respiration (Merritt and Cummins 1996). As with fishes, shifts in community composition in the lower watershed are also likely, where macroinvertebrate species tolerant of warmer thermal profiles would become more commonplace. Although it is uncertain if there will be a significant change in gross production or biomass, species composition would likely be altered. Invertebrates do not suffer from migration barriers the way fishes do since many of them have aerial adult stages that allow them to colonize up and down stream, as well as different water bodies if a stream becomes too impaired. Invertebrate communities are probably the least affected by non-native introductions as compared with fishes and vegetation, however, reservoirs created habitat for lentic invertebrates that would not ordinarily exist in those systems. Some populations of introduced invertebrates certainly exist (i.e., signal crayfish, New Zealand mudsnail), but there has been nowhere near the amount of species manipulation of invertebrates that has occurred with fish and plant communities.

Physical habitat related parameters are least likely to change in response to a warming trend in the Sierra Nevada mountain range. However, a shift in the distribution of vegetation towards higher elevations (Lenihan et al. 2003), as well as changes in hydrology (see Fernandes et al. this report) are expected to occur. Such changes could have considerable impact on certain metrics, especially those based on vegetative cover, which could in turn affect bank stability, epifaunal habitat, sediment deposition, and riparian zone width.

Limitations and Recommendations

General Limitations

This report describes a pilot study of one watershed in the central Sierra Nevada. The comparability of our findings to other watersheds in the Sierra Nevada or elsewhere is inherently limited by the parameters and methods employed. While we used parameters that are both accepted by the general scientific community and readily available for the Sierra Nevada, it does not imply that conditions in other watersheds will be reflected accordingly. Furthermore, although our methods were developed to have broad applicability to other watersheds, there exists the possibility that observations made here (specifically a general agreement of ecological integrity indices across scales) may not hold with the inclusion of additional sites and watershed metrics. These cautions aside, statistical principles suggest that increasing the number of samples in subsequent studies will actually improve model reliability.

Limitations of Instream Indices

In order to have more precision and predictive power using IBIs, future studies need to: 1) increase the total number of sites across the Sierra Nevada to establish inter-watershed reliability, and 2) increase the number of sites within each watershed to allow intra-watershed model validation. Future efforts must also explicitly examine sites above and below hydropower facilities to determine the spatial range of influence for hydrological alteration. Freshwater ecological communities are complex from both trophic and bioenergetic perspectives; thus establishing specific thresholds for habitat alteration, particularly stream warming, will be a challenging endeavor.

There also exist limitations with the use of instream IBIs in general, and IBIs applied to the Sierra Nevada in particular. A central problem with IBIs is that they generalize specific information into broader categories, thereby diminishing the distinctions between sites. Additionally, the Sierra Nevada IBIs are particularly constrained by a lack of low-to mid-elevation reference conditions. Reference conditions are the basis for site assessment and detection of anthropogenic stressors on the aquatic community (Barbour et al. 1999). Poor or inaccurate representation of the reference condition results in data gaps in the range of conditions covered by the model, and consequently, less robust assessments.

Limitations of Watershed Index of Riverine Integrity

Hydrologic Alteration

To depict hydrologic alteration, we chose to use two metrics within the WIRI composite score (i.e., distance to the closest upstream jurisdictional dam, and reservoir capacity for all upstream jurisdictional dams). While the hydrologic alteration scores are significantly, negatively correlated (R = -0.67), we feel that each represents a different impact to stream ecosystems. Specifically, the distance to the closest upstream jurisdictional dam is a localized measure, whereas the summed reservoir capacity for all upstream jurisdictional dams is a cumulative measure. It is not surprising that these metrics are correlated, but their simultaneous inclusion should not jeopardize the WIRI score itself.

Fish Stocking

Although stocking histories from the California Department of Fish and Game are the best available data, they have not been independently verified, nor checked for internal consistency. It is also likely that some present day fish populations are the product of undocumented stocking programs, particularly those populations in headwater reaches. Therefore, in some cases wild rainbow trout populations are indistinguishable from hatchery stocked populations.

Road Impacts

We generated a number of metrics depicting the potential impacts of roads on riverine habitats, including number of road crossings and road densities. Most of these metrics are correlated in some fashion, so choosing the best metric requires consideration of several factors. For this study, the most representative metric was the cumulative density of local roads within 100 m of streams. This measure was chosen in part for its heuristic value in exploratory data analysis, but also because it showed variation throughout the watershed, whereas four-wheel roads and large highways were not always present in each subwatershed.

Riparian Cover

We chose to utilize the tree cover metric as depicted by the USGS National Landuse Classification Database (NLCD). While there are advantages to using NLCD, particularly because it is a national standard, there are also several disadvantages. One shortcoming is that the database is created in ten-year intervals and our data represent land cover 1995-2005, which clearly has the potential to miss recent changes. It is also somewhat coarse with 900 m^2 being the minimum area mapped. Lastly, for this exercise, due in part to the pilot nature of the study and in part to the point calibration approach, we chose to characterize an area within a 100 m radius of each IBI for percent tree cover. This approach has two distinct limitations: 1) tree cover, as a class, does not necessarily indicate riparian community cover *per se*, and 2) it encompasses an area that includes downstream, albeit a small area. These data do, however, generally characterize riparian condition and emphasize the importance of tree cover, regardless of vegetation community.

Recommendations for Freshwater Conservation

Formal approaches to freshwater conservation framework planning have focused on two distinct typologies. One is in regards to the semantic definition of freshwater protected areas (Abell et al. 2007) and the other specifies a range of conservation objectives (Linke et al. 2007). Incorporating the nomenclature of Abell et al. (2007) is certainly one approach to identifying and conserving freshwater and watershed resources in a standardized manner. Linke et al. (2007) continue by suggesting an integrated conservation strategy for freshwater resources that focuses on three primary objectives: 1) *irreplaceability*, capturing the value of its uniqueness, either in terms of habitats, species assemblages, etc.; 2) *condition*, focusing on resources that possess high ecological integrity; and 3) *vulnerability*, incorporating future threats and the degree of human intervention required. Although most attempts at freshwater conservation in California have focused on conditional assessments (e.g., Moyle and Randall 1998), and to a lesser degree irreplaceability (Moyle and Ellison 1991), few have seriously addressed vulnerability in a systematic way.

We feel that the combination of changing climatic regimes and changes in hydropower operations presents new challenges in gauging not only condition, but also in assessing vulnerability. As such, future efforts will need to bridge scales (as we have done here in establishing relationships between site-specific measures to watershed condition) and incorporate future vulnerabilities into both hydropower relicensing and freshwater conservation efforts. Of course thinking about vulnerability is not new, but seriously addressing its constituent parts is only now coming to the fore. For example, Wilson et al. (2005) separated vulnerability into exposure, intensity, and impact. In light of the global nature of climatic change, identifying and quantifying differences in vulnerability intensity should be the focus of future modeling efforts that aim toward a regional conservation strategy.

Considering the policy and legal constraints of hydropower relicensing and the desire to explore regional approaches to license aggregation (see Doremus report), it is important to point out the limited opportunities for freshwater conservation through offsite mitigation. That is to say the project specific conservation efforts, either through negotiated settlements or mandate, are necessarily restricted to the spatiotemporal constraints of the project undergoing relicensure. Furthermore, few opportunities exist to examine and incorporate offsite mitigation as a viable freshwater conservation strategy into relicensing efforts. Such offsite mitigation efforts could address not only the quality and quantity of incoming waters, but also ensure long-term protection status for habitats and populations of high ecological integrity. For example, much of the Mokelumne River watershed (53%) is under the management and jurisdiction of the USDA Forest Service (USFS) (see Table 9). The USFS is responsible for meeting multiple management objectives through the Organic Act, including high quality waters. The USFS is also often party-to negotiated settlements for project licenses that result in increased Forest revenue, recreational opportunities, etc. Therefore, there appears to be mutual interest on behalf of all parties to maintain the delivery of high quality waters from USFS lands--and conceivably the proper and long-term protection of high quality aquatic and riparian habitats as well as robust populations of freshwater species.

Table 8. Land ownership for the Mokelumne River watershed.

Area (ha)	Percent of Watershed	Owner	Agency
58.46	0.04%	Federal	Toiyabe National Forest
210.29	0.14%	State	State Lands - State Lands Commission
6115.87	4.08%	Federal	Bureau of Land Management
35524.77	23.72%	Federal	Stanislaus National Forest
43964.08	29.36%	Federal	Eldorado National Forest
63882.14	42.66%	Private	N/A

Conclusions

Freshwater resources and ecosystems are imperiled globally and acutely stressed in California due to various human activities (Revenga et al. 2000, Moyle 1996). For California's Sierra Nevada, alterations in hydrology through major hydropower development and innumerable smaller diversion dams have significantly altered the integrity of its rivers and streams (Moyle and Williams 1990, SNEP 1996a). Science based efforts to systematically conserve freshwater ecosystems have focused on a combination of identifying irreplaceable habitats and assessing vulnerability of species and habitat condition. Methods to determine level of impairment due to human activities, or ecological integrity, are dependent upon spatial scale of assessment and measures. The results from our comparative analysis indicate that WIRI is a robust indicator of ecological condition and riverine integrity. Most prominent in this finding is that watershed-scale, GIS-derived metrics of hydrologic alteration definitively reflected instream conditions at the site scale.

We asked the question: to what degree can instream-based indices of ecological integrity correspond with indices developed at the riverscape or watershed scale? We addressed the applicability of bridging scales as a method to broaden the assessment framework used to determine the ecological integrity of Sierran rivers and streams. To date, no other study had explicitly aimed to compare indices developed at different ecological scales. Furthermore, systematic evaluation of freshwater ecosystem integrity in the Sierra Nevada has been limited in several respects: 1) the scale and extent of different assessments have been restricted to reach-scale analyses most typically; 2) methods of instream condition indexing are often regionalized, but no such regional indices presently exist; and 3) watershed-scale approaches have been conducted independent of site-based assessments of condition. In regards to the latter, the seminal study of Moyle & Randall (1998) provided the first attempt to systematically evaluate watershed condition with GIS-derived metrics, but subsequent studies have not attempted to validate these findings using site-based measures.

Our assessment of riverine integrity, conducted at different spatial scales and using independent measures of ecological condition, show that spatial scales can be bridged. Thus, our pilot project supports future broad scale indexing to all riverine waterbodies, on a reach scale. This finding therefore allows for a wide-ranging, synoptic assessment of all rivers and streams in the Sierra Nevada. While additional field-based data (either from existing or future biophysical surveys) will be needed for validation, the use of WIRI, a GIS-derived watershed index of riverine integrity can be applied to all watersheds in the Sierra Nevada. Furthermore, our approach and findings support GIS-based scenario modeling in which watersheds can undergo any number of changes in ecological condition, such as changes in hydrology or land use, to depict future riverine integrity.

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Figure 1. Location of Mokelumne River watershed study sites with site names and statistical distribution of watershed index of riverine integrity (WIRI) scores

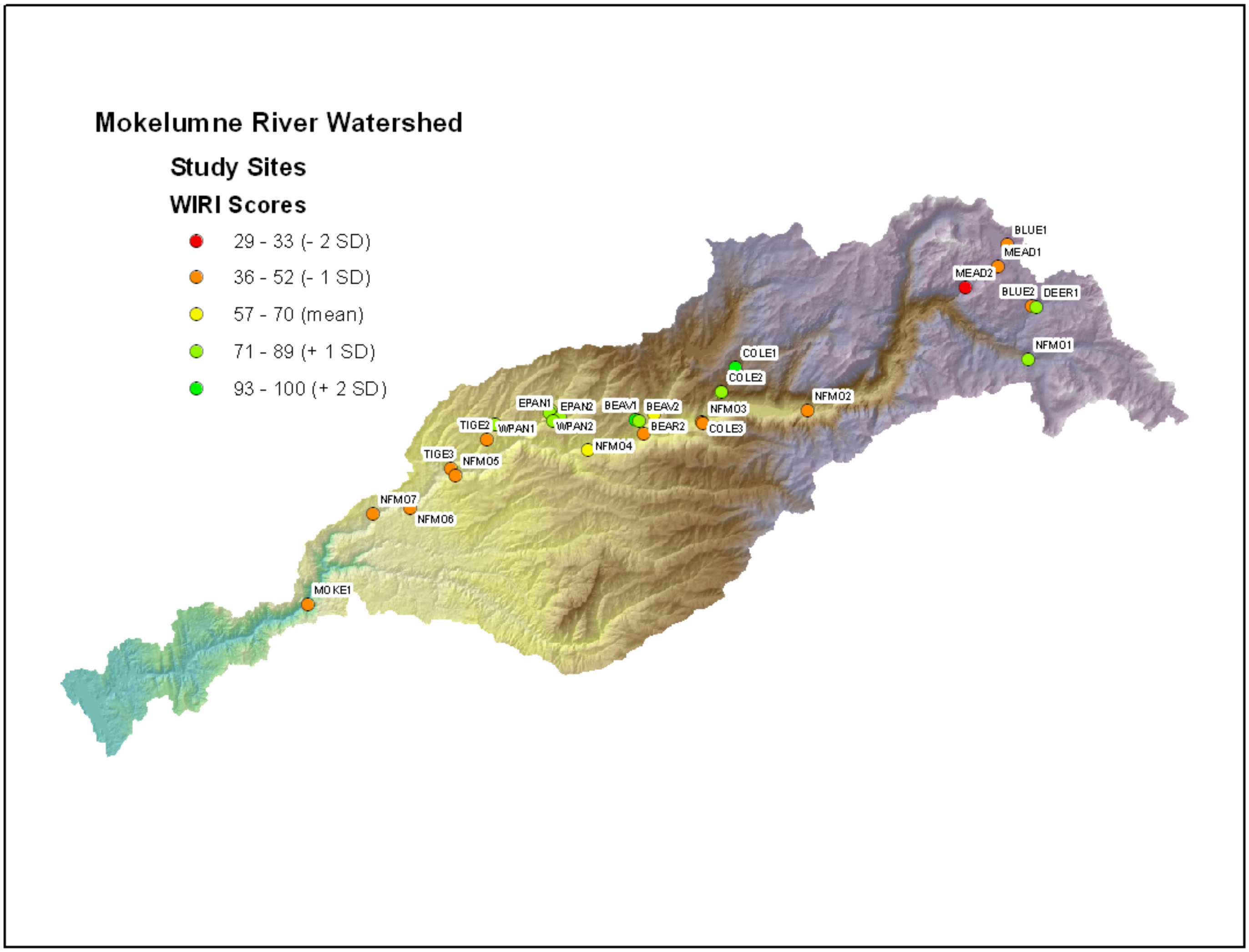


Figure 2. Spatial distribution of watershed index of riverine integrity (WIRI) scores generated for the Mokelumne River watershed.

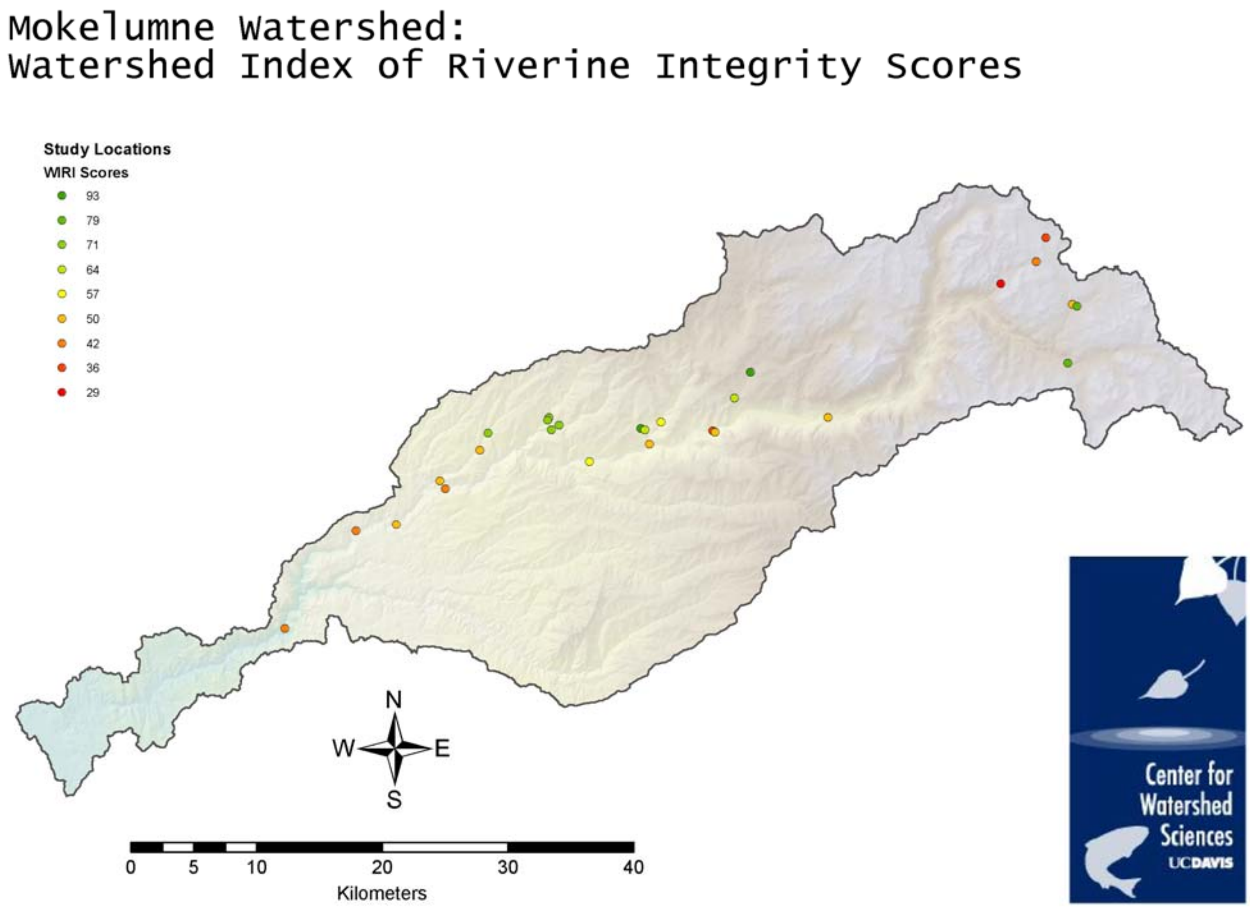


Figure 3. Distribution of Mokelumne River watershed F-IBI scores.

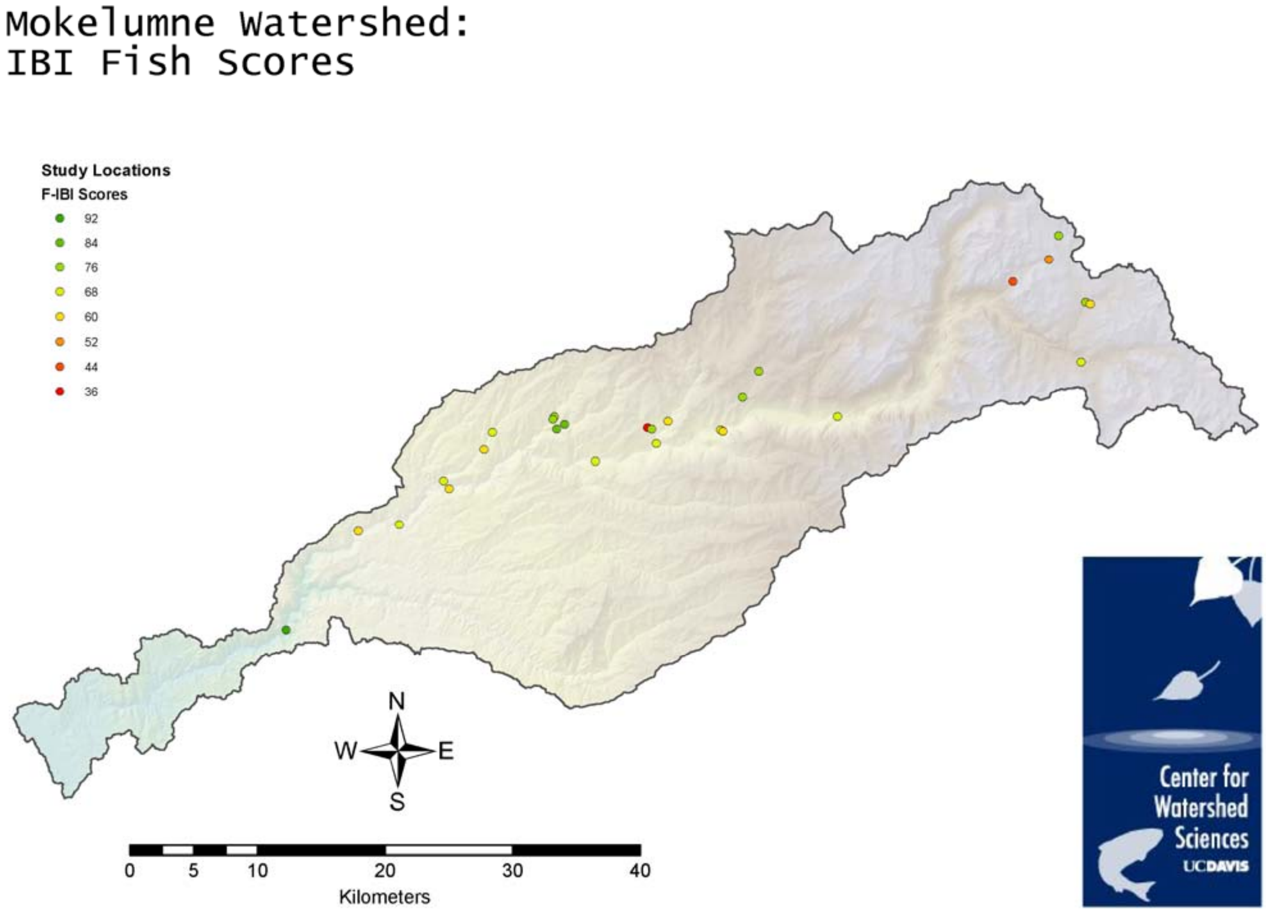


Figure 4. Distribution of Mokelumne River watershed B-IBI scores.

Mokelumne Watershed:
IBI Benthic Macroinvertebrate Scores

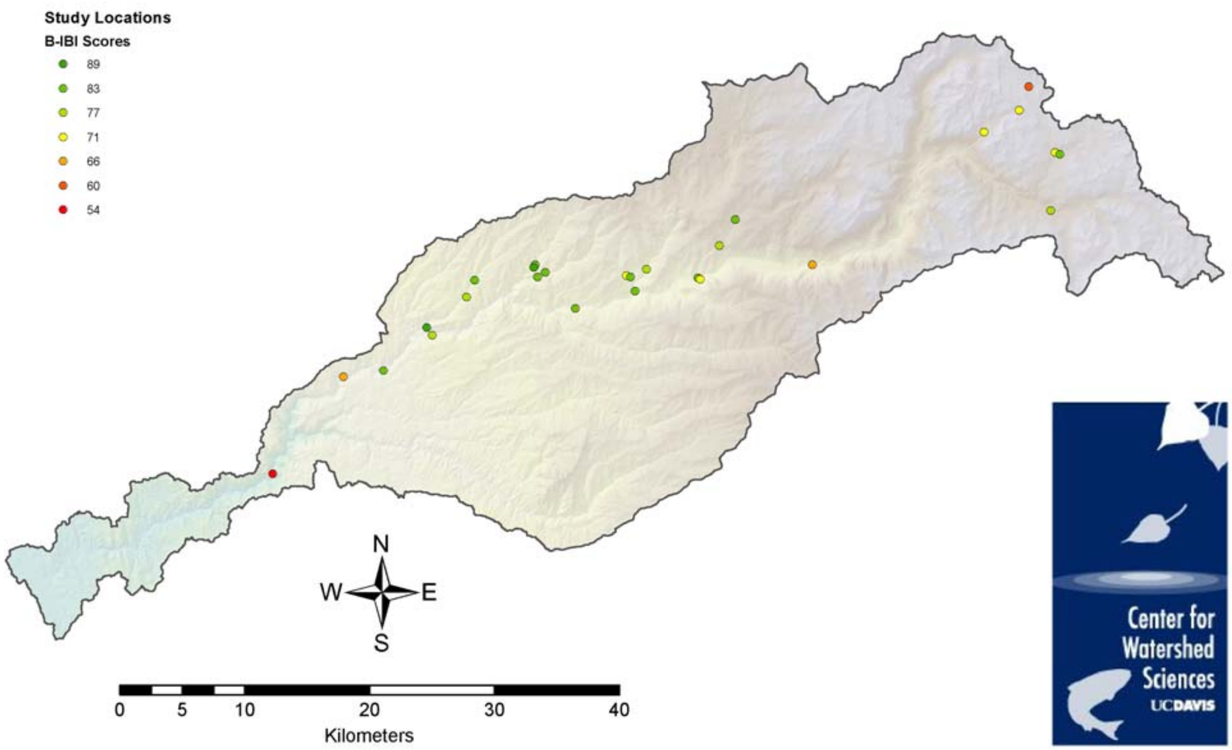
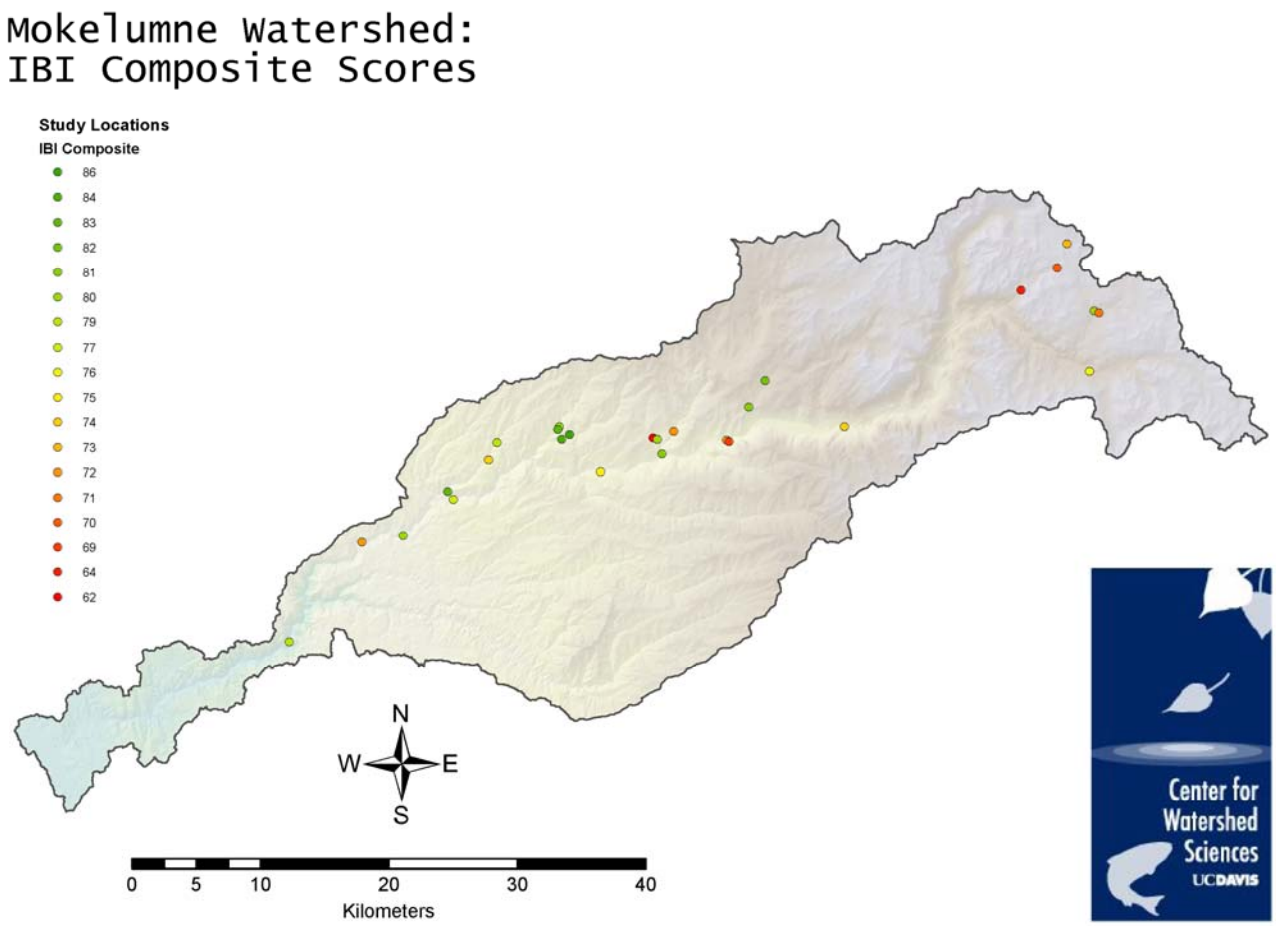


Figure 5. Distribution of Mokelumne River watershed composite IBI scores.



Appendix A. Habitat assessment field sheet used to determine site specific physical habitat conditions (P-IBI) in the Mokelumne River watershed. Modified from Barbour et al. 1999

HABITAT ASSESSMENT FIELD DATA SHEET—HIGH GRADIENT STREAMS

STREAM NAME	LOCATION
SITE ID # REACH ID ________	STREAM CLASS
UTM N __________ UTM E	RIVER BASIN
STORET #	AGENCY
INVESTIGATORS	
FORM COMPLETED BY	DATE ______ TIME . AM REASON FOR SURVEY

Parameters to be evaluated in sampling reach

Habitat Parameter	Condition Category: Optimal	Suboptimal	Marginal	Poor
1. Epifaunal Substrate/ Available Cover	Greater than 70% of substrate favorable for epifaunal colonization and fish cover; mix of snags, submerged logs, undercut banks, cobble or other stable habitat and at stage to allow full colonization potential (i.e., logs/snags that are not new fall and not transient).	40-70% mix of stable habitat; well-suited for full colonization potential; adequate habitat for maintenance of populations; presence of additional substrate in the form of newfall, but not yet prepared for colonization (may rate at high end of scale).	20-40% mix of stable habitat; habitat availability less than desirable; substrate frequently disturbed or removed.	Less than 20% stable habitat; lack of habitat is obvious; substrate unstable or lacking.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
2. Embeddedness	Gravel, cobble, and boulder particles are 0-25% surrounded by fine sediment. Layering of cobble provides diversity of niche space.	Gravel, cobble, and boulder particles are 25-50% surrounded by fine sediment.	Gravel, cobble, and boulder particles are 50-75% surrounded by fine sediment.	Gravel, cobble, and boulder particles are more than 75% surrounded by fine sediment.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
3. Velocity/Depth Regime	All four velocity/depth regimes present (slow-deep, slow-shallow, fast-deep, fast-shallow). (Slow is < 0.3 m/s, deep is > 0.5 m.)	Only 3 of the 4 regimes present (if fast-shallow is missing, score lower than if missing other regimes).	Only 2 of the 4 habitat regimes present (if fast-shallow or slow-shallow are missing, score low).	Dominated by 1 velocity/depth regime (usually slow-deep).
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
4. Sediment Deposition	Little or no enlargement of islands or point bars and less than 5% of the bottom affected by sediment deposition.	Some new increase in bar formation, mostly from gravel, sand or fine sediment; 5-30% of the bottom affected; slight deposition in pools.	Moderate deposition of new gravel, sand or fine sediment on old and new bars; 30-50% of the bottom affected; sediment deposits at obstructions, constrictions, and bends; moderate deposition of pools prevalent.	Heavy deposits of fine material, increased bar development; more than 50% of the bottom changing frequently; pools almost absent due to substantial sediment deposition.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
5. Channel Flow Status	Water reaches base of both lower banks, and minimal amount of channel substrate is exposed.	Water fills >75% of the available channel; or <25% of channel substrate is exposed.	Water fills 25-75% of the available channel, and/or riffle substrates are mostly exposed.	Very little water in channel and mostly present as standing pools.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0

Appendix A. continued.

HABITAT ASSESSMENT FIELD DATA SHEET—HIGH GRADIENT STREAMS

Parameters to be evaluated broader than sampling reach

Habitat Parameter	Condition Category			
	Optimal	Suboptimal	Marginal	Poor
6. Channel Alteration	Channelization or dredging absent or minimal; stream with normal pattern.	Some channelization present, usually in areas of bridge abutments; evidence of past channelization, i.e., dredging, (greater than past 20 yr) may be present, but recent channelization is not present.	Channelization may be extensive; embankments or shoring structures present on both banks; and 40 to 80% of stream reach channelized and disrupted.	Banks shored with gabion or cement; over 80% of the stream reach channelized and disrupted. Instream habitat greatly altered or removed entirely.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
7. Frequency of Riffles (or bends)	Occurrence of riffles relatively frequent; ratio of distance between riffles divided by width of the stream <7:1 (generally 5 to 7); variety of habitat is key. In streams where riffles are continuous, placement of boulders or other large, natural obstruction is important.	Occurrence of riffles infrequent; distance between riffles divided by the width of the stream is between 7 to 15.	Occasional riffle or bend; bottom contours provide some habitat; distance between riffles divided by the width of the stream is between 15 to 25.	Generally all flat water or shallow riffles; poor habitat; distance between riffles divided by the width of the stream is a ratio of >25.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
8. Bank Stability (score each bank) Note: determine left or right side by facing downstream.	Banks stable; evidence of erosion or bank failure absent or minimal; little potential for future problems. <5% of bank affected.	Moderately stable; infrequent, small areas of erosion mostly healed over. 5-30% of bank in reach has areas of erosion.	Moderately unstable; 30-60% of bank in reach has areas of erosion; high erosion potential during floods.	Unstable; many eroded areas; "raw" areas frequent along straight sections and bends; obvious bank sloughing; 60-100% of bank has erosional scars.
SCORE ___ LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0
9. Vegetative Protection (score each bank)	More than 90% of the streambank surfaces and immediate riparian zone covered by native vegetation, including trees, understory shrubs, or nonwoody macrophytes; vegetative disruption through grazing or mowing minimal or not evident; almost all plants allowed to grow naturally.	70-90% of the streambank surfaces covered by native vegetation, but one class of plants is not well-represented; disruption evident but not affecting full plant growth potential to any great extent; more than one-half of the potential plant stubble height remaining.	50-70% of the streambank surfaces covered by vegetation; disruption obvious; patches of bare soil or closely cropped vegetation common; less than one-half of the potential plant stubble height remaining.	Less than 50% of the streambank surfaces covered by vegetation; disruption of streambank vegetation is very high; vegetation has been removed to 5 centimeters or less in average stubble height.
SCORE LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0
10. Riparian Vegetative Zone Width (score each bank riparian zone)	Width of riparian zone >18 meters; human activities (i.e., parking lots, roadbeds, clear-cuts, lawns, or crops) have not impacted zone.	Width of riparian zone 12-18 meters; human activities have impacted zone only minimally.	Width of riparian zone 6-12 meters; human activities have impacted zone a great deal.	Width of riparian zone <6 meters: little or no riparian vegetation due to human activities.
SCORE LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0

Total Score ________

CONCEPTS AND OPTIONS FOR MITIGATION OF HYDROPOWER DAMS IN THE SIERRA NEVADA: A PRELIMINARY REVIEW

PROJECT REPORT

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Abstract

The adverse ecological effects of hydropower dams, such as those in the Sierra Nevada, are increasingly understood and numerous options have been developed to mitigate their impacts. Ecological effects include significant alterations in the hydrology, geomorphology, water quality, fish and other aquatic species, and the terrestrial environment of a watershed at both the local and landscape scales. Mitigation options to address these alterations therefore include those that target habitat structure (including geomorphology), hydrology, water quality, aquatic species, and the terrestrial environment. Options can be local or offsite to help improve overall ecosystem conditions, whether or not the offsite effect is caused directly by a hydropower facility. Licenses and mitigation options (if any) have historically been developed and implemented locally on a single-project basis.

Regionalization and adaptive management are alternative strategies to achieving ecosystem behavior goals and objectives by providing new frameworks for turning available options into promising mitigation solutions. Regionalization includes landscape-scale consideration of cumulative hydropower effects, careful balancing of environmental benefits to minimize hydropower loss, and parallel licensing. Adaptive management is a science-driven approach to environmental management whereby uncertainty is accepted and accounted for, the ecosystem and its response to mitigation options are monitored and studied, and management strategies are regularly adjusted based on monitoring and evaluation. These approaches are greatly enhanced with the use of assistive management tools such as modeling and data development and analyses.

The relicensing process provides a window of opportunity for developing and including promising mitigation options for better management of California's Sierra Nevada hydropower dams. Climate change, while typically seen as a challenge, is also an opportunity to prompt a more adaptive approach to hydropower management that will benefit both hydropower operators and environmental and other stakeholders in the long run.

Introduction

Hydropower facilities are known to have numerous effects on the riverine environment. A broad range of options to mitigate the more adverse of these impacts has been proposed, developed and/or implemented over time, both within California and worldwide, with varying degrees of success.

This document outlines existing mitigation options and highlights strategies for assembling those options into real solutions to mitigate current and future adverse impacts of Sierra Nevada hydropower dams and operations on aquatic ecosystems, with consideration of uncertainty in general and climate change in particular. The specific objectives of this document include:

1. Review adverse environmental impacts of hydropower dams and associated facilities.
2. Identify and organize the range of mitigation options.
3. Explore management strategy concepts and tools for developing comprehensive option-based mitigation solutions, including regionalization, adaptive management, and assistive tools to help decision-making (e.g., computer modeling).
4. Identify some key opportunities for mitigation of adverse environmental impacts of the Sierra Nevada hydropower projects including, in particular, opportunities related to the Federal Energy Regulatory Commission (FERC) hydropower project relicensing process.

The relationship between mitigation options, management strategy and ecosystem behavior, in a general adaptation context is depicted in Figure 23. A management strategy (such as regionalization and adaptive management) applies mitigation options to implement mitigation solutions strategically. These solutions—together with climate change and other uncertainties—

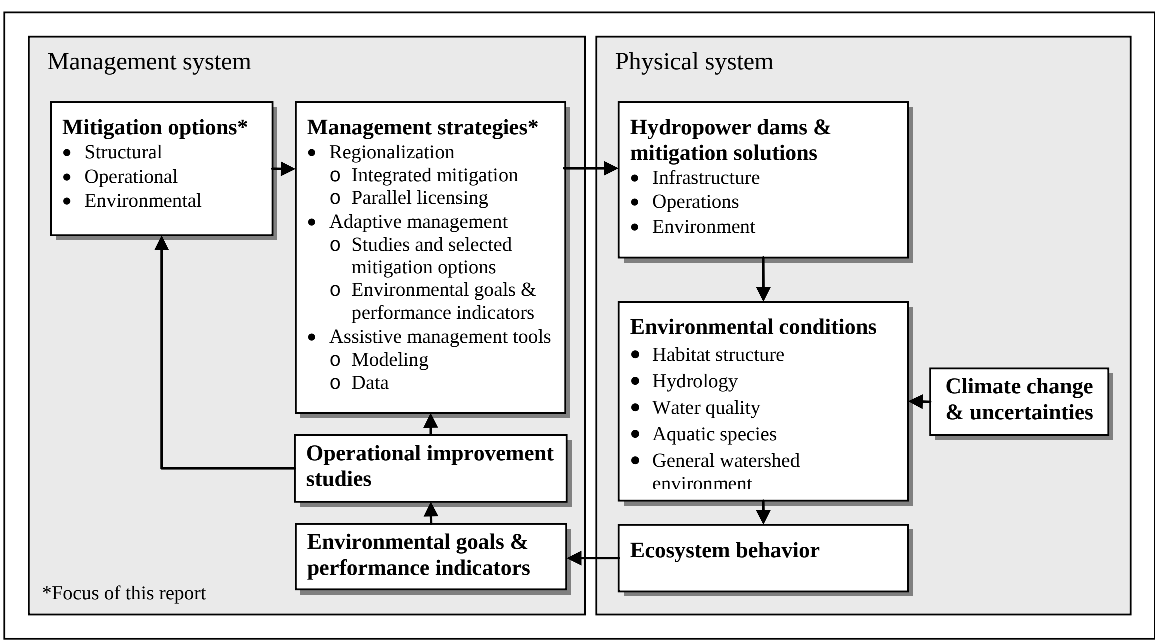

Figure 23. Conceptual Relationship Between Mitigation Options, Management Strategies, and Ecosystem Behavior

affect environmental conditions and, consequently, ecosystem behavior. Ecosystem behavior is measured with performance indicators, which, combined with environmental goals, are used as inputs to operational improvement studies. The outcomes of studies, in turn, affect future management strategies and may inform development of additional mitigation options.

This preliminary identification of hydropower effects, survey of mitigation options, and discussion of option management strategies should serve as a starting point for dam operators, environmental and other stakeholders, and academia in developing solutions to aquatic ecosystem degradation caused by hydropower dams in the Sierra Nevada and in general.

Mitigation options and management strategies are discussed in the context of Sierra Nevada hydropower dams where applicable. However, this document does not address site-specific strategies or solutions.

Hydropower Dam Effects

The range of possible effects of hydropower dams and facilities and their operations are increasingly understood (Marmulla 2001, Poff and Hart 2002, WWF 2004, Stillwater Sciences 2006). Effects vary in spatial and temporal scope, from local to landscape and from minutes and hours to decades and longer. At both local and landscape scales, physical and ecological system components affected by hydropower dams can be broadly grouped in terms of hydrology, geomorphology, water quality, fish and other aquatic species, and the terrestrial environment. These groupings and their corresponding range of effects at the local and landscape scales are described in general terms in this section.

Table A1 in Appendix A provides a more detailed list of the potential environmental effects of hydropower dams and related facilities, adapted from Stillwater Sciences (2006). Table A1 shows the pathway (causal linkage) between specific project facility components and potential effects, and identifies the ecosystem domain variable associated with the potential effect.

Identifying and understanding affected ecosystem variables and tracing causal pathways of impacts from hydropower facilities is a crucial first step towards searching for and identifying a comprehensive range of options to achieve ecosystem behavior objectives. For each identified effect, Table A1 also references the range of potentially available mitigation options, as discussed in this document (see below).

This understanding of the full range of possible pathways and effects is also essential when identifying and quantifying effects at a specific dam (Stillwater Sciences 2006) and particularly important when developing measurable outcome indicators for monitoring ecosystem changes and mitigation option performance.

Local scale effects

Locally, the dominant effects of hydropower dams include 1) changes in the natural streamflow patterns and 2) stream fragmentation. Changes to streamflow patterns include altering the magnitude and duration of streamflow downstream of the dam, at multiple temporal scales (e.g., hourly and seasonal flow patterns, and less frequent flood and drought flows). Stream fragmentation includes the blockage of streams, preventing or limiting movement of aquatic species along a stream and the interruption of sediment flows downstream. These changes, in turn, alter the various processes that shape the environmental conditions upon which ecosystems depend (Poff and Hart 2002).

Drawing from the work of Stillwater Sciences (2006), the most common effects of hydropower dam facilities and their operations on the aquatic ecosystem are summarized below, organized by ecosystem domain. The domains are adapted from, rather than identical to, those in Table A1, which are directly drawn from Stillwater Sciences (2006).

Hydrology

Hydropower dams disrupt the natural flow regime in which the ecosystem has evolved. Alterations to the natural flow regime (flow magnitude, duration, frequency, rate of change, and predictability) play a fundamental role in many of the other ecosystem changes caused by dams (see Table A1), including sediment transport rates (important for substrate maintenance), channel forming processes, instream and riparian biotic processes, and water quality. Important changes to the hydrologic regime caused by hydropower in the Sierra Nevada include diversions of streams in high head systems that lead to reduction or elimination of available aquatic habitat.

Geomorphology

Alterations to the flow regime and subsequent altered sediment transport processes affect the substrate needed for fish and benthic macroinvertebrate habitat (e.g., by channel bed armoring) and reduce larger-scale variations in landforms needed for habitat complexity (e.g., channels tend to have a more uniform gradient downstream of hydropower dams rather than the natural pools and riffles needed by fisheries). Another morphologic effect includes reductions in large woody debris downstream of hydropower facilities.

Water quality

Altered streamflow from hydropower dams can change temperatures downstream of dams (e.g., releasing less water allows downstream temperatures to increase more quickly while releasing colder hypolimnetic waters can decrease downstream temperatures). Water impoundment can lead to eutrophic reservoir conditions including reduced dissolved oxygen concentration in the hypolimnion and a buildup of sediment-bound nutrients (which are subsequently released), accumulation of sediment-bound heavy metals in the reservoir, and thermal stratification altering downstream flow temperatures. Hydropower systems also can cause supersaturated gasses to be released in the tailrace, potentially causing gas bubble disease in fish.

Fish and other aquatic species

In addition to physical and chemical impacts that affect aquatic species, dams can have more direct effects on aquatic species. As a barrier to upstream and downstream fish migration, the dam itself fragments habitat, cutting off species from their original habitat range, preventing key life cycle migrations, and causing genetic isolation. Reduced flow velocities within the reservoir also can delay downstream migration of fish. Hydroelectric turbines can entrain and kill fish and other species. Fish and other aquatic species are also indirectly impacted via the numerous environmental changes caused by hydropower outlined herein.

Terrestrial environment

Hydroelectric facilities affect the terrestrial environment, which in turn affects instream ecosystems. For example, facility-related roads and cleared transmission line corridors can increase sediment concentrations in overland flow to the stream. Roads can fragment fauna habitat and electrical facilities can be electrocution hazards for birds. Mitigation options for only a few of the terrestrial impacts of hydropower facilities are addressed in this document.

While these potential types of effects are fairly well known and understood generally, the particular set of local (and landscape) effects arising from a specific individual or group of dams will be somewhat unique. Determining the nature and extent of local-scale effects on a case-by-case basis is therefore required. Stillwater Sciences (2006) identifies a broad range of scientific methods to evaluate the site-specific environmental (and other) effects of hydropower dams (i.e., the effects listed in Table A1) at the local scale.

Landscape scale effects

Here, the landscape scale is considered to be both the scale of the entire river system and the scale of multiple dams, rather than solely the areas nearby a single dam. The landscape scale effects can be seen within a watershed, across several watersheds, and as changes through time (Nilsson and Berggren 2000). Landscape scale effects of dams have historically received little attention. Indeed, there has been a noted scale discrepancy between studies of unaltered rivers, which are generally at the larger landscape scale, and studies of dam effects, which are generally at the local scale (Nilsson and Berggren 2000, Poff and Hart 2002).

The primary effect of hydropower dams at the landscape scale on the aquatic ecosystem is the cumulative effect of multiple barriers to migrating aquatic species. The sheer numbers of dams that a migrating fish must pass reduces the species population size. In addition, more dams over a wider aquatic habitat area increases genetic isolation by preventing "the dispersal and persistence of inland species" (Poff and Hart 2002). Landscape scale effects also include impacts on terrestrial wildlife (Stillwater Sciences 2006), but these are not addressed in this document.

Mitigation Options

The effects summarized above serve as a starting point for identifying local and offsite options that could be used to mitigate adverse environmental impacts of hydropower facilities. This range of options can be seen as a 'toolbox' available to hydropower dam operators and environmental stakeholders prior to, during, and subsequent to the dam relicensing process. Tables 1 and 2 summarize the range of local and offsite options, respectively, as described below. Contents of these tables are distilled from the detailed presentation in Table A2 in the Appendix.

Identified options are grouped in a slightly different way than the environmental impacts, with mitigation domains as follows:

Habitat structure
These options target the physical structure of the aquatic environment by addressing adverse alterations in geomorphic complexity and substrate as well as the physical blockage by the dam itself.

Hydrology
Hydrology-related options include those that affect the magnitude, duration, frequency, rate of change, and timing of flow releases. These options may also affect other areas of the environment. For example, water may be released from a dam to address water quality concerns such as temperature or nutrients.

Water quality
These options address water quality issues, such as temperature or nutrients.

Aquatic species
These options involve direct manipulation of aquatic species (such as stocking programs).

Terrestrial environment
These options are designed to improve terrestrial (e.g. riparian) environmental conditions as they impact the aquatic environment.

Options range from the tried-and-true to experimental ideas. Those shown to be completely ineffective have been excluded, although a list of ineffective options would be useful and could be developed in the future. Tables 1 and 2 preliminarily identify whether the options have been implemented in California and the Northwest and whether the option is considered experimental. Table A3 in the Appendix additionally identifies whether the options are accepted or in use elsewhere, as follows.

Accepted in California & Northwest – Generally used in California and the Northwest and considered to be effective

Accepted elsewhere – Generally used in other parts of the United States and elsewhere worldwide and considered to be effective

Used in CA and/or elsewhere – Used in California and/or elsewhere but not necessarily considered to be effective or accepted for widespread use

Considered experimental – Still under development in CA and/or elsewhere and considered experimental

An overview of the different kinds of options is provided below. Both local and offsite options are highlighted, but these do not necessarily correspond to local and landscape scale effects as described above, since a local option might mitigate a landscape scale effect and an offsite option might mitigate a local effect. Further, an offsite option may have other unknown effects at the landscape scale.

Development of an integrated suite of options into real solutions—and the spatial and temporal scale at which to implement them—is a management decision that would need to be considered on a project-by-project basis, in the context of management strategies such as regionalization and adaptive management discussed later in this document.

Finally, these options indicate how adverse effects might be at least partially mitigated technically; they do not indicate the specific conditions that should be met or the extent to which a certain option should be implemented to achieve a particular target condition. Furthermore, there is often little information on their costs and cost-effectiveness in reversing negative impacts and achieving desired target outcomes.

Local options

The options considered here are primarily those at the local scale, also known as on-site or project-based options. Table 9 presents a summary of local options. This is not an exhaustive list, but rather a broad range summarizing most mitigation options. Table A2 in Appendix A provides general descriptions of these options while Table A3 is an expanded version of Table A2; both include key reference documentation for each option. These options were compiled from a survey of books, journal articles, reports, internet sources, and individuals. These local options have generally been developed as single engineered fixes to specific ecological concerns, with little attention to potential interaction with other single-fix options.

Local options include physical solutions to hydropower facility effects and are divided into three types:

(Infra)Structural options – These include infrastructural additions and modifications to base dam facilities (e.g., fish ladders or oxygen injectors).

Operational options – These include changes to the operating policies for existing or new facility components (e.g. water release rates or selective withdrawal).

Environmental options – These include enhancements to instream and riparian conditions separate from dam facilities and operations (e.g. gravel supplementation or riparian revegetation).

Some options are structural but can also be operated in a number of ways. Generally, the closer the environmental effect is to the dam, the more likely a structural option would be useful for mitigation. For example, reducing the impact of blockage of migrating aquatic species is best achieved with structural modifications. Hydrologic regime issues are often better addressed by operational changes, though may require new infrastructure (e.g., a re-regulation facility). Water quality goals can generally be achieved with structural and/or operational options.

Table 1 also indicates if 1) a local option might also be suitable for implementation offsite and 2) whether the option would affect hydropower operations. The latter information helps identify where potential trade-offs with hydropower generation may occur and, consequently, where modeling would be particularly useful. A subsequent step to identify specifically which aspect

Table 9. Local Options for Mitigating Adverse Environmental Effects of Hydropower Dams

Control variables and mitigation options for ecosystem domains	Type (S/O/E)†	Accepted CA & Northwest	Considered experimental	Hydropower impact
Habitat structure				
Passage – upstream				
Fish passes; locks; elevators	S	✓		✓
Passage – upstream & downstream				
Bypass channel	S		✓	✓
Fish ramp	S			✓
Trap and transport	S, O	✓	✓	
Pumping	S, O		✓	
Passage – downstream				
Spillway passage/design	S		✓	✓
Turbine passage	S,O		✓	✓
Barrier/guidance devices	S	✓	✓	
Complementary bypasses, chutes, & sluiceways	S	✓		✓
Intake relocation	S	*	*	
Hydrology				
Instream flows				
Environmental flows (& support infrastructure)	S, O	✓	✓	✓
Temperature flows	O	✓		✓
Flushing flows	O	*	✓	✓
Bypass flows	O	*		✓
Water quality (headwater and tailwater)				
Temperature in tailwater				
Selective withdrawal	S, O	✓		✓
Operations optimization	O	✓		✓
Dissolved oxygen				
Artificial circulation (reservoir)	S	✓		
Hypolimnetic aeration (reservoir)	S	*		
Direct oxygen/air addition	S	*		✓
Surface aeration (tailwater)	S	✓		
Total dissolved gases				
Spill deflectors	S		✓	
Operations optimization	O		✓	✓
Other options	S, O		✓	✓
Sedimentation in reservoir				
Sediment pass-through	O	*	✓	✓
Dredging	E	*		
Nutrients in reservoir				
Sediment removal		(see *Sedimentation in reservoir*)		
Incoming nutrient removal	E	✓		
Dilution and flushing	O	✓		✓
Hypolimnetic withdrawal	S, O	✓		
Heavy metals in reservoir				
Sediment removal (see #9)		(see *Sedimentation in reservoir*)		
Algal production in reservoir				
Nutrient control (see #10)		(see *Nutrients in reservoir*)		
Lubricants and hydraulic fluids				
Environmentally acceptable lubricants and fluids	O	*	✓	
Greaseless components	S	✓		
Sediments and pollutants from riparian zone				
Riparian vegetation		(see *Riparian vegetation*)		
Aquatic species populations				
Fish propagation				
Habitat segregation weir	S	*		
Comprehensive options				
Complete dam facility				
Dam decommissioning	S, O, E	✓		✓

† 'Type' key: S = [Infra]Structural; O = Operational; E = Environmental
* status unknown based on the literature reviewed

of hydropower operations is affected by each option will be important for modeling and analysis of potential trade-offs.

Offsite options

Offsite options aim to improve overall aquatic environmental conditions (including improving the terrestrial environment as needed) in ways conducive to achieving ecosystem behavior improvement goals, but may or may not be intended to reverse or mitigate a particular facility's direct impacts. The objectives of offsite mitigation are 1) to account and mitigate for hydropower impacts at the landscape scale and 2) to compensate for or offset the impacts of other system disturbances, consistent with concepts of regional management discussed below.

Table 2, similar to Table 1, summarizes options that could be implemented offsite (but are not limited to offsite implementation). These are all generally environmental options, but would, for the most part, be expected to complement structural, operational, and local environmental options. For example, offsite downstream flood management options would complement controlled flooding options implemented at local scale.

Some offsite options overlap with local options. For example, riparian zone revegetation and management could be implemented locally (e.g., within the project boundary) and/or offsite as a more comprehensive mitigation solution.

Table 10. Options with Offsite Opportunities for Mitigating Adverse Environmental Effects of Hydropower Dams

Control variables and mitigation options for ecosystem domains	Type (S/O/E)†	Accepted CA & Northwest	Considered experimental
Habitat structure			
Habitat complexity			
Gravel augmentation	E	✓	✓
Channel improvement	E	✓	✓
Structural habitat supplementation	S, E	✓	
Spawning bed enhancement	E	✓	✓
Water quality (headwater and tailwater)			
Temperature in tailwater			
Riparian revegetation	E	*	
Aquatic species populations			
Fish propagation			
Hatcheries/stocking	S, O	✓	✓
General watershed ecosystem			
Riparian vegetation			
Riparian zone restoration	E	✓	
Riparian zone protection/ management	E	✓	
Downstream flood management			
Storage in retention basins	S	✓	
Flood water bypass	S	✓	
Levee setback	S	✓	

† 'Type' key: S = [Infra]Structural; O = Operational; E = Environmental
* status unknown based on the literature reviewed

Strategies for Integrating Options

Mitigation options have historically been developed and implemented as specific, local solutions to specific, local problems as the problems manifested themselves and hydropower dams are licensed on a project-by-project basis. The cumulative, landscape scale effects of dams have historically not been considered in FERC licenses. In this historical context, alternative management strategies for integrating mitigation options into promising solutions are discussed.

A key challenge in improving environmental performance of Sierra Nevada rivers affected by hydropower dams is deciding which mitigation efforts and options to employ, where to employ them, how to adapt their design to site-specific conditions, and how to integrate them into a comprehensive set of effective solutions while minimizing hydropower losses. Management strategies refer to the non-structural, decision-based methods used to determine promising options to achieve desired environmental performance goals in the face of this challenge. These strategies seek to:

- define the physical and organizational timeframe and system boundary of mitigation efforts;
- identify environmental performance goals and indicators by which system performance with and without options can be evaluated against status quo operations, trade-offs between hydropower and various environmental performance goals explored, and degree of success of selected options evaluated and judged once they have been implemented;
- choose and integrate the appropriate suite of mitigation options to consider for use under cost, time, legal, and other constraints;
- establish methods to adapt to changing environmental and other conditions (e.g., climate change) and new knowledge about ecosystem performance (i.e., reduced uncertainty); and
- use assistive management tools and processes to help choose and develop mitigation options and monitor and evaluate system performance after selected options are implemented .

This section highlights potentially useful approaches for addressing these aspects of hydropower project management, with an emphasis on mitigation option development, implementation, monitoring, and improvement.

Regionalization, which includes the planning and management of mitigation options at larger regional scales and the coordination of relicensing efforts, provides a framework for determining the system boundary. Adaptive management explicitly recognizes uncertainties in ecosystem behavior and our understanding of that behavior by incorporating flexibility to change management plans. Adaptive management plans typically include operational improvement studies, performance indicators and monitoring, and consider climate change and other kinds of uncertainties, and provide a framework for on-going adaptation of hydropower management under changing conditions and new knowledge. Finally, assistive management tools, including computer-based modeling, and data development and analyses, support both regionalization and adaptive management strategies. These concepts provide alternatives to the historical single-project approach to hydropower dam operations relicensing efforts.

Regionalization

Hydropower dams in the Sierra Nevada, as elsewhere, have historically been relicensed on a project-by-project basis, per the traditional FERC license process (as reviewed in HRC 2005). However, recently exceptions have occurred (e.g., Upper American River Project/Chili Bar Hydroelectric Project) and interest on the part of licensees in using the Alternative Licensing Process (ALP), which allows all stakeholders to participate in the application development process, has grown (e.g., Southern California Edison for their Big Creek System in the upper San Joaquin River, Pacific Gas and Electric for the Mokelumne River Project, and the California Department of Water Resources for their Oroville Facilities Project on the Feather River). These early experimental efforts with the ALP have fostered initiatives towards adaptive management (e.g., the Mokelumne River Project) and more regional approaches to relicensing (e.g, the Big Creek System and Oroville Projects). In the Big Creek System projects relicensing process under the ALP, simultaneous or parallel re-licensing of multiple projects has been underway as a way to facilitate cross-project negotiations on mitigation actions and efforts to address ecosystem conditions at broader scales within the watershed rather than at project-by-project scales.

In these early experimental efforts mitigation options are generally constricted to project boundaries or at most to areas affected by the individual projects (again, UARP/Chili Bar serves as an example) with little consideration of Sierra-wide environmental goals. However, efforts to protect and enhance aquatic biotic health in the Sierra Nevada should ideally be aimed at the watershed scale (Moyle et al. 1998). It is therefore important for hydropower facilities and other stakeholders to develop and implement mitigation options beyond the limited spatial scope of project boundaries and project-affected areas.

Regionalization in the context of managing multipurpose hydropower systems in the Sierra Nevada would involve:

- Sierra Nevada-wide consideration and coordination of mitigation efforts, where offsite mitigation options can be integrated with local options and optimization operations modeling can be used to explore the range of inevitable trade-offs between hydropower and environmental assets (integrated mitigation) and
- coordination of dam relicensing efforts among licensees (parallel licensing) within a wider system boundary, to more effectively support Sierra-wide ecosystem improvement goals.

These are both explored below, with a focus on technical, methodological, and process aspects of these approaches. A legal analysis of these concepts is explored by H. Doremus in a companion report.

Integrated mitigation

Several approaches that could be useful in integrating mitigation options into more effective management strategies by enlarging the spatial context are described conceptually. It will be important to identify where these approaches have been used (both successfully and unsuccessfully).

Balancing mitigation efforts among watersheds – Ideally, mitigation efforts and options should be balanced against the need for minimal hydropower loss. This could be achieved with a careful balancing of mitigation efforts between watersheds, or even within one watershed, where greater mitigation efforts are implemented in high ecosystem priority watersheds or sub-watersheds while lesser efforts are implemented in other watersheds of lower ecological priority. The result could be a significant amount of hydropower loss but high environmental gain in the high priority area, accompanied by little to no hydropower loss, and perhaps even small hydropower gain, but low or no environmental gain in the lower priority area. This situation would arise when the same amount of investment in a mitigation option yields different results and benefits in different places, and where mitigation investments are limited. This balancing has been proposed by Richter and Thomas (2007), but further work is needed to identify where—if at all—this approach has been applied with satisfaction.

Coordinated dam operations – Some mitigation options may require that operations of a cascade of hydroelectric dams and other dam projects be coordinated within a watershed at appropriate temporal scales to achieve specific management objectives. Such options may included those related to flow regimes and temperature and other water quality variables. For example, if a flow regime pattern is needed downstream of the lower most dam in a series of dams (Richter and Thomas 2007), then flow releases from each dam would need to be coordinated, depending on the size of the downstream dam relative to the flow requirements. Such coordination would necessarily require computer modeling to optimize operations, such as the work examined by M. Olivares et al, in a companion report.

Offsite mitigation – Alternative mitigation approaches could include implementing mitigation options offsite, outside of the official hydropower project boundaries, as previously discussed (see Table 2). Offsite mitigation would allow the hydropower project to achieve ecosystem performance objectives by enhancing environmental conditions that may or may not be directly caused by dam operations, but where improvement of such conditions would offset some of the cumulative adverse impacts of river regulation.

Coordinated studies and monitoring – Studies and monitoring (as discussed below) could be coordinated on a regional scale to maximize the usefulness of scientific and operational improvement studies. Thus, testing of a potentially promising experimental mitigation approach might be conducted in a basin where loss of hydropower would be less significant than loss in another basin. Paired basin studies could be particularly advantageous in the Sierra Nevada due to the relative similarity of many adjacent watersheds. Sierra Nevada-wide coordination and sharing of monitoring could help ensure that lessons learned from one project or area, are shared throughout the basin as input to adaptive management strategies, described below.

Parallel licensing

Integrated, coordinated efforts to mitigate adverse environmental impacts, as described above, can most likely be best achieved if agreed upon during inter-project, multi-stakeholder relicensing negotiations such as those that occur under ALP. For example, if opportunities for prioritization are identified, where more resources would be put to enhancing ecosystem integrity in one watershed than another (as described above), then coordinated, parallel licensing negotiations and settlement agreements provide an opportunity for the details of those tradeoffs—including specific mitigation options to be implemented—to be determined and agreed upon. This would work particularly well if the projects are in the same watershed and closely related, as in the case of the joint relicensing of the Upper American River Project and the Chili Bar Hydroelectric Project (SMUD/PG&E 2007), but should also be explored where mitigation efforts need to be coordinated at a wider scale.

Adaptive management

Historically, hydropower dams have been licensed and operated in a predictable manner, with little to no changes in operations for instream ecological needs, resulting in numerous effects (as described above). Allowing some future adaptation of hydropower operations to occur in response to changed environmental conditions and new knowledge is one way to help meet ecosystem behavior goals in the long run.

Adaptive management, as described by others and as envisioned here, is an ecosystem management approach whereby uncertainty is explicitly recognized and management strategies are routinely improved with new scientific knowledge gained by continually monitoring and assessing environmental conditions and studying ecosystem responses to those conditions, whether naturally or experimentally created. In addition to simply changing management strategies based on updated scientific information, an adaptive management approach incorporates hypotheses about and, often, models of ecosystem responses to mitigation options and then tests those hypotheses and models with strategic operational modifications to learn about the system (Holling 1978, Walters 1986, Lee 1999, Prato 2003, Failing et al. 2004, Pearsall et al. 2005).

Adaptive management has been explicitly implemented in some relicensing settlement agreements, with varying degrees of scope (e.g., Pearsall et al. 2005, UARP/Chili Bar 2007, Mokelumne River Project 2000). A more detailed and thorough review of where and how adaptive management has been used to improve ecosystems and an evaluation of the concrete outcomes and achievements of using this approach is needed.

General concepts

Adaptive management approaches have been described as either passive or active (Prato 2003, Pearsall et al. 2005). Passive adaptive management begins by using predictions about ecosystem responses based on present knowledge to inform management decisions. As new knowledge is gained, the predictions are updated and management decisions adapted accordingly.

Active adaptive management is more proactive and involves changing management strategies to test new hypotheses. While the goal of passive adaptive management is to improve existing management approaches, the goal of active adaptive management is to learn (i.e., by implementing new mitigation options) in order to find the best management strategy (Walters 1986, Walters and Holling 1990, Prato 2003, Gregory et al. 2006). An adaptive management strategy could begin passively, using existing knowledge, and become more active by incorporating strategic operational and other studies over time (Pearsall et al. 2005).

Adaptive management must be scaled appropriately, both spatially and temporally, given system boundaries, the nature of the specific mitigation options, environmental performance objectives, learning objectives, and project timeframe constraints. Structural options that allow for little to no operational modification (e.g., a fish ladder) may be essential, but are expensive to explore in an adaptive management scheme. Even local structural options with limited room for operational variability (e.g., an in-reservoir option for increasing dissolved oxygen levels) do not allow for much adaptation spatially or temporally.

On the other hand, operational options (e.g., flow releases alterations) are the easiest target for passive or active management, since operations are more readily changed, whether as a response to new knowledge or as part of a strategic study. Operational options that involve multi-dam coordination would be much more beneficial if managed adaptively at the broader scale beyond a single project dam facility. Current adaptive approaches to managing flow releases typically stipulate operational changes every five years (e.g., Pearsall et al. 2005), although this time period is somewhat arbitrary.

Operational improvement studies

One goal of active adaptive management is to learn about how the ecosystem responds to environmental conditions to aid in achieving environmental management objectives. Operational improvement studies include field-based experiments and computer based modeling studies designed to test a hypothesis about system response to changed environmental conditions, in order to improve mitigation strategies. Ultimately, operational improvement studies would be used to test the efficacy of strategic alterations in operational mitigation options and possibly, albeit to a lesser degree, small-scale environmental options.

There is some risk in trying to apply a new strategy to managing a hydropower project and associated aquatic habitat and species (Walters 1997). Such risk can be managed by 1) careful model development prior to study implementation, 2) balancing potential for learning against potential hydropower losses or ecosystem degradation by strategically choosing experimentation sites within a region (see Regionalization, above), 3) providing predictability in operations through agreed-upon change schedules and procedures, 4) multi-party input to study planning efforts, and 5) carefully thought out performance indicators and monitoring plans for informing studies and future operational changes.

Adaptive management of the Roanoke Rapids Dam includes, for example, studying the effect of alternative flow release schemes on riparian species of concern. Models were used to develop testable hypotheses and a 5-year time period between release schemes was chosen to give time to learn and also time for the licensee to prepare for changed operations. Furthermore, the licensee agreed to as-yet-unknown studies after 30 years if the ecosystem objectives are not met, subject to a multi-party committee review (Pearsall et al. 2005).

Performance indicators and monitoring

Performance indicators and monitoring used to evaluate option performance and inform future implementation of all types of mitigation options, are fundamental to both passive and active adaptive management approaches. In an adaptive management framework, evaluation of indicators and monitoring results provides the crucial link between implementing mitigation options and improving management of those options.

Environmental performance indicators

An environmental performance indicator is a qualitative or quantitative representation of the degree to which ecosystem behavior goals are being met and are determined through the use of comprehensive short term and long term monitoring and interpretation of monitoring results, tailored to the system to be managed. Performance indicators help measure the current and projected ecosystem behavior as affected by hydropower operations and mitigation options. Indicators can be:

- directly monitored ecosystem variables (e.g., monitored fish population size),
- calculated indicators or indices (e.g., percent change in fish population), or
- proxy indicators (e.g., water temperature as an indicator for fish survival).

Calculated indices are often useful to summarize a variety of other indicators. Moyle and Randall (1998), for example, developed an index of biotic integrity for the Sierra Nevada at the watershed scale in which measures of infrastructure density were used as input variables to calculate a single biotic integrity indicator.

Indicators should be carefully developed at the onset of the dams' licensing period, in coordination with deciding upon mitigation options. Additionally, performance indicators for similar objectives should be standardized across the Sierra Nevada to aid in comparing management options efficacy and learning.

Ecological performance indicators should:

- be easy to measure (by way of monitoring as discussed below),
- be easy to understand,
- be sensitive to stresses on the system and respond to those stresses in a predictable manner, whether those stresses are anthropogenic or natural disturbances,
- anticipate impending changes in the system that can be averted by management actions, and
- collectively cover key gradients across the systems (e.g., hydrology, water quality, aquatic species, etc.) (adapted from Dale and Beyeler 2001).

In addition to these points, performance indicators should ideally cover the range of hierarchical levels in the watershed, from the organism or species to the ecosystem (Dale and Beyeler 2001). Meeting the above criteria in a complex, poorly understood ecosystem is a challenge, so that ecological performance indicators would need to be continually improved using an adaptive management framework.

Monitoring

Monitoring refers to sampling or measuring selected physical, chemical, or biological ecosystem variables affected by hydropower dams and facilities (Roni 2005). Monitoring should serve as inputs to performance indicators and therefore be linked to specific management performance goals and defined objectives, rather than "monitoring for monitoring sake". Historically, monitoring has, for the most part, been inadequate, due to limited funding, long time periods often required to detect ecosystem responses to changes, and poor understanding of how to effectively monitor and evaluate projects (Roni 2005).

Roni (2005) provides a detailed review of a variety of watershed restoration monitoring projects, including how to design a monitoring and evaluation program. Their approaches could be extended to other mitigation options. Key steps in a successful monitoring and evaluation program, as adapted from Roni (2005), include:

Define goals and objectives (including performance indicators)

Define key questions, hypotheses, and monitoring scales

Select appropriate monitoring design

Determine parameters to monitor

Determine number of sites and number of years to monitor

Determine sampling scheme for collecting parameters

Implement monitoring program

Analyze and report results

Refine management and future restoration projects

The last step—refinement of future projects—is a key component of adaptive mitigation management.

The spatial scales of monitoring of mitigation option performance will correspond to the scales of the ecosystem variables of concern, ranging from the habitat unit (meters) to the watershed. Variables to be monitored will depend on the management objectives and performance indicators needed, which will be site-specific, but could include, for example, characteristics, attributes, or changing state of water quality, flora and fauna species and/or communities, or downstream incision.

Some variables may not be measurable directly (or may be economically prohibitive to measure directly) but can be estimated by modeling if the right model input data is available and collected. Examples include sedimentation accumulation in a reservoir or extent of flood inundation area (e.g., Pearsall et al. 2005).

To increase the value of monitoring, lessons learned from management strategies should be shared amongst dam and watershed managers throughout the Sierra Nevada. This includes sharing both results of specific, one-time studies as well as findings from monitoring of ongoing, routine operations.

Climate change and uncertainties

An adaptive approach to management explicitly recognizes and accounts for uncertainty. Uncertainties in the Sierra Nevada include environmental changes, such as climate change, as well as ecosystems' responses to those changes. Management strategies must be able to respond not only to climate change, but also to changes in climate predictions.

As a whole, California's water resources are likely to be able to adapt to the most likely climate change scenarios, but successful adaptation is not straightforward and can be costly, and water resource operations will need to be properly managed to minimize costs and damages (Tanaka et al. 2006). In the San Joaquin and Sacramento Rivers' tributaries, adaptation to climate change will pose a significant challenge, given both the anticipated changes in climate and the uncertainties associated with those changes (Dracup et al. 2005).

Computer modeling tools will be essential to develop adaptive management strategies for climate change, as discussed below.

Assistive management tools

Assistive management tools include methods, data and information, and analytical tools that help hydropower project managers and other stakeholders make more informed decisions, develop realistic goals and objectives, develop mitigation option solutions, and better employ performance indicators and monitoring. Assistive tools discussed here include computer-based modeling, and associated data and information development and analyses.

Modeling

Computer-based modeling allows us to explore the economic and environmental impact of operations and actions under a wide range of conditions with relatively little investment, greatly reducing the uncertainty and expense of field implementation. Models can support both single-dam and system-wide management decision-making in several areas, as described below.

Planning analysis

At the watershed and regional (i.e., landscape) scales, water resources simulation models can be used to represent and understand watershed environmental processes and existing and future hydropower and other infrastructure and operations under alternative water management policies, by predicting system responses to changes in those processes, infrastructure, operations, and policies.

The Water Evaluation And Planning System (WEAP, www.weap21.org), for example, is a simulation-based model designed to aid in water resource planning and infrastructure operations and other policy analysis. When developed for and applied across the entire Sierra Nevada, computer simulation models such as WEAP could help provide a much more thorough understanding of Sierra Nevada water resources with and without hydropower infrastructure, and how resources and hydropower operations would respond to climate and policy changes, than is currently possible (Tellus/SEI 2007, Yates et al. 2007).

Other planning analysis models could include standard GIS-based models to represent existing morphologic, hydrologic, and environmental conditions, as has been done concurrently in a companion reports (for example, by J. Viers and others).

Operations optimization and simulation modeling

Operations optimization models are computer-based methods to assist in identifying the best way to operate one or more components of a hydropower system based on system performance objectives and physical and policy constraints. Simulation models, on the other hand, predict in more realistic detail the resultant performance of a system in terms of hydropower and environmental conditions and outcomes, given a defined set of rules for how the system is to be operated, and appropriate environmental parameters and performance indicator models to represent ecosystem response. Operational mitigation options can be efficiently explored and developed in a general way using optimization models (see for example the companion report by M. Olivares et al.), and insights tested and refined in detail for site-specific conditions using simulation models, in a complementary fashion.

Usually, optimization models have been built and used for modeling hydropower systems in the Sierra Nevada by system owners. Every major hydropower system has one or more computer model representation used to aid in hourly, daily, and monthly operational decisions and explore alternatives for short and long-term system planning of hydropower operations. Modifying such models to explore environmental and instream objectives—as well as climate change—at local and landscape scales is possible and would allow exploration of novel solutions using a range of mitigation options by incrementally examining the integration of new options into existing system operations.

Optimization-driven operations modeling can be used to develop operating trade-off curves (representing the maximum possible trade-offs between environmental needs and hydropower revenue under optimized operating policies) for particular options for both existing and future conditions, as depicted in Figure 2. When conditions change, generally operations must adapt, and new optimized operating trade-off curves developed in order to achieve maximum performance objectives under the new conditions. In contrast, continuing to use current operating policies under future or changed conditions would likely lead to suboptimal performance. M. Olivares (et al.) develop operating trade-off curves between instream flow requirements and hydropower revenue for optimized operation of a flow re-regulation facility, while K. Madani (et al.) examine the ability of the Sierra high-elevation hydropower dams to adapt to future climate warming scenarios and explore characteristics of optimized operational changes this adaptation would entail, in two separate companion reports.

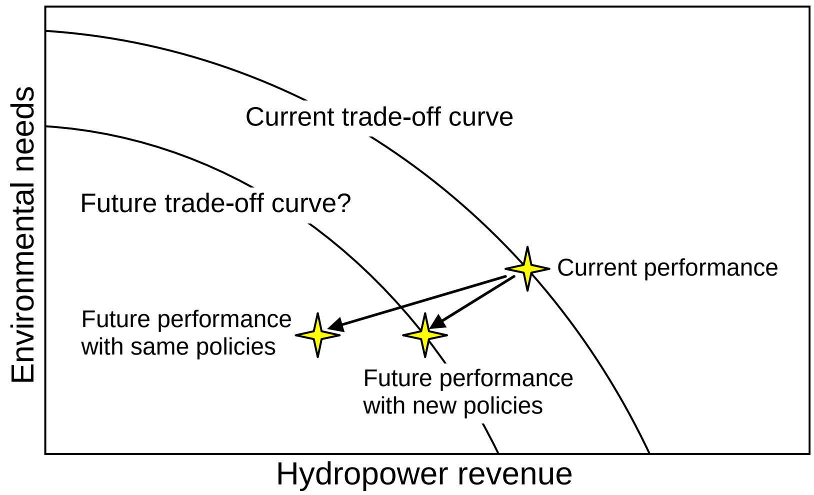

Figure 2. Conceptual Hydropower vs. Environment Performance Tradeoff Curves with Future Policies Optimized to Future Conditions

Two important considerations for successful model development and implementation include:

- definition of modeling objectives (e.g., temperature flow objectives, hydropower operating objectives) and
- context of the problem solving process and the role of model developers and users within that process.

Key optimization and simulation model characteristics include the spatiotemporal scale, including extent of dam aggregation (i.e., how many dams to explicitly include), and the degree to which uncertainty is represented in the model. Different kinds of models would need to be used at different scales, with, for example, output from courser resolution models used as input conditions for finer resolution models, or finer resolution performance results incorporated into courser models. Temporal resolution generally ranges from hourly to annual timesteps in hydropower management modeling, with a range of hydrologic conditions and situations represented in the analysis. Managers of the Roanoke Rapids Dam, for example, use two flow release optimization models: one to optimize day-to-day releases over a month, and the other to optimize energy generation, constrain ramping rates, and/or maximize revenue from hour-to-hour within a day (Pearsall et al. 2005).

Uncertainty can be incorporated into modeling in different ways, to account for the reality that hydrologic and environmental conditions and power generation requirements, for example, are not entirely predictable. Explicitly adding more dams and/or greater uncertainty in the models equates to potentially greater accuracy but also greater model complexity and computational requirements, both of which could be prohibitive, as well as requirements for increasingly large amounts of data, which are often unavailable (M. Olivares, pers. comm.).

Operations optimization modeling is critical not only for dam-based options, but also for any mitigation option that can be operated in a number of ways to achieve different results. For example, in M. Olivares' (et al.) companion report, an optimization model is used to determine how an afterbay for flow re-regulation can be used to achieve instream flow requirements with minimal hydropower revenue loss.

Monitoring support models

In general, monitoring any environmental condition can be supported with the use of modeling to estimate the spatial and temporal distribution of a wide range of characteristics of concern. Thus, modeling can be used as a partial substitute for monitoring everywhere and at all times, which would be cost prohibitive. Water temperature throughout a stream reach, for example, can be estimated by using a hydrodynamic single or multi-dimensional (calibrated) model using measured climate variables, water temperature at inflow locations, and water flow rates as inputs (Dortch and Martin 1989). Extent of flood inundation of a species of concern can be monitored using a model, as is being done downstream of Roanoke Rapids Dam in support of bottomland hardwood forest restoration (Pearsall et al. 2005).

Often monitoring support modeling requires use of biophysical models to represent important physical processes of concern in the system (for example, flow dynamics, water heating/cooling processes, and sediment transport processes) which are affected by hydropower facilities and their operations and which, in turn, change environmental conditions. Models of this kind can be helpful in predicted and estimating changes in environmental conditions of recognized importance and value as indirect indicators for the health of ecosystems and aquatic species.

Shared vision models to support negotiations

Shared vision modeling is an approach for using models that could be quite appropriate to support FERC license negotiations conducted under the Alternative Licensing Process. Shared vision modeling involves the development of a single accepted-by-all water resources system computer model (perhaps with several sub-models) by all stakeholders involved in the water resources planning process. The model is used to explore trade-offs and system performance under alternative scenarios. This approach is specifically aimed toward water resource planning scenarios where conflict (i.e., disagreement) over resources is likely to occur in stakeholder decision-making processes. The model is developed as a group with input and consensus from all stakeholders, with assistance from technical experts, in a collaborative environment where modelers and non-modelers alike equally contribute to the model development, including specifications and assumptions. A shared vision model is a representation of the water system and its response behavior that is agreed to by all stakeholders and reflects their views, knowledge, and concerns including the various model components (e.g., hydropower systems, ecosystem behavior, etc.) and their interactions (Palmer 2000, USACE 2007). Since a shared vision model is developed for stakeholders and by stakeholders, the model must be flexible, transparent, and easy to use (Stephenson 2003).

Palmer (2000) states that a shared vision model must:

> "provide insight into those questions and concerns that are generating the conflict under study;
>
> represent the water resource system in a way that is understood by participants;
>
> include information that is relevant to all participants' diverse perspectives;

obtain joint endorsement by all planning participants, such that the model [is] viewed as an unbiased and valid source of information in a group decision-making context; and

be considered non-proprietary: the shared vision model is equally accessible [for examination and use by] all groups represented in the planning effort, and a common level of proficiency in model use should be attained."

The shared vision model might ultimately be used as a guiding framework for developing and implementing more detailed models for various system components (i.e., detailed temperature or recreation flow models would be component models within the shared vision modeling framework). As shared vision modeling is a collaborative, stakeholder-driven process, it is ideally suited for use in support of and during a negotiation process.

Climate change modeling

Modeling tools have been developed to assess the impacts of climate change on water resources and water resource systems in California, with results generally indicating some ability of systems to adapt to climate change (Dracup et al. 2005, Tanaka et al. 2006, Madani and Lund 2007).

Optimization and simulation modeling can be used to explore the adaptability of the Sierra Nevada hydropower systems under climate change and environmental needs. New models need to be developed and existing models improved to do this while minimizing revenue loss. The results of such modeling tools—which will need to be updated as climate predictions are updated—could then be used to aid in developing long term climate-based mitigation solutions to hydropower dam operations.

Madani and Lund (2007), for example, in a preliminary study examined the adaptability of California's high-elevation hydropower system to climate warming. Their preliminary results show that the system has some flexibility in adapt operations given the available storage capacity at high-elevation. However, Madani and Lund (2007) have not considered the effects of environmental constraints on system performance or how these constraints might be affected by climate change. Climate warming effects on the environment could result in changes in environmental flow requirements, which in future work should be considered when studying climate change effects on hydropower systems' operation.

Data and information development and analyses

Whether for planning analysis, monitoring support, or shared vision modeling, data and information across several domains are required to 1) quantitatively represent system components, characteristics, and response behavior, 2) provide inputs and parameters for models and the relational equations used in them, and 3) validate and calibrate models to acceptable standards. Successful modeling in support of solution development will depend on obtaining, compiling, developing, and analyzing good information and appropriate data sets to build and run models, and represent mitigation option characteristics and their interactions with existing hydropower operations. Data and information analysis is also required to represent the effects option design features are likely to have on environmental conditions and to interpret subsequent ecosystem system behavior.

Domains and examples of the types of information and data needed for modeling Sierra high-elevation hydropower systems, the performance of environmental mitigation options, and potential changes in environmental conditions and ecosystem response, encompass the following:

Engineering system domain

This domain of information and data refers to the physical facilities and components, operating capacities, system objectives and characteristics, and connectivity of the hydropower generation project system and stream network to be modeled. Similar information and data for mitigation options would also be included in this domain. Engineering system data is best captured by a physically-based schematic of the system developed from and linked to geographic locations that can be viewed in a geographic information systems (GIS), and accompanied by a database in which schematic component characteristics and operating information is stored. Major sources of this kind of information include hydropower system owners, water agencies, and other public organizations who operate facilities or are active in modeling water resources in the Sierra Nevada, in addition to existing GIS-based maps of such infrastructure. A preliminary database design and initial efforts to assemble a GIS-based Sierra-wide physically-based network schematic of high-elevation hydropower systems and their engineering physical and operating characteristics have been initiated (see the companion report by J. Viers and others).

Operational, regulatory, and policy domain

This domain includes information and data on the environmental and other regulations and policies that govern and constrain hydropower project generation operations and stream flow regimes for each project system. These would include regulatory flow and release requirements for environmental, recreational, water supply, and flood management demands for each system and the development of data sets and parameters to represent these operational requirements and constraints appropriately in optimization and simulation models of system operations at selected spatial and temporal scales. This kind of information and data can be obtained from regulatory agreements such as FERC licenses and others mandated by the California State Water Resources Control Board, and from existing modeling studies of Sierra high-elevation reservoirs and facilities by facility owners and others, such as the USACE Comprehensive Study HEC-5 reservoir simulation flood control re-operations models (USACE 2002).

Economic domain

This domain refers to data and information to estimate the economic costs and benefits of changes in hydropower system operations for operators and of mitigation option implementation. Energy prices, for example, which capture the demand for hydropower generation can be easily, and have already been collected from the California Independent System Operators (Cal ISO) and compiled to model changes in the performance of hydropower system operations (see companion operations modeling reports). Economic data are also needed to represent the demand for and value of other kinds of hydropower services, for example, spinning reserve. Costing and performance information for estimating the costs and benefits of various mitigation options would eventually be required to fully evaluate the cost-effectiveness of different options. However, this kind of economic information about option effectiveness would necessarily involve a large effort to compile and analyze actual site-specific costs of implementing mitigation options across actual project sites, and the development of generalized cost equations and parameters to allow option cost estimation for new sites.

Hydrologic and meteorological domain

This domain refers to time series of natural runoff and streamflow data at different spatial and temporal scales, and associated climatic and meteorological data over representative periods of hydrologic variability for both historical and predicted climate change conditions. These kinds of data can be obtained from recorded streamflow and climate monitoring gauges from agencies like the USGS and others, or can be simulated using physical models of rainfall-runoff processes using climate and land-based data and information as inputs. Hydrologic and climatic data are used as inputs to drive models and represent the spatial and temporal availability of natural water resources under seasonal, inter-annual, and climate change variations.

Bio-physical domain

This domain refers to information and data on environmental conditions important for ecosystem health and includes water quality, geomorphology, habitat structure, flow regime, and sediment variables of concern. Generally, these data along with data derived from hydrologic and operations modeling are used to develop and run biophysical models of environmental conditions. These models generally form a subsequent layer of models that use results from hydropower systems simulation and optimization modeling as input, to further analyze and model the implications of changes in system operations on changes in environmental conditions at specific locations of concern and interest.

Ecosystem behavior domain

Information and data are needed to characterize the existing ecosystem condition, characteristics, and species of interest across the landscape and to examine the direction and magnitude of different responses of these ecosystem phenomena to changes in bio-physical environmental conditions. Generally, expert opinion is required for interpreting and analyzing data to develop qualitative and quasi-quantitative relationships of this kind. Alternatively, by compiling and synthesizing spatial and temporal variations in environmental conditions into indices across a landscape or at locations of concern, relative differences in potential ecosystem response for alternative scenarios can be evaluated and judged. Data collection and data and information development in this domain inevitably comprises a combination of large-scale GIS-based analyses and field-based measurement and monitoring of coupled environmental-ecosystem response variables at varied spatial and temporal scales.

In general, data and information development and analyses are needed to support 1) the need for site-specific mitigation options, 2) the planning, design and operation of the option, 3) the development of performance indicators, and 4) the effective coordination of options in planning and operational time frames. For some of these purposes, data will already exist (i.e. from previous studies, monitoring, and modeling efforts) before the option is implemented. However, there is currently a general lack of historical data on environmental ecosystem conditions in the Sierra Nevada watersheds (P. Moyle, pers. comm.). The third need for data would be met by strategic monitoring efforts, as described above. Data from a new operational improvement study could be used to establish the need for a new mitigation option.

Management Opportunities

Opportunities currently exist that, if taken advantage of, will allow for better management of hydropower facilities, as discussed below.

FERC relicensing process

The FERC relicensing process—the settlement agreement in particular—provides the best existing opportunity for hydropower dam stakeholders to influence dam management goals and objectives and the strategies and the options to achieve them. In addition, modeling tools can be used during relicensing to support planning decisions about which options to include and where.

Through negotiations, specific options can be included in the settlement agreement as specific proposed license articles. Indeed, stipulating specific management options in the settlement agreement has become the standard approach by which relicensing stakeholders have had a direct input to hydropower dam management in recent years (Hydropower Reform Coalition 2005).

The relicensing negotiation process (and the resulting settlement agreement) provides a venue for identifying environmental modeling needs and laying the conceptual framework for developing those models, such as via a shared vision model.

Adaptation for climate change and uncertainties

While climate change can be seen as a challenge, it also provides a powerful incentive to develop new adaptable management approaches and strategies that are flexible enough to provide needed services such as hydropower under a variety of environmental and power demand scenarios. If operations optimization models that incorporate climate change are developed, tested, and used for Sierra Nevada hydropower facilities both during the relicensing phases and during the terms of the respective licenses, better solutions in other areas can also be achieved in a more robust, yet flexible manner.

Conclusions and Recommendations

This document reviews the range of promising options that have been used or proposed to mitigate some of the adverse environmental effects of hydropower dams and highlights management approaches that can be used to assemble promising packages of options. Additionally, it highlights some current management challenges and opportunities in adapting these options and concepts to the Sierra Nevada hydropower dams.

A complex array of options is available to better adapt hydropower operations and infrastructure to changed climate, social, and economic conditions and demands, many of which occur offsite. These options will be most effective if strategically integrated as packages of local to offsite options with a view toward the local to landscape scale effects they are designed to mitigate.

Adapting hydropower facility management to uncertain future environmental conditions is therefore possible, but will need to be supported by the appropriate use of performance indicators, monitoring, and continual refinement of management strategies. This adaptation will be best accomplished with the support of modeling tools to optimize operations of key mitigation options.

The introduction of promising mitigation solutions and new management approaches into the FERC license during the relicensing process, coupled with the modeling efforts needed to support implementation of those solutions, is a not only a key opportunity to improve overall hydropower facility environmental management in California's Sierra Nevada, but will be essential to achieve ecosystem performance objectives.

This study could be enhanced in several ways.

<u>Mitigation options tailored more specifically to the Sierra Nevada</u> – A comprehensive survey of the existing mitigation options in use in the Sierra Nevada hydropower projects, coupled with even a preliminary assessment of the environmental challenges that currently exist (i.e., as determined from existing fish population or other studies) for those projects, could be used to narrow the options list included here to those that show the most potential for usefulness in the Sierra Nevada. The options in this narrowed list could then be explored further, for example by reviewing specific instances of success or failure in instances similar to those found in the Sierra Nevada, and as discussed in the next point.

<u>Improve understanding of scope and cost of mitigation options</u> – Critical to both modeling and realistic mitigation option recommendations would be to identify all important attributes of mitigation options (tailored to the Sierra Nevada) in terms of:

- the degree of severity and type (pathway) of impact on hydropower systems performance (i.e., impact on total generation, peak and seasonal generation and associated revenues, and ancillary services such as spin reserve and voltage support);
- additional costs of implementation beyond hydropower losses (e.g. capital, operations and maintenance, environmental, and social costs);
- to what degree the option's performance would be affected by climate change (not at all, a little, a lot); and
- ease of representing option performance with computer modeling.

This information will be essential toward the goal of developing real solutions for better management of the Sierra Nevada hydropower facilities.

<u>Review of adaptive management lessons</u> – Adaptive approaches to hydropower facilities management, where uncertainty has been explicitly recognized, whether with only continual improvement (passive) or strategic operational studies (active) have only

recently been implemented. A thorough review of existing adaptive management schemes from both the United States and elsewhere is needed. Such a review would include the purpose and scope of the adaptive management schemes as originally intended, how the purpose and scope changed over time, if at all, and what some of the approaches' successes and pitfalls have been, particularly with respect to mitigation options development and implementation, performance indicators, and monitoring.

Identify modeling needs – There is an opportunity to incorporate both new and/or improved modeling tools into operations of hydropower facilities to assist in achieving ecosystem performance goals. A more thorough understanding of the kinds of mitigation options that are most likely to be needed in the Sierra Nevada (first point above) combined with identification of which mitigation options need to be modeled the most (second point above) would allow identification of where modeling resources should be focused.

FERC relicensing support – The use of modeling to explore novel solutions and support FERC relicensing negotiations should be developed further.

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Appendix A – Detailed Effects and Mitigation Options

Table A1. Hydropower Project Effects (Adapted from Stillwater Sciences 2006)
*** indicates further review is needed to determine available mitigation options, given pathway and effect**

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
Hydrology and geology				
Dams	High-magnitude flow releases	Bank erosion	Geomorphology	Geomorphology 4.a Instream flows 5.a; 5.c
		Channel bed armoring	Geomorphology	Geomorphology 4.a Instream flows 5.a; 5.c
		Bed scour	Geomorphology	Geomorphology 4.a Instream flows 5.a; 5.c
	Passage of fine sediment	Altered sediment transport rates	Sediment transport	Geomorphology 4.a Instream flows 5.c
	Trapping of large woody debris	Reduced large woody debris inputs to downstream reaches	Geomorphology	Geomorphology and habitat complexity 4.c
Reservoirs and forebays	Impoundment of water	Delta formation	Geomorphology	[further review needed]
		Spatial shifts in groundwater infiltration	Groundwater*	[further review needed]
	Impoundment of sediment	Sediment trapping and associated change in streambed sediment composition downstream	Sedimentation	Geomorphology and habitat complexity Sediment pass-through Gravel augmentation Flushing flows

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
		Decreased delivery of sediment to coastal ecosystems	Geomorphology*	Sediment pass-through
	Water surface elevation fluctuations	Shoreline erosion	Turbidity*	[further review needed]
Powerhouses	High-magnitude flow releases from outlet structures	Scour at outlet	Geomorphology*	[further review needed]
		Entrainment of fine sediment near outlet	Geomorphology*	[further review needed]
Intake structures and conduits	Cross-basin water transfer	Re-sizing of channels to accommodate altered hydrograph	Geomorphology*	[further review needed]
Project-affected stream reaches	Altered flow regimes	Alterations in channel sediment storage	Geomorphology	Geomorphology and channel complexity 4.a; 4d Instream flows 5a; 5.c
		Alterations in bed mobility	Geomorphology	Geomorphology and channel complexity 4.a Instream flows 5.a; 5.c
		Changes in channel morphology (e.g., pool-riffle frequency and size/depth of pools)	Geomorphology	Geomorphology and channel complexity 4.a Instream flows 5.a; 5.c
		Alterations in stream gradient	Geomorphology	Geomorphology and channel complexity 4.a Instream flows 5.a; 5.c

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
		Alterations in planform curvature (channel sinuosity)	Geomorphology	Geomorphology and channel complexity 4.b Instream flows 5.a
		Bank erosion	Geomorphology	Geomorphology and channel complexity 4.b Instream flows 5.a
		Alterations in bankfull width	Geomorphology	Geomorphology and channel complexity 4.b Instream flows 5.a
		Channel bed armoring	Geomorphology	Geomorphology and channel complexity 4.a; 4.d Instream flows 5.a; 5.c
		Alterations to overbank flow and sedimentation	Geomorphology	Instream flows 5.a
		Shift in flood recurrence intervals	Instream flows	Instream flows 5.a
		Vegetation encroachment	Riparian vegetation*	[further review needed]
Transmission lines	Maintenance of transmission line corridor	Surface erosion	Geomorphology	Riparian zone 16.a; 16.b
		Increased runoff	Surface runoff	Riparian zone 16.a; 16.b
		Increased hillslope instability	Surface sediment	Riparian zone 16.a; 16.b

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
Roads	Increased amount of impervious surface/decreased vegetative cover	Surface erosion	Surface sediment	Riparian zone 16.a; 16.b
		Increased runoff	Surface runoff	Riparian zone 16.a; 16.b
		Increased hillslope instability	Surface sediment	Riparian zone 16.a; 16.b
		Decreased large woody debris supply to stream reaches near roads	Habitat complexity	Habitat complexity and geomorphology 4.c
	Construction and use of road/stream crossings (e.g., rolling dips, and culverts)	Accelerated hillslope failure	Surface sediment	Riparian zone 16.a; 16.b
		Increased hillslope instability	Surface sediment	Riparian zone 16.a; 16.b
		Increased sediment delivery to stream	Surface sediment	Riparian zone 16.a; 16.b
	Construction and use of streamside roads	Channel confinement	Geomorphology	Riparian zone 16.a; 16.b
		Rip-rap along channels to protect roads hardens banks and can lead to erosion on opposite banks	Geomorphology*	[further review needed]
Maintenance and recreational facilities	Increased amount of impervious surface	Surface erosion	Surface sediment	Riparian zone 16.a; 16.b
		Increased runoff	Surface runoff	Riparian zone 16.a; 16.b
		Increased hillslope instability	Surface sediment	Riparian zone 16.a; 16.b
	Creation and use of non-designated trails	Surface erosion	Surface sediment	Riparian zone 16.a; 16.b

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
		Increased runoff	Surface runoff	Riparian zone 16.a; 16.b
		Increased hillslope instability	Surface sediment	Riparian zone 16.a; 16.b
Water quality				
Dams	Low-magnitude flow releases from outlet structures	Altered levels of total dissolved gases	Total dissolved gases	Total dissolved gases 8.a; 8.b; 8.c
		Release of hypolimnetic waters with low levels dissolved oxygen	Dissolved oxygen	Dissolved oxygen 7.a; 7.b; 7.c; 7.d
		Release of hypolimnetic waters with high levels of ammonia	Nutrients in reservoir	Nutrients 10.a; 10.b; 10.c; 10.d
		Releases of algae from reservoir to downstream reaches	Algal production	(nutrient control) 10.a; 10.b; 10.c; 10.d
		Altered water temperatures downstream	Temperature	Temperature 6.a; 6.b; 6.c
	High-magnitude flow releases from outlet structures	Increased levels of total dissolved gases	Total dissolved gases	Total dissolved gases 8.a; 8.b; 8.c
		Altered water temperatures downstream	Temperature	Temperature 6.a; 6.b; 6.c
		Increased turbidity	Turbidity*	[further review needed]
	Spill operations	Increased levels of total dissolved gases	Total dissolved gases	Total dissolved gases 8.a; 8.b; 8.c
		Increased turbidity	Turbidity*	[further review needed]
	Sediment pass-through operations	Increased turbidity	Turbidity*	[further review needed]

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
		Release of accumulated metals, nutrients, and other sediment-bound pollutants	Heavy metals and toxics Nutrients	(sediment removal) 9.a; 9.b Nutrients 10.a; 10.b; 10.c; 10.d
		Decreased dissolved oxygen	Dissolved oxygen	Dissolved oxygen 7.a; 7.b; 7.c; 7.d
Reservoirs and forebays	Impoundment of water	Increased algal productivity	Algal production	(nutrient control) 10.a; 10.b; 10.c; 10.d
		Decreased dissolved oxygen levels with depth	Dissolved oxygen	Dissolved oxygen 7.a; 7.b; 7.c; 7.d
		Mobilization of methyl mercury from submerged vegetation	Heavy metals and toxics	(sediment removal) 9.a; 9.b
	Impoundment of sediment	Accumulation of metals, toxic compounds, and nutrients from upstream inputs	Heavy metals and toxics Nutrients	(sediment removal) 9.a; 9.b Nutrients 10.a; 10.b; 10.c; 10.d
		Increased sediment oxygen demand	Dissolved oxygen	(sediment removal) 9.a; 9.b Dissolved oxygen 7.a; 7.b; 7.c; 7.d

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
		Decreased dissolved oxygen	Dissolved oxygen	(sediment removal) 9.a; 9.b Dissolved oxygen 7.a; 7.b; 7.c; 7.d
	Eutrophication	Increased nutrient levels	Nutrients	(sediment removal) 9.a; 9.b Nutrients 10.a; 10.b; 10.c; 10.d
		Increased algal productivity	Algal production	(sediment removal) 9.a; 9.b Nutrients 10.a; 10.b; 10.c; 10.d
		Reduced water clarity	Turbidity*	(sediment removal) 9.a; 9.b Nutrients 10.a; 10.b; 10.c; 10.d
		Hypolimnetic oxygen deficits	Dissolved oxygen	(sediment removal) 9.a; 9.b Dissolved oxygen 7.a; 7.b; 7.c; 7.d
		Diel fluctuation in dissolved oxygen and pH	Dissolved oxygen pH*	(sediment removal) 9.a; 9.b Dissolved oxygen 7.a; 7.b; 7.c; 7.d

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
		Increased exchange of metals and nutrients at sediment/water interface	Heavy metals and toxics Nutrients	(sediment removal) 9.a; 9.b Nutrients 10.a; 10.b; 10.c; 10.d
		Increased instances of aquatic toxicity from algal production	Heavy metal and toxics	(sediment removal) 9.a; 9.b
	Water surface elevation fluctuations	Increased turbidity from shoreline erosion	Turbidity	[further review needed]
Powerhouses	Increased hydrostatic pressure within penstocks	Increased levels of total dissolved gas	Total dissolved gases	Total dissolved gases 8.a; 8.b; 8.c
		Increased variations in pH levels	pH*	[further review needed]
	Cooling water contact with turbine generator	Altered water temperatures	Temperature	Temperature 6.a; 6.b; 6.c
		Release of oil and grease	Lubricants and hydraulic fluids	Lubricants and hydraulic fluids 13.a; 13.b
Intake structures and conduits	Cross-basin water and sediment transfer	Altered water temperatures	Temperature*	[further review needed]
		Transport of sediments, metals, algae, toxic chemicals, nutrients	Heavy metals and toxics* Algal production* Nutrients*	[further review needed]
		Introduction of toxic chemicals from maintenance activities	Heavy metals and toxics*	[further review needed]
Project-affected stream reaches	Altered flow regimes	Altered water temperature dynamics	Temperature	Temperature 6.a; 6.b; 6.c Instream flows 5.b

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
		Altered fine sediment deposition due to alterations in flows causing bedload mobility	Sediment transport	Geomorphology 4.a Flushing flows 5.c
		Altered water column and intra-gravel dissolved oxygen	Dissolved oxygen	Dissolved oxygen 7.a; 7.b; 7.c; 7.d
		Altered diel variation in dissolved oxygen and pH	Dissolved oxygen pH*	Dissolved oxygen 7.a; 7.b; 7.c; 7.d
		Altered production of bottom attached algae	Algal growth (instream)	Instream flows 5.a
Transmission lines near water bodies	Maintenance of transmission line corridor	Increased water temperatures and alterations in water temperature dynamics	Temperature	Temperature 6.c Riparian zone 16.a; 16.b
		Decreased dissolved oxygen and increased variation in diurnal dissolved oxygen levels	Dissolved oxygen	Dissolved oxygen 7.a; 7.b; 7.c; 7.d Riparian zone 16.a; 16.b
		Increased runoff of herbicides and fine sediment inputs during storm events	Heavy metals and toxics Turbidity	(sediment removal) 9.a; 9.b Riparian zone 16.a; 16.b
Roads	Decreased vegetative cover and increased amounts of impervious surface	Increased water temperatures and alterations in water temperature dynamics	Temperature	Temperature 6.c Riparian zone 16.a; 16.b
		Increased runoff and fine sediment inputs during storm events	Fine sediments	Riparian zone 16.a; 16.b

Ecosystem domain & Facilities and features	**Pathway leading to potential effect**	**Potential effect**	**Impacted variable(s)**	**Control variable(s) (w/ Table A3 mitigation option references)**
		Increased turbidity from decreased slope stability	Turbidity	Riparian zone 16.a; 16.b
Maintenance and recreational facilities	Increased human use near water bodies	Discharge of fuel, oil, and grease	Anthopogenic pollutants*	[further review needed]
		Increased fecal coliform from water contact and restroom facilities	Anthopogenic pollutants*	[further review needed]
	Decreases in vegetative cover	Discharge of fertilizers and herbicides	Anthopogenic pollutants	Riparian zone 16.a; 16.b
		Increased water temperatures and alterations in water temperature dynamics	Temperature	Temperature 6.c Riparian zone 16.a; 16.b
Fish and other aquatic species				
Dams	Passage of water via spillways or sluice gates	Injury or mortality from entrainment or impingement on screens or trash racks	Passage	Passage – Upstream & downstream 2.a; 2.c Passage – Downstream 3.a; 3.f
		Disruptive attraction flows	Passage	Passage – Upstream 1.a; 1.c; 1.d Passage – Upstream & downstream 2.a; 2.c
	Flow releases from outlet structures	Altered quality of rearing and spawning habitat from alterations in water temperatures	Temperature	Temperature 6.a; 6.b; 6.c Temperature flows 5.b

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
		Disruptive attraction flows	Passage	Passage – Upstream 1.a; 1.c; 1.d Passage – Upstream & downstream 2.a; 2.c
	Barrier to aquatic species	Blocked access to upstream and or downstream habitats; reduced habitat connectivity; genetic isolation	Passage	Passage – Upstream 1.a; 1.b; 1.c; 1.d Passage – Upstream & downstream 2.a; 2.b; 2.c; 2.d Passage – Downstream 3.a; 3.b; 3.f; 3.g
		Delay or elimination of downstream migration	Passage	Passage – Upstream & downstream 2.a; 2.c Passage – Downstream 3.a; 3.b; 3.f; 3.g
	Barrier to sediment and large woody debris	Degradation of spawning and rearing habitats	Geomorphology	
		Injury or mortality during passage	Passage	Passage – Upstream & downstream 2.a; 2.c Passage – Downstream 3.a; 3.b; 3.c; 3.d; 3.e; 3.f; 3.g; 3.h

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
Reservoirs and forebays	Impoundment of water	Alteration in fish community composition and abundance	Fish propagation*	[further review needed]
		Delay in outmigration	Aquatic species migration	Passage – Upstream & downstream 2.a; 2.c
		Increased habitat for large piscivorous predators	Predation*	[further review needed]
		Alterations in food availability	*	[further review needed]
		Alterations in quality and quantity of spawning and rearing habitat	*	[further review needed]
		Altered access to tributaries	*	[further review needed]
		Creation of population "sink" for stillwater breeding amphibians	*	[further review needed]
	Water surface elevation fluctuations	Stranding	Native fish population*	[further review needed]
		Alterations in available habitat	Native fish population*	[further review needed]
		Reduced access to tributaries	Native fish population*	[further review needed]
		Decreased habitat stability and therefore increased predation/stress due to fish continually having to move to remain within preferred habitats	Native fish population*	[further review needed]
		Alteration of benthic macroinvertebrate assemblage	Benthic macroinvertebrate community*	[further review needed]

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
		Desiccation of amphibian egg masses at perimeter	Amphibian population*	[further review needed]
	Fish stocking	Increased fishing mortality on native fish from increased angling effort for stocked fish	Native fish population*	[further review needed]
		Disease introductions	Fish population*	[further review needed]
		Increased competition and predation on fish and amphibians	Native fish population*	[further review needed]
		Alteration in fish community composition and abundance	Fish population*	[further review needed]
		Hybridization	Fish population*	[further review needed]
Powerhouses	Passage of water through turbines and bypass valves	Injury or mortality from entrainment or impingement on screens or trash racks	Passage	Passage – Downstream 3.b; 3.c; 3.d; 3.e; 3.f
	Discharge from turbines and bypass valves	Upstream migration delay from false attraction	Passage	Passage – Upstream 1.a; 1.c; 1.d Passage – Upstream & downstream 2.a; 2.c
		Injury or mortality from swimming up draft tubes, including turbine strike	Passage	Passage – Upstream 1.a; 1.c; 1.d Passage – Upstream & downstream 2.a; 2.c
Intake structures and conduits	Water intake	Injury or mortality from entrainment or impingement on screens or trash racks	Passage	Passage – Downstream 3.b; 3.c; 3.d; 3.e; 3.f; 3.h

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
	Cross-basin water transfer	Introduction of non-native species	Invasive species*	[further review needed]
		Alterations of species composition and abundance	Native and invasive species communities*	[further review needed]
		Genetic mixing	Native and invasive species communities*	[further review needed]
		Alterations in available habitat	Aquatic habitat availability*	[further review needed]
Project-affected stream reaches	Altered flow regimes	Alterations in available habitat	Instream flows	Instream flows 5.a
		Reduced access to side channels, upstream habitat, tributaries, and floodplain habitat	Instream flows	Instream flows 5.a
		Alterations in food productivity and delivery due to changes in macroinvertebrate community	Instream flows	Instream flows 5.a
		Alterations in intra-gravel oxygen supply in redds	Dissolved oxygen	Instream flows 5.a Dissolved oxygen 7.a; 7.b; 7.c; 7.d
		Alterations of species composition and abundance	Aquatic species diversity	Instream flows 5.a Fish propagation 14.a; 14.b
		Alteration of benthic macroinvertebrate assemblage	Benthic macroinvertebrate community	Instream flows 5.a
	Flow fluctuations	Alterations in available habitat	Instream flows	Instream flows 5.a

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
		Reduced access to side channels, upstream habitat, tributaries, and floodplain habitat	Instream flows	Instream flows 5.a
		Alterations in food productivity and delivery due to changes in macroinvertebrate community	Macroinvertebrate community	Instream flows 5.a
		Alterations in intra-gravel oxygen supply in redds	Dissolved oxygen	Instream flows 5.a Dissolved oxygen 7.a; 7.b; 7.c; 7.d
		Alterations of species composition and abundance	Aquatic species diversity	Instream flows 5.a Fish propagation 14.a; 14.b
		Alteration of benthic macroinvertebrate assemblage	Benthic macroinvertebrate community	Instream flows 5.a
		Forced movement or migration	Instream flows	Instream flows 5.a
		Stranding of fish or their redds	Instream flows	Instream flows 5.a
		Dewatering of redds	Instream flows	Instream flows 5.a
		Stranding, desiccation, or scour of larval amphibians and egg masses	Amphibian population	Instream flows 5.a
		Displacement of amphibians	Amphibian population	Instream flows 5.a
Transmission lines	Maintenance of transmission line corridor leading to increased solar radiation	Decreased habitat availability resulting from reductions in water quality	Temperature	Temperature 6.c

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
Roads	Runoff of fine sediment	Changes to water quality affecting fish habitat and survival	General habitat quality	Riparian zone 16.a; 16.b
		Changes to gravel permeability affecting fish habitat and survival	Fine sediments	Riparian zone 16.a; 16.b
	Decreased vegetative cover leading to increased water temperatures and decreased large woody debris and leaf litter inputs	Decreased habitat quality	Temperature Habitat complexity	Temperature 6.c Habitat complexity 4.c Riparian zone 16.a; 16.b
	Road/stream crossings	Limiting or blocking fish passage to upstream habitat	Habitat complexity	Habitat complexity 4.b
Recreational facilities	Angling, including introduction of bait fish	Injury or mortality to fisheries	Fish populations	Fish propagation 14.b
		Poaching	Fish populations	Fish propagation 14.b
		Degradation of spawning and rearing habitat	General habitat quality	Habitat complexity 4.d
		Alterations in species composition and abundance	Fish populations	Fish propagation 14.b
	Travel of recreationists and use of recreational equipment	Introduction and dispersal of non-native and invasive species	Native fish populations	[further review needed]
Special-status plants, lichens, and fungi, and plant communities				
Reservoirs and forebays	Impoundment of water	Alterations in aquatic and reservoir perimeter species abundance and community composition	*	[further review needed]
		Alteration of wetland hydrology and communities	*	[further review needed]

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
		Establishment of aquatic weeds	*	[further review needed]
	Water surface elevation fluctuations	Alteration of plant species abundance and community composition	*	[further review needed]
		Alteration of wetland hydrology and communities	*	[further review needed]
		Drowning or desiccation of special-status plant species	*	[further review needed]
Intake structures and conduits	Cross-basin water transfer	Spread of noxious/non-native invasive plant species (e.g., aquatic weeds or reservoir margin weeds that can be dispersed by water)	*	[further review needed]
Project-affected stream reaches	Altered flow regimes and sediment supply/transport	Encroachment of riparian vegetation into the channel (due to decreases in scouring flows)	Riparian vegetation	Instream flows 5.a
		Alteration of riparian plant community composition and structure	Riparian vegetation	Instream flows 5.a Riparian zone 16.b
		Impacts to special-status aquatic or riparian plant communities or species (distribution, abundance, and composition/structure)	Plant communities	Instream flows 5.a
		Alteration of wetland hydrology and communities	Wetland hydrology Wetland species	Instream flows 5.a
		Altered sediment supply to wetlands	Wetland geomorphology	Instream flows 5.a; 5.c

Ecosystem domain & Facilities and features	Pathway leading to potential effect	Potential effect	Impacted variable(s)	Control variable(s) (w/ Table A3 mitigation option references)
Transmission line and roads	Maintenance of transmission line corridor	Alterations to plant community composition and structure	Riparian vegetation	Riparian zone 16.a; 16.b
		Impacts to special-status plant species and fungi and their habitats	Riparian vegetation and fungi	Riparian zone 16.a; 16.b
		Increased edge effects (e.g., changes in microclimate)	Riparian microclimate	Riparian zone 16.a; 16.b
		Corridor for introduction and spread of noxious/non-native invasive plant species	Riparian vegetation	Riparian zone 16.a; 16.b
		Dispersal of noxious/non-native weeds and disease-carrying fungi to new locations	Riparian vegetation	Riparian zone 16.a; 16.b
Powerhouses, switchyards, and maintenance facilities	Ground-disturbing activities and vegetation clearing	Degradation of habitat and/or eradication of populations of special-status plants, fungi and their habitats	Riparian vegetation and fungi	Riparian zone 16.a; 16.b
Recreational facilities	Ground disturbing activities and vegetation clearing (e.g., during trail maintenance), use of non-designated areas, travel of recreationists	Dispersal of noxious/non-native weeds and disease-carrying fungi and introduction to new locations	Riparian vegetation	Riparian zone 16.a; 16.b
		Degradation of habitat and/or eradication of populations of special-status plants, fungi and their habitats	Riparian vegetation and fungi	Riparian zone 16.a; 16.b

Table A2. Dam Effects Mitigation Options Descriptions

Control variable/ Mitigation option	Description/Discussion
Habitat Structure	
Passage – Upstream	
Fish pass	A fish pass is a passage allowing migrating fish to pass from the tailwater near the powerhouse (at the turbulent zone downstream of the turbine) to the headwater. The fish pass is integrated into the weir/powerhouse and is designed with high velocities into the tailwater for attraction flows. Variations include weir-type pass, vertical slot pass, and Denil pass. Physical and operating characteristics of the dam as well as ecological/hydrological characteristics will be significant factors in the fish pass design. [1-3]
Eel ladder	Eels need a particular type of passage facility separate from a fish pass since they do not simply swim against the current. An eel ladder provides clusters of vertical wires along its floor to allow for eel passage and has been developed in a variety of configurations. [1-5]
Fish lock	A fish lock is similar to a navigation lock. First, fish enter on the tailwater side of the lock. Then, a gate is closed preventing downstream flow of water and water is pumped into the lock until the water is level with the headwater. The gate is then opened, allowing upstream fish passage. [1-3]
Fish elevator	A fish lift traps fish and other species into a tank as they migrate upstream and periodically and regularly lifts them vertically upward to release them in the headwater. This has been used in instances of high head difference between headwater and tailwater, low flow volume, and space constraints. [1-3]
Passage – Upstream & downstream	
a. Bypass channel	A bypass channel resembles a natural stream and allows migrating fish to pass from the tailwater to the headwater or vice versa. The bypass channel can be either on the powerhouse side if it is the main fish passage or the weir side if it is to supplement a fish pass. Appropriate measures must be taken to ensure sufficient water quantity is released into a bypass channel and that fish are prevented from entering the turbines, especially in the headwater area. Bypass channels can also be used to facilitate minimum flow releases. [2, 6, 7]
Fish ramp	Fish ramps are wide, low gradient fish passages designed to mimic some of the natural substrate characteristics of a stream, built along side a low head weir which may or may not be at small hydropower facility. The head of the ramp is built just below the level of the weir, so that minimum flows along the ramp are maintained. A fish ramp can be seen as a cross between a fish pass and a bypass channel. [1, 2]
Trap and transport (truck or barge)	Trucking or barging migrating fish upstream or downstream involves transporting juvenile salmon in a tank using a truck via road or a barge via the river itself. This has been used in the Columbia River Basin by the U.S. Army Corps of Engineers with varying degrees of success. [3]

Control variable/ Mitigation option	Description/Discussion
Pumping	Pumping fish to move fish either upstream or downstream is a technology that has been transferred from the aquaculture and fishing industry and is largely in the experimental stage. The U.S. Fish and Wildlife Service has banned its use in some areas due to the problems it can cause to the fish. [3]
Under-used dam removal	Removing unused or underused hydropower and non-hydropower dams alike within the watershed, either in the mainstem or tributaries, can help minimize aquatic habitat fragmentation within the watershed. Dam removal should be accompanied by at least partial restoration of channel geomorphological conditions, sufficient to allow fish to pass upstream and downstream unimpeded. (Note that this differs from main, currently used dam removal. See below under "Comprehensive" options.) [8-10]
Passage - Downstream	
a. Spillway passage/design	If fish migrate downstream over a spillway, the spillway should be designed such that passage over the spillway is as harmless as possible. This includes ensuring adequate flow (e.g. maximum spill in one particular section), reducing the roughness of the spillway, and ensuring adequate depth in the plunge pool. Spillways may include the free fall spillway, ski jump spillway, Ogee spillway with hydraulic jump, and Ogee spillway with flow deflector. Proper spillway design can also help reduce total dissolved gases. [1, 3, 11]
Turbine passage	Turbine passage includes options that enhance the survivability of aquatic species that pass through the turbine, whether by design or not. [1, 3, 12-14]
Turbine operations	Turbine operation, including efficiency of operation, affects the mortality rate of juvenile salmon passing through the turbines. Turbines should be operated at maximum efficiency during high migration periods. This has been shown to increase fish mortality to 90-98% during migration periods. [1]
Turbine design	"Fish-friendly" turbines have been developed that allow for the passage of fish through the turbines with a much lower juvenile mortality rate than older designs. In addition to reducing mortality, new designs are generally more efficient and could incorporate other features to reduce adverse environmental impacts such as oxygen entrainment. [3, 12-14]
Physical barrier devices	Physical barrier devices physically prevent downstream passing fish from entering into the powerhouse intake. Such systems include: traveling screen, fixed screen, Eicher screen, modular inclined screen, and barrier net/mesh. Some fish can pass through these devices (in some cases by design) while others can be caught in them. Some of these devices are subject to clogging. [1, 3, 15, 16]

Control variable/ Mitigation option	Description/Discussion
Structural guidance devices	Whereas physical barrier devices (above) prevent migrating species from entering the intake, structural guidance devices additionally aid the migrants in diverting the fish away from the intake toward the appropriate downstream passage device (e.g. bypass chute or spillway). Examples include: angled bar/trash rack, louver array, surface collector, and guide wall. These options are preferable to the physical barrier devices. [1, 3, 16, 17]
Alternative behavioral guidance devices	Non-structural behavioral guidance devices involve using alternative means to either deter migrants from the intake and/or attract them to the correct downstream pass. Technologies include acoustic arrays, strobe and mercury lights, electric arrays, water jet curtains, air bubble walls, hanging chains, etc. The advantage of these systems is they require little maintenance, since they do not physically block passage of water and debris. However, there is great uncertainty as to their effectiveness and are generally considered experimental. [1, 3, 16]
Complements to technologies	Complements to technologies include the dams downstream passage feature that allows migrating aquatic species to pass successfully from the reservoir to the tailwater. These are the features that a guidance system would guide the species to. These features generally include bypass chutes, conduits, sluiceways, and/or plunge pools, each of which must be properly designed themselves to prevent fish mortality and promote quick downstream recovery during passage. [1, 3, 16, 18]
Intake relocation	An intake can be relocated entirely in order to reduce the likelihood of passing fish becoming entrained.
Habitat complexity	
a. Gravel augmentation	Gravel augmentation includes supplying additional gravel as needed to provide adequate substrate for fish and other aquatic organisms in key spawning areas. This should be supplemented with the flows needed to redistribute gravel along the stream bed. This is likely to be an important option downstream of the high elevation hydropower dams in the Sierra Nevada (G. Pasternack, *pers. comm.*). [19-23]
b. Channel improvement	Channel improvement includes enhancing stream channel shape on and off the mainstem of the river (on the mainstem, in existing tributaries, or in other side channels such as manmade ditches) and to generally increase channel complexity in order to provide more critical habitat areas. This can include, for example, converting dam-induced constant gradient reaches to repeated pool-riffle configurations. This could also be at least partially achieved by proper riparian vegetation improvements and management to increase bank root complexity. [22, 24-27]
c. Structural habitat supplementation	Structural habitat supplementation includes providing additional material such as large woody debris and other cover to key spawning areas, generally in smaller streams, in order to enhance habitat structure suitable for aquatic species. Constructed options include deflectors and low dams or weirs. [22, 24, 26, 28-31]

Control variable/ Mitigation option	Description/Discussion
d. Spawning bed enhancement	Spawning bed enhancement involves direct manipulation of spawning habitat, for example with riffle construction and/or cleaning. For long term effectiveness, this must be accompanied by appropriate upstream geomorphic and hydrologic processes. [22, 27]
Hydrology	
Instream flows	
a. Environmental flows (& supporting infrastructure)	Environmental flows fulfill downstream needs for flow patterns for instream aquatic species, riparian processes, and geomorphic processes. These can be achieved by releasing water from a dam in such a way as to mimic the natural flow regime or to supply water needed in a pattern for a particular target species or process. Flow release magnitude, duration, frequency, timing (or predictability/seasonality), and flow rate of change all need to be considered and should be determined on a river-by-river basis. Environmental flows, when combined with other important restoration activities such as gravel supplementation, support native aquatic species and deter invasive species, among many other ecosystem support functions. Many methods exist to determine both the natural flow regime and the flow regime needed to achieve a particular environmental objective. While there are many hydrologic features of the “natural flow regime”, essential components that should be integrated into flow regime restoration program include low flows, extreme low flows, high flow pulses, small flood flows, and large flood flows. Obtaining an appropriate balance between environmental flow needs and hydropower is difficult but can be achieved partly with the assistance computer optimization models. Environmental flows can be achieved through re-operation of existing dam infrastructure or with the support of additional infrastructure including re-regulation facilities such as an afterbay. [32-40]
b. Temperature flows	Temperature flows are releases designed specifically to aid in achieving particular downstream temperature targets. This would generally be coupled with a selective withdrawal system, where releases are from particular water temperature pools. [41-43]
c. Flushing flows	Course sediment flows are releases to aid in the redistribution of course sediments within a river reach downstream of a dam. [44-46]
d. Bypass flows	Bypass flows includes those minimum and maximum flows needed within bypass channels to ensure continued, uninterrupted use of the bypass by migrating fish. [2, 6, 7]
Water Quality (headwater and tailwater)	
Temperature	
a. Selective withdrawal	Intake structure(s) can be designed to allow for the selective withdrawal of water from various depths, where each withdrawal depth (or “pool”) may have different temperatures due to thermal stratification. Selective withdrawal should be combined with operations optimization. This option is widely used throughout the world. [41-43, 47]

Control variable/ Mitigation option	Description/Discussion
b. Operations optimization	If a selective withdrawal system is in place, operations can be optimized over time such that hydropower revenues are maximized given downstream temperature target constraints. [41]
c. Riparian revegetation	Establishing or re-establishing riparian vegetation in key locations provides increased shading of a stream, resulting in lower instream water temperatures, especially in smaller streams (i.e., offsite). [48, 49]
Dissolved oxygen	
Artificial circulation	Any method of complete artificial circulation in the reservoir will increase dissolved oxygen concentration by ensuring maximum exposure to the surface air. General approaches include air-lift systems (where air is introduced into the bottom of the reservoir then rises forcing water circulation), mechanical pumps, fan blades, or water jets. Artificial circulation methods generally will reduce thermal stratification, but destratification can be minimized. Artificial circulation can also aid in preventing eutrophication (see *nutrients*, below). [42, 50]
Hypolimnetic aeration (reservoir)	Hypolimnetic aeration methods introduce oxygen into the hypolimnion by either mechanical agitation (where water is drawn from the hypolimnion to be aerated on shore then pumped back into the reservoir) or direct oxygen or air injection to the hypolimnion. One of the objectives of this approach is to not disturb the thermal stratification in the reservoir, so as to maintain the ability to draw from various temperature pools for temperature control purposes (i.e. by selective withdrawal). [42, 50]
Direct oxygen/air addition (turbine)	Oxygen or air can be pumped either directly into the penstock just above the turbine or even in the reservoir itself just before the intake so that oxygen goes immediately to the tailwater without being wasted in the entire reservoir if not needed there. Air can also be entrained directly at the turbine. [42, 51, 52]
Surface aeration (tailwater)	Generally surface aeration involves an aerating weir in the tailrace. The aerating weir forces the tailrace water to be exposed to air, thus increasing dissolved oxygen levels, but can decrease power capacity due to increased head just below the outlet. [42, 51]
Total dissolved gases	
a. Spill deflectors	Spill deflectors force spillway water to be deflected at the bottom to flow along the surface of the tailrace, rather than deep into the plunge pool. This allows the water maximum surface exposure for degassing. However, spill deflectors have been shown to reduce survival rates of passing juvenile salmonids by as much as 7% in the Lower Snake River dams. [53, 54]
Operations optimization	Under high spill conditions, power generation can be maximized at a those dams in a series where high total dissolved gases is more of a concern during spill operations and spill can be maximized at those dams where spillways can effectively reduce total dissolved gases. [53, 55]
Other options	Numerous other options exist. See reference. [53, 56, 57]

Control variable/ Mitigation option	Description/Discussion
Sedimentation in reservoir	
a. Sediment pass-through	Sediment pass-through removes sediment using the force of water to pass sediment from the reservoir to the tailwater. Low-level outlets in the dam can be used to flush out settled sediment at high velocities under certain conditions, such as during high flow events. [58, 59]
Dredging	Dredging involves removing sediment from the bottom of a reservoir by either mechanical or hydraulic means. A grab bucket dredge, for example, scoops sediment from the bottom and empties it on shore. The common feature of the various hydraulic techniques in use include a suction mechanism that pumps sediment to the surface. Other features that have been used include agitators to loosen compact sediment and gas collectors to collect gas that is released when the sediment is loosened. Two problems associated with dredging include 1) the possibility of re-suspension of contaminated sediments during dredging operations and 2) the difficulty and expense of disposing of contaminated sediments. Dredging is rarely done as a mitigation option for hydropower dams due to its high costs. [50, 59]
Nutrients in reservoir	
a. Sediment removal	Since nutrients generally accumulate within the settled sediments in a reservoir, the sediment removal options above also serve to remove sediment-bound nutrients. [50]
Incoming nutrient removal	Nutrients can be removed from incoming waters using, for example, a basin just upstream of the main reservoir where soluble and sediment-bound nutrients can be removed from the water. Such a basin would be designed to hold water just long enough to allow nutrient consumers (e.g. phytoplankton) to convert the nutrients to biomass, which can then be settled. [50, 60]
Dilution and flushing	Low-nutrient water can be used to flush out nutrients in a nutrient-rich reservoir. In some instances this has been achieved by using a cross-watershed transfer of water. [50]
Hypolimnetic withdrawal	Hypolimnetic withdrawal involves withdrawing nutrient-rich waters from the lower hypolimnion of the reservoir rather than from the upper, low nutrient epilimnion, thus reducing the residence time of nutrients in the reservoir. This would be particularly effective if nutrients are due to internal loading (i.e. from nutrient-laden bottom sediments). This could be easily achieved with a selective withdrawal system. Hypolimnetic withdrawal would necessarily impact downstream temperature targets (possibly for the better) since the hypolimnion is the location of the coldest coldwater pool in a thermally stratified reservoir. [50]
Heavy metals in reservoir	
a. Sediment removal	Since heavy metals generally accumulate within the settled sediments in a reservoir, the sediment removal options above also serve to remove heavy metals. [50]

Control variable/ Mitigation option	Description/Discussion
Algal production in reservoir	
a. Nutrient control	Although there are numerous factors affecting algal growth, the primary cause of algal (phytoplankton) growth in a reservoir is nutrient loading. In particular, phosphorous (P) loading is generally considered the limiting nutrient in lakes and reservoirs. Therefore, usually nutrient (P) control options are employed to limit algal production in reservoirs. [50]
Lubricants and hydraulic fluids	
a. Environmentally acceptable lubricants and fluids	Hydroelectric facilities traditionally use mineral-based lubricants, such as oil and grease, and hydraulic fluids. More environmentally acceptable alternative lubricants have been developed that are non-toxic to fish and other aquatic species, plants, and wildlife and are readily biodegradable. There is a wide range of such lubricants and fluids, however, and the terms non-toxic and biodegradable may be ambiguous and used differently by different organization. [61]
Greaseless components	Components of a turbine such as bushings and bearings can be made greaseless. (The references include one example company that supplies the hydroelectric industry with greaseless components.) [13, 62]
Sediments and pollutants from riparian zone	
a. Riparian vegetation	Riparian zone revegetation, protection, and management (see *Riparian vegetation*, below) is the most effective way of preventing or controlling fine sediment and pollutants carried by runoff from and/or through degraded riparian areas (such as developed roads or other riparian development) into affected water bodies. [63]
Aquatic species populations	
Fish propagation	
a. Habitat segregation weir	A fish habitat separation scheme may be needed if two migrating fish are forced to share the same spawning area due to diminished habitat availability. Fish monitoring weirs can be used to distinguish between different fish species while a segregation weir (fish weir) can be used to ensure separation of different species' habitats and, as a result, to prevent potential interbreeding and undesired habitat competition. [64]
Hatcheries/stocking	Hatcheries are off-stream fish propagation facilities that can aid in the rearing of threatened or endangered fish species and their reintroduction into natural waters (stocking). However, hatcheries have, in general, not been an effective method of restoring fish populations where other significant contributions to mortality exist. Poor hatchery operation practices have even been known to cause declines in natural fish production. [65-68]
General watershed environment	
Riparian vegetation	

Control variable/ Mitigation option	Description/Discussion
a. Riparian zone restoration	Riparian areas that have been damaged—causing numerous effects, such as increased runoff-induced fine sediments and pollutants, on aquatic habitats—due to past land use practices can be restored through revegetation and other various efforts. Revegetation would necessarily need to be coupled with riparian zone protection/management (below) to prevent future degradation. In general, the riparian zone is a critical component of the aquatic ecosystem. Restoration can improve a wide range of aquatic and terrestrial environmental conditions where restoration as a mitigation option for a particular issue is not explicitly stated. For example, large woody debris—an important component of aquatic habitat structure—is significantly enhanced with riparian zone restoration and management. [26, 48, 63, 69]
Riparian zone protection/management	Riparian zone protection includes limiting access to riparian areas along rivers, reservoirs, and wetlands as needed within an appropriate distance from the water body to protect, restore, or enhance aquatic ecosystems. In particular, this includes limiting grazing livestock access to riparian areas. Land acquisitions and conservation easements are an integral part of riparian zone protection and management, especially in critical habitat areas such as high quality stream reaches, side channels, and confluences. [26, 63, 70]
Downstream flood management	
a. Storage in retention basins	A natural depression off the mainstem can be used to store excess water during high flows. Stored water is then allowed to drain back into the main river channel as high water levels recede. [33]
Flood water bypass	A flood bypass is an engineered system that diverts floodwaters away from the mainstem, where flooding is undesirable) into a floodplain area where land use is adapted to allow for occasional flooding. Floodwaters then re-enter the mainstem downstream of the diversion. [33, 71]
Levee setback	Levees can be rebuilt farther away from the river they are designed to control, allowing for at least some restoration of natural fluvial geomorphologic processes along the river channel. This could be accompanied by either the complete abandonment of the riparian flood zone or, as with a bypass, could accommodate some land use adapted to occasional flooding. [33, 72]
Comprehensive options	

Control variable/ Mitigation option	Description/Discussion
Complete dam facility	
a. Hydroelectric dam decommissioning	Complete decommissioning of a hydropower project is the most comprehensive option but can yield the maximum ecological benefit at the cost of hydropower and other dam uses. The scope of dam decommissioning can range from partial spillway removal to complete dam removal with restored streambed. This option can be a complex process due to the unknown environmental impacts of removal and other issues, but is generally the best long term ecological option. Although generally expensive, removal may in some cases be more cost effective than retrofitting existing dams. This should be distinguished from removing unused dams (above), although some of the same principles during removal would apply. [8, 73-75]

Table A3. Local Mitigation Options Acceptability and Use

'Type' key: S = Structural; O = Operational; E = Environmental

Mitigation options for control variables	Type (S/O/E)	Accepted California & Northwest	Accepted elsewhere	In use in CA and/or elsewhere	Considered experimental	Offsite opport'y?	Hydropower impact?	References
Habitat Structure								
1. Passage – Upstream								
b. Fish pass							Y	[1-3]
Weir-type pass (orifice and/or pool)	S	✓	✓	✓			Y	[1-3]
Vertical slot pass	S	✓	✓	✓			Y	[1-3]
Denil pass	S	✓	✓	✓			Y	[1-3]
Eel ladder	S	*	✓	✓			Y	[1-5]
Fish lock	S			✓			Y	[1-3]
Fish elevator	S	✓	✓	✓			Y	[1-3]
Passage – Upstream & downstream								
c. Bypass channel	S			✓	✓		Y	[2, 6, 7]
Fish ramp	S			✓			Y	[1, 2]
Trap and transport (truck or barge)	S, O	✓	✓	✓	✓			[3]
Pumping	S, O				✓			[3]
Under-used dam removal	S	✓	✓	✓		Y		[8-10]
Passage – Downstream								
d. Spillway passage/design	S		✓	✓	✓		Y	[1, 3, 11]
Turbine passage								[1, 3, 12-14]
Turbine operations	O			✓	✓		Y	[1]
Turbine design	S		✓	✓	✓		Y	[3, 12-14]
Physical barrier devices								[1, 3, 15, 16]
Traveling screen	S	✓		✓				[3]
Fixed screen	S	✓		✓				[3]
Eicher screen	S			✓	✓			[1, 3]
Modular inclined screen	S				✓			[3, 15, 16]
Barrier net/mesh	S		✓	✓	✓			[1, 3, 16]
Structural guidance devices								[1, 3, 16, 17]

Mitigation options for control variables	Type (S/O/E)	Accepted California & Northwest	Accepted elsewhere	In use in CA and/or elsewhere	Considered experimental	Offsite opport'y?	Hydropower impact?	References
Angled bar/trash rack (and variations)	S		✓	✓				[3, 16]
Louver array	S		✓	✓				[1, 3, 16]
Surface collector	S			✓	✓			[3, 17]
Guide wall	S		✓	✓				[16]
Alternative behavioral guidance devices								[1, 3, 16]
Acoustic array	S			✓	✓			[3, 16]
Strobe and mercury lights	S			✓	✓			[3, 16]
Electric field	S			✓	✓			[3, 16]
Complements to technologies								[1, 3, 16, 18]
Bypass chute or conduit	S	✓	✓	✓			Y	[1, 3, 16, 18]
Sluiceway	S		✓	✓			Y	[3, 18]
Plunge pool	S	✓	✓	✓			Y	[16]
Intake relocation	S	*	*	*				
Habitat complexity								
e. Gravel augmentation	E	✓	✓	✓	✓	Y		[19-23]
Channel improvement	E	✓	✓	✓	✓	Y		[22, 24-27]
Structural habitat supplementation	S, E	✓	✓	✓		Y		[22, 24, 26, 28-31]
Spawning bed enhancement	E	✓	?	?	✓	Y		[22, 27]
Hydrology								
Instream flows								
f. Environmental flows (& supporting infrastructure)	O	✓	✓	✓	✓		Y	[32-40]
Temperature flows	O	✓	✓	✓			Y	[41-43]
Flushing flows	O	*	*	✓	✓		Y	[44-46]
Bypass flows	O	*	✓	✓			Y	[2, 6, 7]
Water Quality (headwater and tailwater)								
Temperature in tailwater								
g. Selective withdrawal	S, O	✓	✓	✓			Y	[41-43, 47]
Operations optimization	O	✓	✓	✓			Y	[41]

Mitigation options for control variables	Type (S/O/E)	Accepted California & Northwest	Accepted elsewhere	In use in CA and/or elsewhere	Considered experimental	Offsite opport'y?	Hydropower impact?	References
Riparian revegetation	E	*	*	✓		Y		[48, 49]
Dissolved oxygen								
h. Artificial circulation (reservoir)	S	✓	✓	✓				[42, 50]
Hypolimnetic aeration (reservoir)	S	*	✓	✓				[42, 50]
Direct oxygen/air addition (at turbine, for tailwater)								[42, 51, 52]
Turbine aeration	S		✓	✓			Y	[42, 51, 52]
Low pressure air blowers	S	*	✓	✓			Y	[42, 51]
Surface aeration (tailwater)	S	✓	✓	✓				[42, 51]
Total dissolved gases								
i. Spill deflectors	S			✓	✓			[53, 54]
Operations optimization	O			✓	✓		Y	[53, 55]
Other options				✓	✓			[53, 56, 57]
Structural options (multiple)	S			✓	✓			[53, 56]
Operational options (multiple)	O			✓	✓		Y	[53, 57]
Sedimentation in reservoir								
j. Sediment pass-through	O	*	*	*	✓		Y	[58, 59]
Dredging	E	*	✓	✓				[50, 59]
Nutrients in reservoir								
k. Sediment removal			see *Sedimentation*, above					[50]
Incoming nutrient removal	E	✓	✓	✓				[50, 60]
Dilution and flushing	O	✓	✓	✓			Y	[50]
Hypolimnetic withdrawal	S, O	✓	✓	✓				[50]
Heavy metals in reservoir								
l. Sediment removal			see *Sedimentation*, above					[50]
Algal production in reservoir								
m. Nutrient control			see *Nutrients*, above					[50]

Mitigation options for control variables	Type (S/O/E)	Accepted California & Northwest	Accepted elsewhere	In use in CA and/or elsewhere	Considered experimental	Offsite opport'y?	Hydropower impact?	References
Lubricants and hydraulic fluids								
n. Environmentally acceptable lubricants and fluids	O	*	*	✓	✓			[61]
Greaseless components	S	✓	✓	✓				[13, 62]
Sediments and pollutants from riparian zone								
o. Riparian vegetation			See *Riparian vegetation*, below					[63]
Aquatic species populations								
Fish propagation								
p. Habitat segregation weir	S	*	*	✓				[64]
Hatcheries/stocking	S, O	✓	✓	✓	✓	Y		[65-68]
General Watershed Ecosystem								
Riparian vegetation								
q. Riparian zone restoration	E	✓	✓	✓		Y		[26, 48, 63, 69]
Riparian zone protection/ management	E	✓	✓	✓		Y		[26, 63, 70]
Downstream flood management								
r. Storage in retention basins	S	✓	✓	✓		Y	Y	[33]
Flood water bypass	S	✓	*	✓		Y		[33, 71]
Levee setback	S	✓	*	✓		Y		[33, 72]
Comprehensive Options								
Complete dam facility								
s. Dam decommissioning	S	✓	✓	✓			Y	[8, 73-75]

* status unknown based on literature reviewed

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SIERRA'S HIGH-ELEVATION HYDROPOWER AND CLIMATE CHANGE

PROJECT REPORT

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Abstract

Climate warming is expected to shift the runoff peak from spring to winter in California as a result of the reduction in snowpack. The Sierra's high-elevation hydropower system supplies roughly 74 percent of California's in-state hydropower supply and is composed of more than 150 power plants with relatively small reservoirs associated with them. Such low capacity reservoir systems have been designed to take advantage of snowpack, the natural reservoir. With climate warming, adaptability of the high-elevation hydropower system is in question as a shift in runoff peak can have important effects on power generation and its economic value. The changes in hydroelectricity generation under three different climate warming scenarios (dry warming, wet warming, and warming only) are simulated and compared to the historic generation to investigate the adaptability of Sierra's high-elevation hydropower system to climate warming. Overall, climate warming results in average revenue reduction. Energy spill increases dramatically under all types of climate warming, whether dry or wet. However, the available storage and generation capacities can compensate for snowpack losses to some extent. Expected revenue reductions of 16, 2 and 5 percent are estimated for dry, wet and warming only scenarios, respectively. Storage capacity expansion, and to some extent generation capacity expansion, result in increased revenues. However, these expansions might not be economically justified.

Keywords: California, climate change, climate warming, global warming, hydropower, energy, No-Spill approach, optimization, simulation, generation, shortage, spill.

Introduction

California relies on hydropower for 9 to 30 percent of the electricity used in the state, depending on hydrologic conditions, averaging 15 percent (Aspen Environmental Group and M. Cubed 2005). Hydroelectricity's low cost, near-zero emissions, and ability to be dispatched quickly for peak loads are particularly valuable characteristics. As climate change affects temperature and precipitation, future hydrologic conditions will change and affect hydropower generation.

Much of California has cool, wet winters and warm, dry summers, and a resulting water supply which is poorly distributed in both time and space (Zhu et al. 2005). On average, 75 percent of California's annual precipitation of 584 mm occurs between November and March, while urban and agricultural demands are highest during the summer and lowest during the winter. Spatially, more than 70 percent of California's 88 billion cubic meters (bcm) of average annual runoff occurs in the northern part of the state (CDWR 1998). Temperature changes due to climate change can affect the amount and timing of runoff. Climate warming is expected to shift seasonal runoff to the wet winter months with less snowmelt runoff occurring during spring. Such a shift might hamper California's ability to store water and generate electricity for the spring and summer months if storage capacity is insufficient. Currently, the Sierra's winter snowpack melts in the spring and early summer, replenishing water supplies during these drier months.

In California both snowpack and reservoirs serve to regulate hydropower generation. Snowpack is controlled by nature and reservoirs by man. As temperatures increase, water stored in the natural snowpack reservoir will be released earlier in the year as runoff while less precipitation will tend to fall as snow. California has benefited from natural and manmade reservoirs for a long time. However, the high-elevation hydroelectricity system has benefited more from snowpack regulation, while the low-elevation system more from larger downstream reservoirs. The vast majority of reservoir storage capacity, over 17 million acre-feet (MAF), lies below 1,000 feet elevation, while most in-state hydropower generation capacity is at higher elevations (Aspen Environmental Group and M. Cubed 2005) and mostly in northern California. Lower elevation storage capacity is used mostly for water storage and flood control, and was not constructed with hydroelectric output as its primary objective, although these low-elevation units produce a notable amount of electricity. Roughly 74 percent of in-state generated hydropower is supplied by high-elevation units although only about 30 percent of in-state usable reservoir capacity is situated at high-elevation (Aspen Environmental Group and M. Cubed 2005).

Because the high-elevation hydropower system has less manmade storage, it may be vulnerable to climate change if existing storage capacity cannot accommodate the high flows in winter and early spring. Most low elevation hydropower plants (below 1,000 feet) benefit from relatively high storage capacities and will be affected less than high-elevation hydropower generation. Storage and energy generation capacity limits at high-elevation will affect the ability of high-elevation hydropower systems to adapt to climate warming.

Studies that have addressed the effects of climate change on hydropower generation in California have been largely restricted to analyses of large lower-elevation water supply reservoirs (Lund et al. 2003; Vanrheenen et al. 2004; Tanaka et al. 2006) or have inspected only a single high-elevation hydropower system (Vicuña et al. 2005). There remains a lack of knowledge about climate warming's potential effects on California's statewide hydroelectricity generation by high-elevation facilities and the adaptability of the Sierra's high-elevation hydropower system to hydrologic changes. Such potential changes may be particularly important to understand in the context of increasing societal demands for environmental protection and for recreation in the Sierra's, in the future. By focusing on the high-elevation hydropower system in the Sierras and its adaptability to changing hydrology, this study fills a gap in the analysis of climate warming effects on water management in California.

Method

One hundred fifty-six high-elevation (above 1,000 feet) hydropower plants in California were identified in this study (see Appendix C). Since runoff patterns vary by elevation, three different elevation ranges have been considered (1,000-2000 feet, 2000-3000 feet, and above 3000 feet). Monthly hydropower energy generation information from U.S. Energy Information Administration Databases for the period 1982 to 2002 was used to calculate the average amount of monthly hydropower energy generation and the generation capacity of each power plant. Instead of using the name-plant capacity of each hydropower plant in this study, the maximum value of actual monthly generation over the 1982-2002 period was considered a more realistic estimate of monthly generation capacity for operations purposes. These results are provided in Appendix C. Studying individual changes in generation patterns for more than 150 reservoirs by conventional simulation and optimization models would be costly and tedious, especially when basic required information such as stream flows, turbine capacities, storage operating capacities, and energy storage capacity at each reservoir are not readily available for each individual plant. This study investigates the climate change effects on generation through a different approach based on energy instead of water volume balances. We call this the 'No-Spill' approach.

'No Spill' approach

The No Spill approach assumes existing storage capacity at high elevation is sufficient to accommodate the historical runoff in an average water year without water spilling from the reservoir. Thus, all water that could have been stored behind a reservoir during months when demand for electricity is low in an average year is assumed to be stored and released later in the year when demand is higher. Lack of spill in an average year was confirmed in conversations with private hydropower operators for many of these plants.

A big obstacle in this study was difficulty obtaining storage capacity for many individual high-elevation hydropower reservoirs. Even if such data were readily available, estimation of energy storage capacities (that portion of the reservoir storage capacity which is used for storing water for electricity generation) would have been tedious to do and probably unreliable. With the No-Spill assumption, the available storage capacity can be estimated in energy units by finding the area between the monthly runoff and monthly generation curves when they both are expressed in terms of percentage of the annual average quantity, as described in Appendix A.

Significantly, this method produces a lower bound estimate of energy storage capacity, as many reservoirs will not spill in wetter than average years and many reservoirs will not fill in an average year. This method estimates the portion of storage capacity which is used in an average year. We also assume reservoirs have negligible over-year storage, which is true with a few exceptions (Lake Almanor, for example). Thus, true energy storage capacities are likely to be higher than the estimates used in this study making this approach somewhat pessimistic.

Generally, turbine head in high-elevation hydropower facilities results mostly from penstock drops, rather than storage elevations. In this case, a linear relationship between the amount of water stored in the reservoir and energy generation is a reasonable assumption, and water storage capacity of a reservoir can be expressed in energy units.

Runoff data were obtained for several U.S. Geological Survey (USGS) gauges representing selected elevation ranges. These sample gauges were selected in consultation with the former chief hydrologist at California Department of Water Resources (DWR). For each elevation range, mean monthly discharge and mean annual runoff were estimated. Mean monthly values were then normalized into percent of mean annual runoff to characterize the average seasonal distribution of available water runoff for each elevation range. Assuming a fixed energy head, un-regulated water runoff is linearly equivalent to available energy runoff. (This coarse approach can be made more sophisticated, but suffices for this preliminary study.) Thus, under the No Spill assumption, the total annual average year energy generation of a hydropower plant (from observed energy production data) is equal to the total annual average year available energy runoff at its location, and only the seasonal distributions of the two differ.

Optimization model setup

After estimation of available energy storage capacities, maximum monthly generation capacity (Appendix C) and elevation specific average monthly energy runoff distributions, a monthly hydropower reservoir operations optimization model was developed to investigate the adaptability of the system to different types of climate warming. The optimization problem was set-up and solved in Microsoft Excel separately as a linear and non-linear model and solved with "What'sBest", a commercial solver package for Microsoft Excel.

Most high-elevation hydropower plant operators are interested primarily in net revenue maximization. Hydropower plants have almost no variable operating costs (at monthly scale), so a surrogate for net revenue maximization would be revenue maximization (operating costs being essentially fixed). Off-peak and on-peak energy prices were captured in the model by using a defined relationship between monthly generation and monthly revenue based on recorded hourly prices, as described in Appendix B.

The model was formulated to identify the optimal reservoir refill and drawdown cycles for each hydropower plant, for each year of the analyzed hydrologic period. Optimal refill and drawdown months may not be the same for different reservoirs even if they are located in the same elevation range because of their different storage capacities. The optimal reservoir refill-drawdown cycle was found assuming the reservoir is operated only for hydropower benefit maximization and carryover storage each year is constant for the reservoir. This might not be true for reservoirs where recreation or environmental purposes are also important objectives for high-elevation reservoir storage operations.

This optimization problem is not linear, because prices fluctuate on an hourly and daily basis causing the relation between monthly generation and monthly revenue to have a concave form where marginal revenues decrease (due to decreasing price) as monthly generation increases. Different methods can be applied for solving a non-linear problem and each method has advantages and disadvantages. Here, we set-up and solved the problem once by nonlinear formulation and once by linear formulation (through piecewise linearization of the non-linear problem).

Climate hydrology development

Suitable sets of seasonal flow perturbation ratios were obtained and adjusted for each elevation range to represent three selected climate warming scenarios. Dry and Wet climate warming scenarios result in 20 percent drier and 10 percent wetter hydrologies at each elevation band, respectively. The Warming-Only scenario is neither wetter nor drier and only timing of flow changes at each elevation band under this climate warming scenario. It was decided to run the model for a long enough period including both wet and dry years. The ratios were applied to each month of historic runoff to create the perturbed climate change scenario hydrology over the selected multi-year sequence. This enables investigation of overall system adaptability and how each hydropower reservoir might perform over a range of wet, dry and average years under climate warming.

Climate change scenarios and model runs

Historical generation data was complete for 137 of high-elevation plants for the period of 1984-1998. The linear and non-linear optimization models were run on an annual basis to determine optimal monthly reservoir storage and energy generation decisions for these 137 power plants which maximize annual benefits for each year over this period. The model was run for four different hydrologic scenarios including the base case (historical) hydrology and three climate change hydrologies (Dry Warming, Wet Warming, and Warming-Only). Since the model optimizes decisions one year at a time, 15 years of results were required for modeling variations in performance over the 1984-1998 period.

It might be interesting if each reservoir's hydropower operations could be optimized over several years (multi-year optimization), rather than for one year at a time. In practice, however, information about next year's hydrology might not be readily available to operators. In such cases, it may be preferable to generate as much energy as possible in summer's high-value months instead of waiting to see what the next year' hydrology is like. If operators choose not to empty the reservoir by the end of draw-down cycle, and next year is wet, they risk spilling water that could have been used to generate energy and loosing revenue. Therefore, in this preliminary work we have assumed each reservoir has no (constant) carry-over storage from year to year.

In addition to running the model for 15 years (1984-1998), we also ran the model for a year of average runoff for the period 1982 to 2002 to examine the difference between energy generation results optimized for an average year (period 1982 to 2002) and the average of energy generation results optimized for each individual year, over the period 1984-1998. Since the generation and flow distribution patterns in this simplified climate analysis are the same for all hydropower plants in the same elevation band (perturbation ratios and the runoff distribution pattern is uniform for an elevation band for the preliminary course scale climate hydrology used here), there might not be any difference between the results for an average year and the average of results of the 15 years if storage capacity is sufficient to avoid spills in the system. If this is so, studies can focus just on an average year to reduce time, effort, and cost.

Results and Discussion

Figures 1 and 2 show the average energy generation and energy generation in an average hydrologic year, respectively, for the period 1982 to 1998 for different climate change scenarios. Results are summed from all 137 power plants modeled in this study. (The results reported in this section are the average of the results from the piecewise linear and non-linear programming model versions.) These figures also show the average actual (recorded) generation over those years as well as recorded generation in an average hydrologic year.

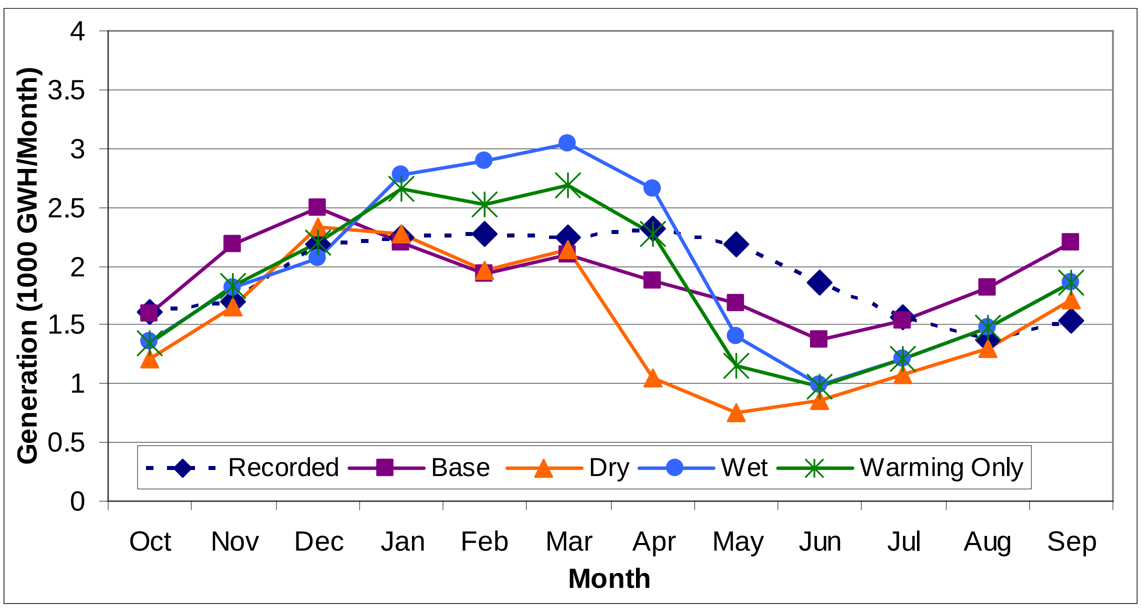

Figure 1. Average Monthly Generation (1984-1998) under Different Climate Scenarios

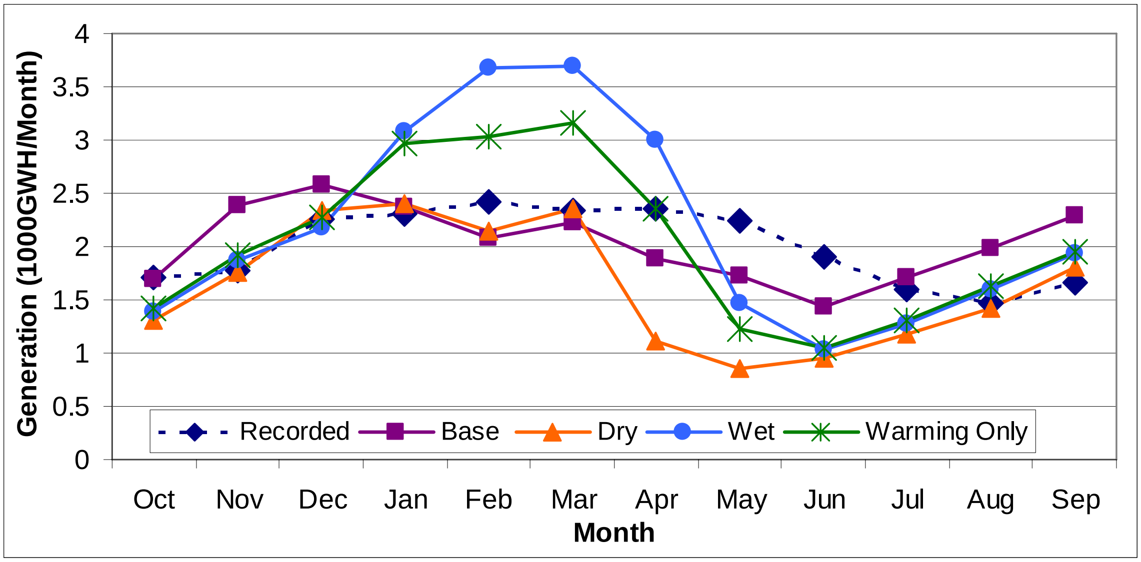

Figure 2. Monthly Generation in an Average Year (1982-2002) under Different Climate Scenarios

Base case results

The base scenario results have been optimized for the historic climate, and differ from what has happened historically (the "recorded" scenario). This is due to a combination of factors including the roles of other non-hydropower operating factors, changes in hydropower prices over the recorded years, non-energy hydropower operations such as spinning reserves, and perfect foresight of the model about the incoming flows during the year. Compared with the average recorded generation pattern, under the historical climate, model results suggest less generation in months with lower average energy prices to store energy for months with higher energy prices.

Average year versus multi-year modeling

Generation under climate warming in an average year differs from the average of monthly generation over all years, because of energy spills in wet years. Flexibility of the system to accommodate climate change is overestimated when we look at results for an average year (Figure 2) compared to those for the whole period which includes wet years (Figure 1). In wet years, under climate warming, more water is spilled from the system (bypassing the turbines), due to storage and generation capacity limits. Although the system might be adaptable for average and dry years, climate warming and its accompanying seasonal shifts increase the frequency and magnitude of spills in wetter years. The difference in results might also be the result of differences in the considered time horizons. Here, we calculated the average monthly generation over the 1984-1998 period while the average hydrologic year belongs to the 1982-2002 period (6 more years of data) which includes 1983, one of the two wettest years in the historic record. Thus, the average year of 1982-2002 period might be wetter than the average year of 1984-1998 period, resulting in more annual generation in the former.

Climate scenario energy generation, spill, and revenue changes

Table 1 indicates how energy generation, energy spill and annual revenue changes on average under different scenarios over the study period. Revenue is greatest under the Base scenario and least for the Dry scenario hydrology. Although annual inflow is 10 percent higher than the Base case under the Wet scenario, revenue is about 2 percent lower than the Base scenario when optimal operations are applied. This is due to storage capacity limits and the system being designed to take advantage of historical snowpack. Thus, although generation is slightly higher under the Wet scenario, revenue is higher under the Base case. Note that energy spill is greatest under this scenario due to limited storage and generation capacities. This system has some limits adapting to warmer climatic conditions, even wetter ones. Even when total annual inflow does not change for the Warming-Only scenario (which only affects the timing of runoff), total revenue is reduced by about 5 percent due to limited storage capacity and perhaps limited generation capacity, and spills greatly increase over the Base case.

Table 1. Model Results (Average of 1984-1988 Period) under Four Climate Scenarios

	Scenario			
	Base	**Dry**	**Wet**	**Warming-Only**
Generation (1000 GWH/yr)	23.0	18.3	23.5	22.2
Generation Change with Respect to the Base Case (%)		- 20.4	+ 2.2	- 3.5
Spill (MWH/yr)	86.2	305.2	1,908.5	915.3
Spill Change with Respect to the Base Case (%)		+ 254	+ 2,114	+ 962
Revenue (Million $/yr)	1,529	1,287	1,503	1,458
Revenue Change with Respect to the Base Case (%)		- 15.8	- 1.7	- 4.6

It is clear from these results that the timing of snowmelt and the form of precipitation (as snow or rain), in addition to total precipitation volume, have significant effects on generation patterns and overall quantity and value. One reason for reduced revenue in the Wet and Warming-Only cases is the monthly energy price pattern which follows the historical generation pattern. When storage capacity is unable to store the peak flow from snowpack melt for release in high-value months, revenues are reduced as a result of energy spill or unwanted energy generation in months when energy price is not the highest. However, some storage capacity is available to handle the extra runoff in winter months under a warmer climate. This provides some flexibility in operations to store winter water to be released later when energy demand is higher. As a result, although annual inflow under the Dry scenario is 20 percent less than in the Base case, Dry scenario revenues are reduced by about 16 percent even though the energy generation reduction under this scenario is greater than 20 percent. Energy spills under this scenario increase relative to the Base case during peak runoff months, resulting in some off-peak generation losses.

Generation patterns and variability under climate change

Summer generation always is less than the Base case under all three climate scenarios. Generation under the Wet and Warming-Only scenarios is higher than the Base scenario from January to April (Figures 1 and 2) as a result of increased runoff peaks and limited capacity to store this shift in peak runoff. More storage capacity would help to flatten the monthly generation curves under different climate warming scenarios. If more storage capacity was available and reservoirs filled steadily, there would less likelihood of water bypassing turbines in the January to April period. Instead this water would be stored and released in summer, reducing generation in late winter and early spring in order to increase it in summer. Generation under the Dry scenario is always less than generation under the Base scenario, except over the January to March period (Figures 1 and 2) when runoff peaks occur under the Dry scenario.

Figure 3 shows the frequency of optimized monthly generation for each month over the 15 year period (1984-1998) summed for all units, under different climate hydrologies. The frequency of recorded monthly generation over the same period (1984-1998) is also shown for comparison. Frequency curves of recorded and base monthly generation are very similar for this hydrologic period. Dry climate warming results in considerably less generation than Recorded and Base generation in over 80 percent of months over the 15 year period, with similar levels occurring in the remaining 10 to 20 percent of months. Under the Wet and Warming-Only scenarios, while generation is also less than the base and recorded cases for 80 percent of the time, the reduction is very small. It greatly exceeds Base and Recorded generation the rest of the time. If more storage capacity was available, generation frequency curves under the Wet and Warming-Only scenarios could be more similar to the Base scenario, with higher revenues. Generation curves under the Wet and Warming-Only scenarios are higher than the Base case for 20 percent of the time when insufficient storage capacity exists to store abundant wet winter flows for summer and spring month generation, forcing operators to release up to the turbine capacity or spill excess flows as reservoirs fill in January to April.

Figure 4 shows the annual total frequency of optimized generation at all units under different scenarios for the study period. Similar to the monthly generation frequencies, annual frequencies of recorded and base generation are very similar for the 15 year period. Annual generation under the Dry scenario is always less than the Recorded and Base generation because of significant reductions in runoff under this scenario combined with limited energy storage and generation capacities. Wet generation is higher than Recorded and Base generation in 60 percent of years, due to increased runoff under this scenario during these years and availability of energy generation capacity to capture some of this increased runoff. Generation is less than the Base case under the Wet and Warming-Only scenarios in more than 40 and 60 percent of years, respectively, due to mis-matched timing of runoff flow and storage space.

Reservoir storage changes under climate change

Figure 5 shows how average end-of-month energy storage in all reservoirs combined, changes with climate when reservoirs are operated for energy generation benefits only. Under the Base scenario, reservoirs reach their minimum storage level by the end of December in preparation to capture expected inflow from winter precipitation and later spring snowmelt. On average, reservoirs are full by April and gradually emptied for energy generation over summer months when energy demand and prices are higher and there is little natural inflow. Under historical conditions, refill starts in January and drawdown starts in June. Although climate warming results do not appear to change these cycles very much, snowpack loss results in generally higher average reservoir storage levels (more stored energy) between February and May than in the Base case. Generally, energy storage peaks earlier with climate warming, and drawdown begins one to three months earlier.

Figure 6 shows the end-of-month energy storage frequency curves for different climate warming scenarios over the study period, indicating how snowpack loss leads to higher energy storage levels in almost 60 percent of months, even for dry climate warming.

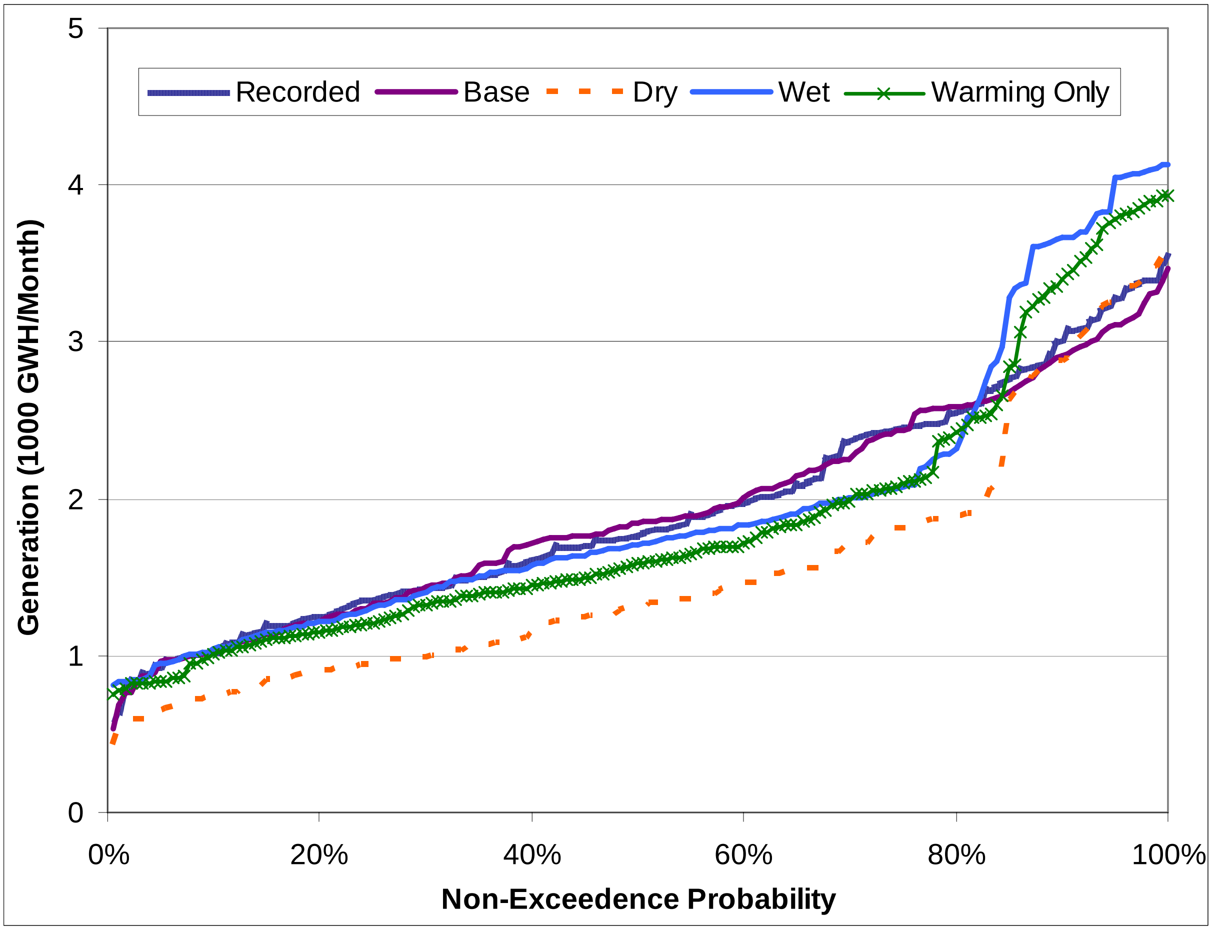

Figure 3. Frequency of Optimized Monthly Generation (1984-1998) under Different Climate Scenarios (All Months, All Years, All Units)

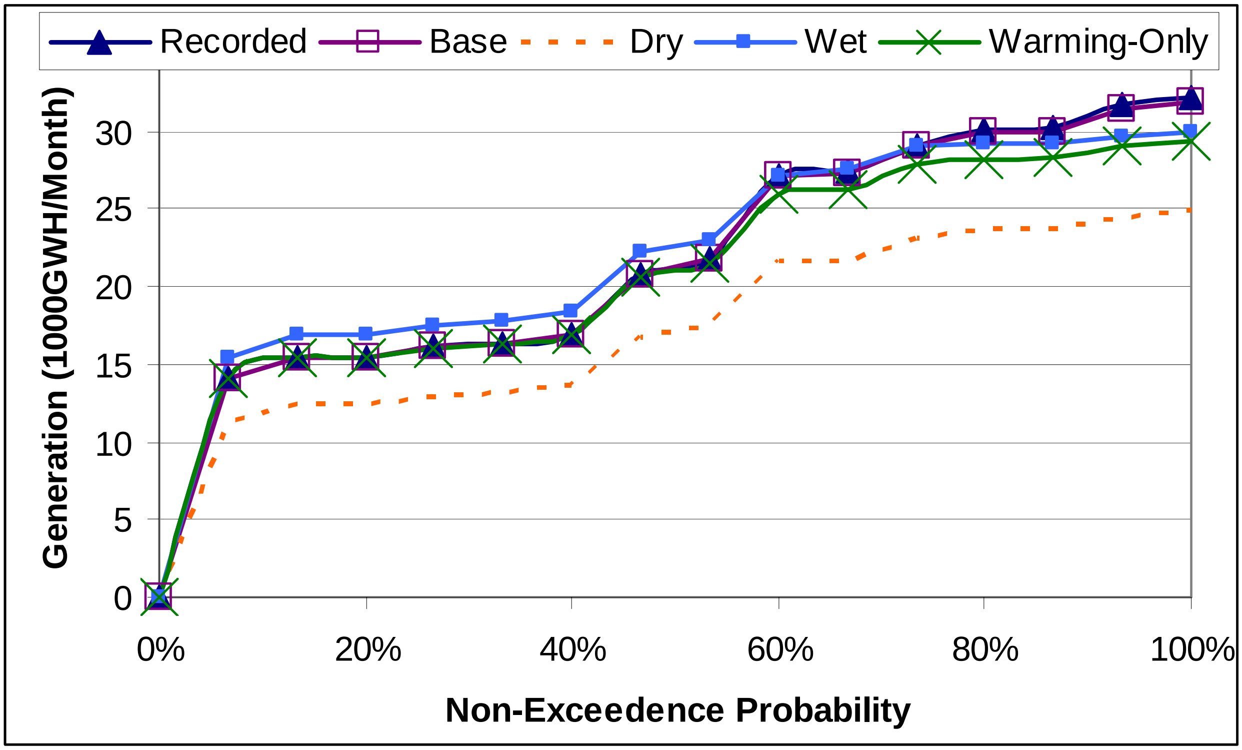

Figure 4. Frequency of Optimized Annual Generation (1984-1998) under Different Climate Scenarios (All Years, All Units)

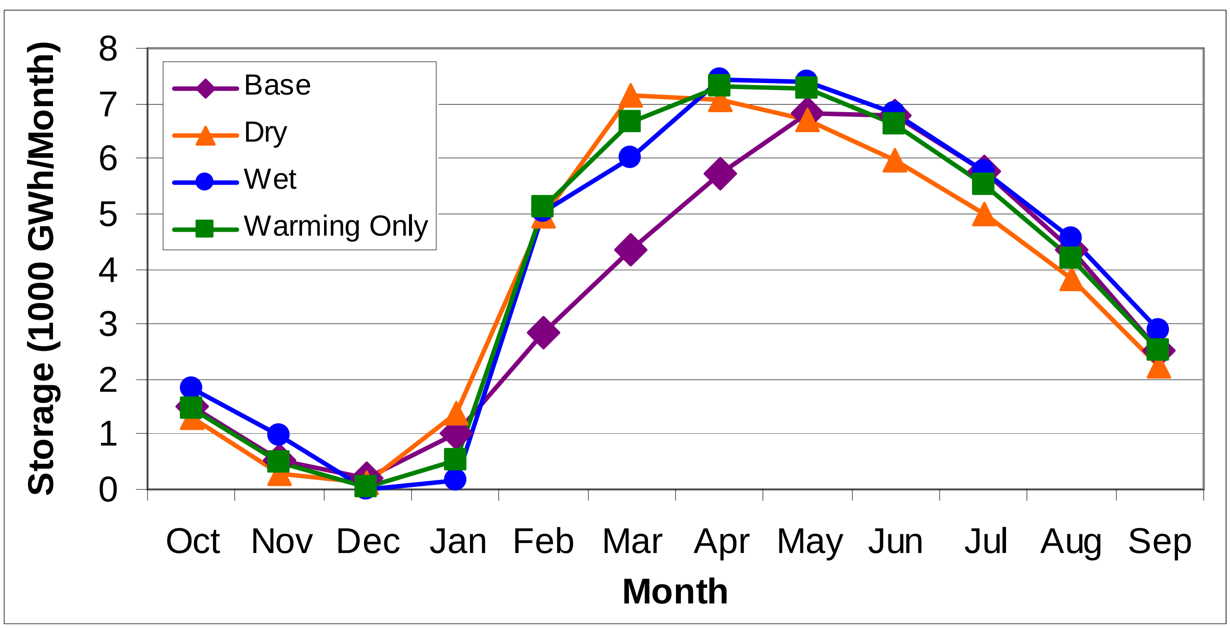

Figure 5. Average Total End-of-month Energy Storage (1984-1998) under Different Climate Scenarios

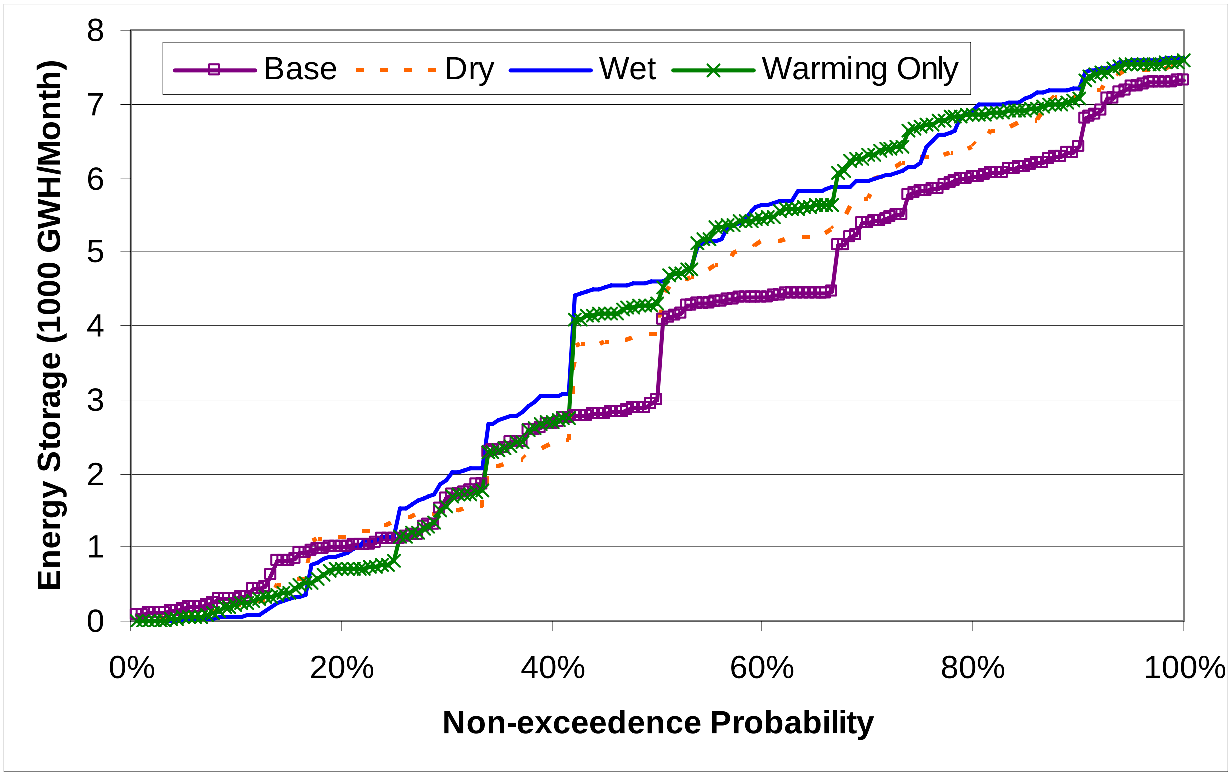

Figure 6. Frequency of Total End-of-month Energy Storage (1984-1998) under Different Climate Scenarios (All Months, All Years, All Units)

Reservoir spill patterns under climate change

Figure 7 shows the frequency of total monthly energy spill from the system for the study period when the system is optimized for revenue maximization. Energy spill results from runoff that can neither be stored nor sent through the turbine because of limited turbine capacity. Energy spill is the equivalent energy value of the available runoff water which cannot contribute to energy production at each site. Energy is spilled by the system in 30 percent of months under all climate scenarios, including the Base scenario. However, the magnitude of spills increases for all warming scenarios, and especially so for the Wet scenario. Although under Dry scenario annual runoff is less than Base (historical) annual runoff, energy spills are greater due to the timing of peak runoff during wetter years. Existing storage capacity cannot compensate for the loss of snowpack, the natural reservoir, during wetter years, and overall earlier snow melt, but appears able to compensate in drier years.

Figure 8 shows the distribution of total average monthly energy spill under different climate scenarios. Energy spills from December to March when inflow to the system peaks. Although historical spill in that period is not considerable, the amount of energy lost under climate warming scenarios is a point of concern and highlights the importance of runoff inflow timing to the performance of this system.

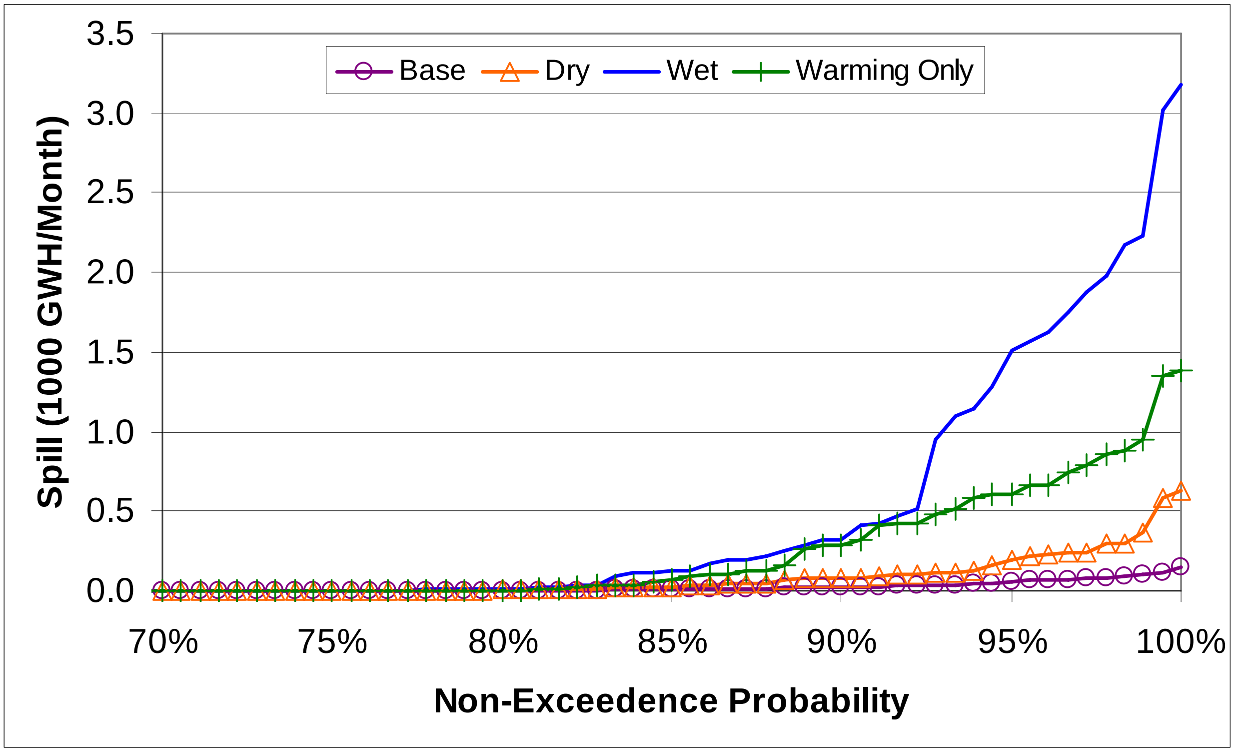

Figure 7. Frequency of Total Monthly Energy Spill (1984-1998) under Different Climate Scenarios (All Months, All Years, All Units)

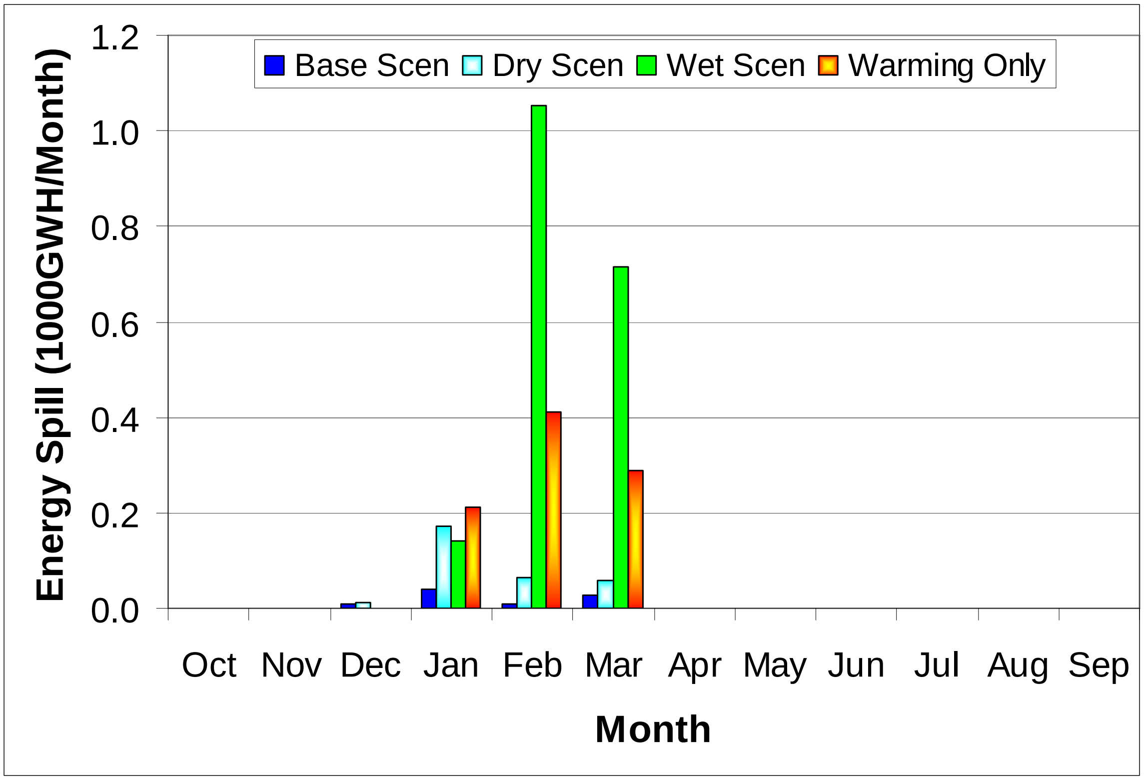

Figure 8. Average Monthly Total Energy Spill (1984-1998) under Different Climate Scenarios

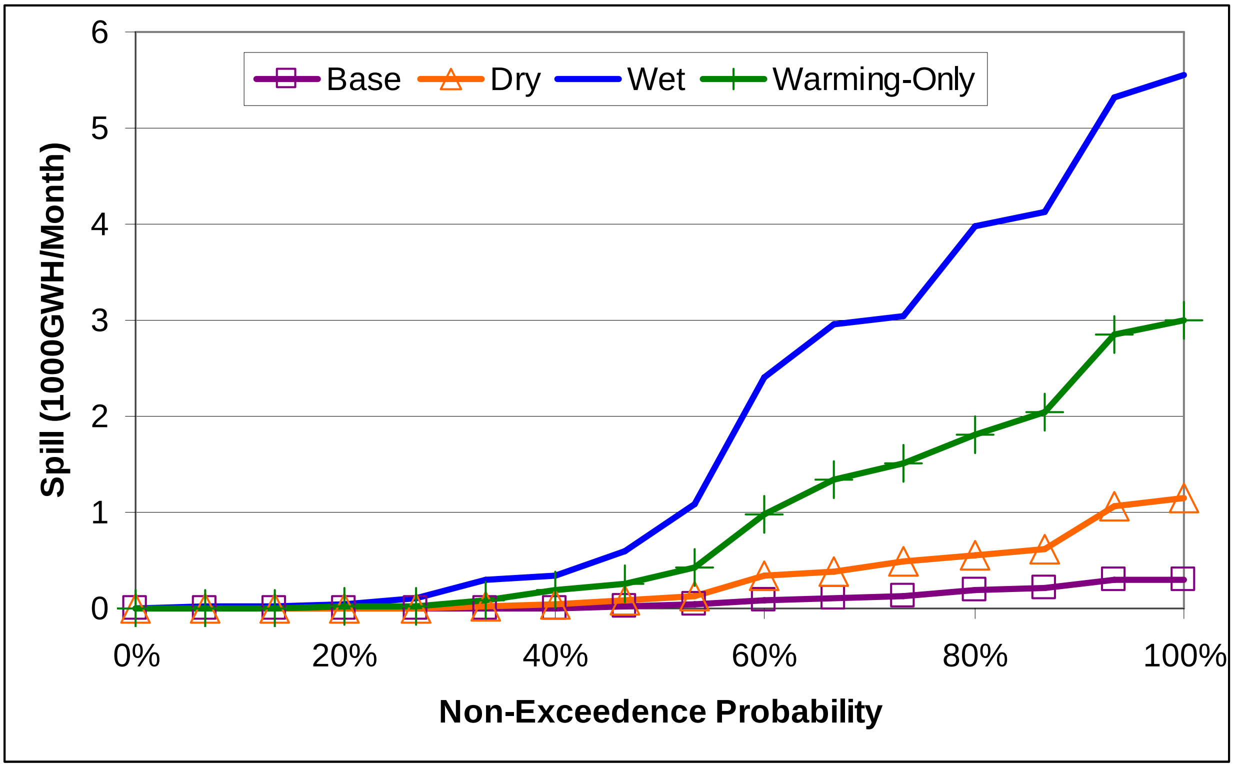

Figure 9. Frequency of Total Annual Energy Spill (1984-1998) under Different Climate Scenarios (All Years, All Units)

Figure 9 plots the frequency curve of total annual spill from the system for the study period. Energy does not spill under the Base scenario for about 50 percent of years. Consultation with private operators suggests energy spills roughly in one-third of years. Model results show energy spill of less than 100 GWH occurring in two-third of years in the study period, somewhat similar to reported operator experience. The small difference between study results and operator experience might be due to different lengths of period under consideration and the number and type of wet and dry years in this study's analysis period. Figure 9 clearly shows that annual energy spill frequency and magnitude both increase under climate warming. As more precipitation falls as rain than snow and snow melts sooner at high elevation under climate warming, annual energy spills increase in both size and frequency as monthly runoff distribution patterns and amounts no longer match well with existing storage and generation capacities. Most energy spill occurs under the Wet scenario, and in more than 80 percent of years. Under the Warming-Only and Dry scenarios, energy spills in more than 70 and 60 percent of years, respectively.

Revenue prices and patterns under climate change

Figure 10 indicates the climate warming effects on monthly average price received for generated energy during the study period. The figure shows climate warming generally results in higher average energy prices in about 75 percent of months. As expected, the rise in prices is highest under the dry climate warming (given the non-linear relationship between electricity price and generation quantity). Maximum monthly price under the Wet and Warming-Only scenarios is generally less than in the Base scenario. The opposite is true for the Dry scenario. Average received energy price frequency curves for Wet and Warming-Only scenarios largely show the same behavior, which highlights the greater importance of runoff timing over quantity for optimal system operations.

In this study, the effects of climate warming on energy demand were neglected. It was assumed that only energy suppliers have control over the energy price they receive through changing the generation amount and demand changes under climate change have no effect on energy prices (in a perfect market both supply and demand have effects on the price). To improve the model, in future, the effects of climate change on energy demand can be studied by defining different relationships between energy generation quantity and energy price for various scenarios, as explained in Appendix B.

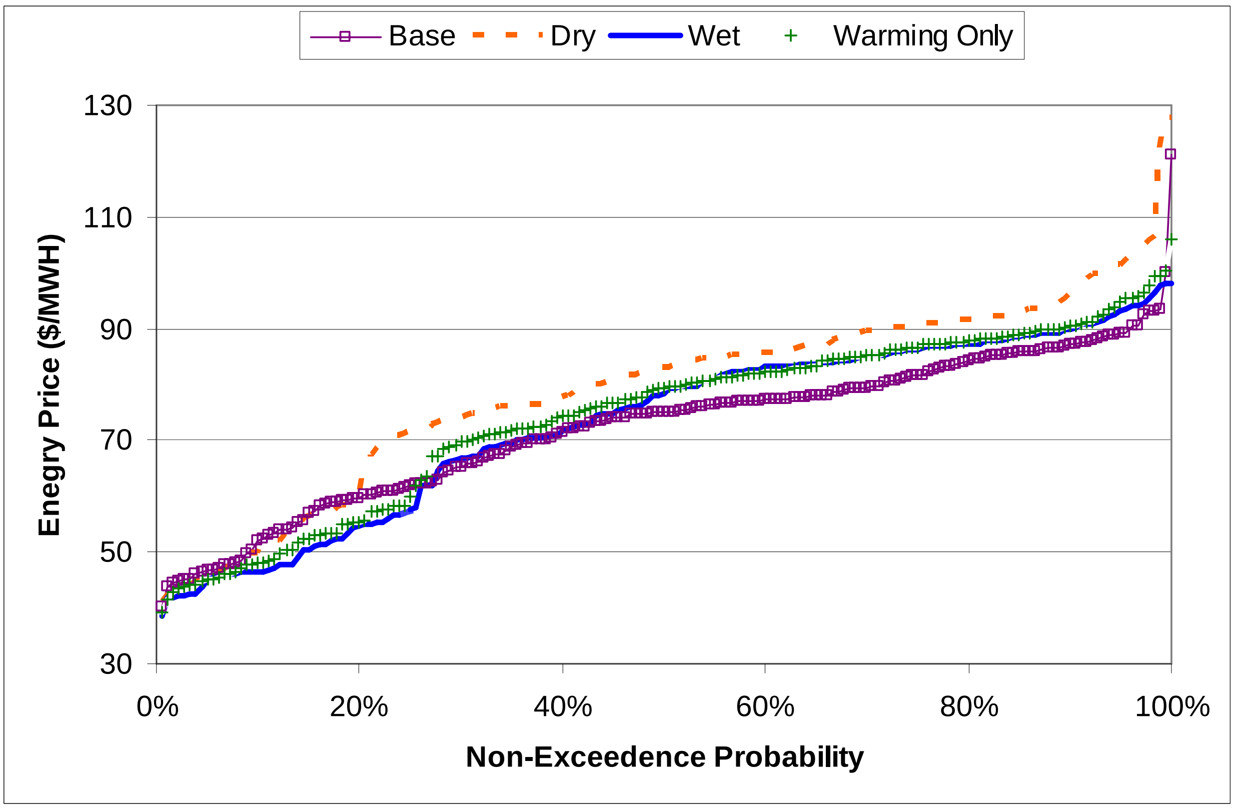

Figure 10. Frequency of Monthly Energy Price Received (1984-1998) under Different Climate Scenarios (All Months, All Years, All Units)

Figure 11 shows the effects of climate warming on the frequency of combined total annual revenues of the 137 hydropower plants studied for the period 1984 to 1998. Although monthly average prices received for generated energy were higher under the Dry scenario, the increase does not compensate for the Dry scenario reduction in energy generation. Thus, revenue is always the lowest for this scenario during the whole study period. Annual revenue under the Wet scenario exceeds Base scenario revenue in 50 percent of years but is less during the rest of the time. The higher revenues under the Wet scenario occur in dry and probably average years

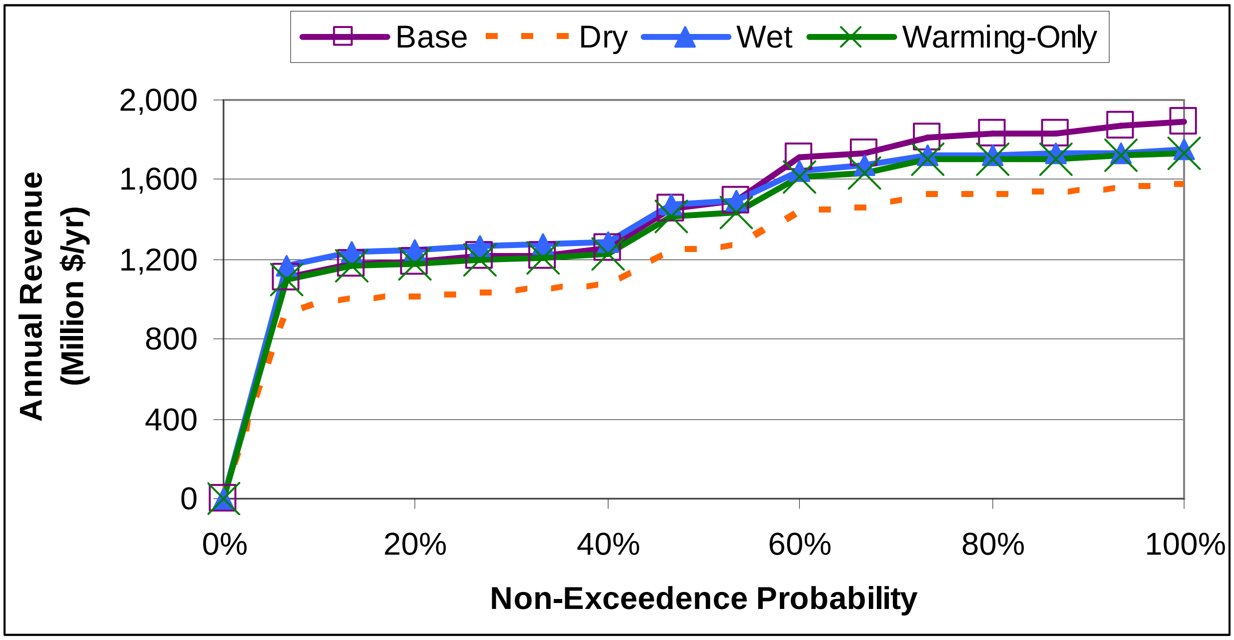

Figure 11. Frequency of Total Annual Revenue (1984-1998) under Different Climate Scenarios (All Years, All Units)

during the study period. In those years, total energy generation is lower and reservoirs do not get full. With greater total energy runoff under the Wet scenario in Dry years, available storage capacity can be used for storing energy in low-value months to generate in high-value months. The available generation capacity is helpful in avoiding spills. Thus, total annual generation (Figure 4) and revenue both increase under the Wet scenario in dry and perhaps average years. In wetter years, annual revenue and generation tend to be less than in the Base scenario due to insufficient storage and generation capacities which result in energy spill and revenue loss. Annual revenue under the Warming-Only scenario is less than the Base scenario in 50 percent of years and about the same the rest of years, due to similar changes in wet, average and dry years over the study period as those explained for the Wet scenario.

Benefits of storage capacity expansion under climate change

Figure 12 shows, on average, how storage capacity expansion changes hydropower generation revenues under different scenarios over the study period (15 years). The vertical axis is the average marginal benefit (measured in percent annual revenue increase) of storage capacity expansion across the 137 units studies. In other words, this value measures how much the annual revenue of each unit increases on average, over the 15 year period with the addition of one unit of storage capacity at each unit. Even with the historical hydrology, expanding storage capacity increases total annual revenues in all years because more storage capacity allows for more flexibility operations needed to generate more energy during peak price times.

As expected, benefits of capacity expansion are greater under climate warming. The annual marginal benefit of storage capacity expansion is greatest under the Wet scenario. Expanding storage capacity results in less spilling and helps store energy runoff in low-value months for later generation in high-value months. However, the costs of capacity expansion may well exceed the benefits it produces.

Figure 13a and 13b (Figure 13b shows 3 of the curves of Figure 13a with better resolution) show the frequency of annual average (across plants) marginal revenue gains from generation capacity expansion over the study period (15 years). The value on the vertical axis indicates how much annual revenue at a hydropower plant increases on average, when generation capacity is expanded by one unit at each plant. As seen in Figure 13b, generation capacity expansion produces higher revenues in more than 60 percent of the years under the Base scenario. Higher marginal benefits occurs in 90 percent of years under climate warming scenarios where additional generation capacity produces more total benefits to the system than it does under the historical scenario.

Comparing Figures 12, 13a and 13b, one sees that in more than 90 percent of years, the average gains from a unit of storage capacity expansion are much greater than the average gains from a unit of generation capacity expansion for the system overall. Only under the Wet scenario gains from generation capacity expansion reach high levels, but this occurs in less than 10 percent of the time. In absence of additional storage capacity, more generation capacity helps avoid energy spills across the system. Although generation capacity expansion produces benefits for the system, the cost of such expansion might make it infeasible.

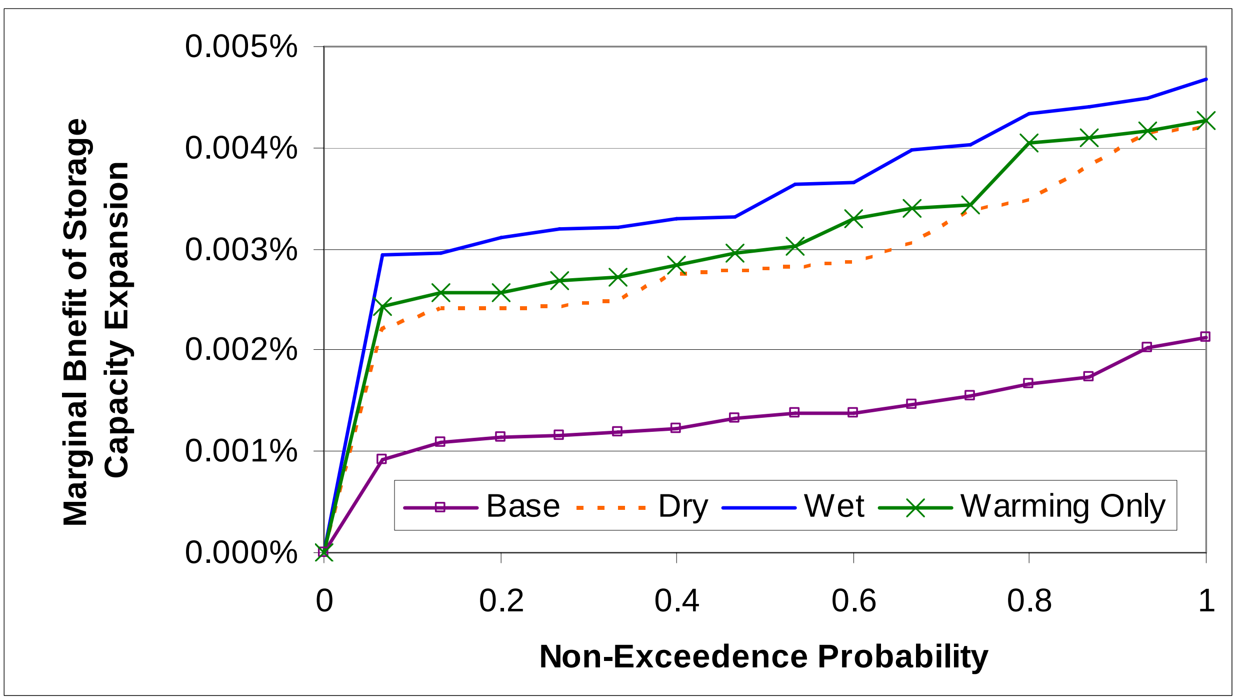

Figure 12. Frequency of Annual Marginal Benefit of Storage Expansion* (1984-1998) under Different Climate Scenarios

* The value on the vertical axis shows how much the annual revenue of each unit increases on average, with the addition of one unit of storage capacity at each unit.

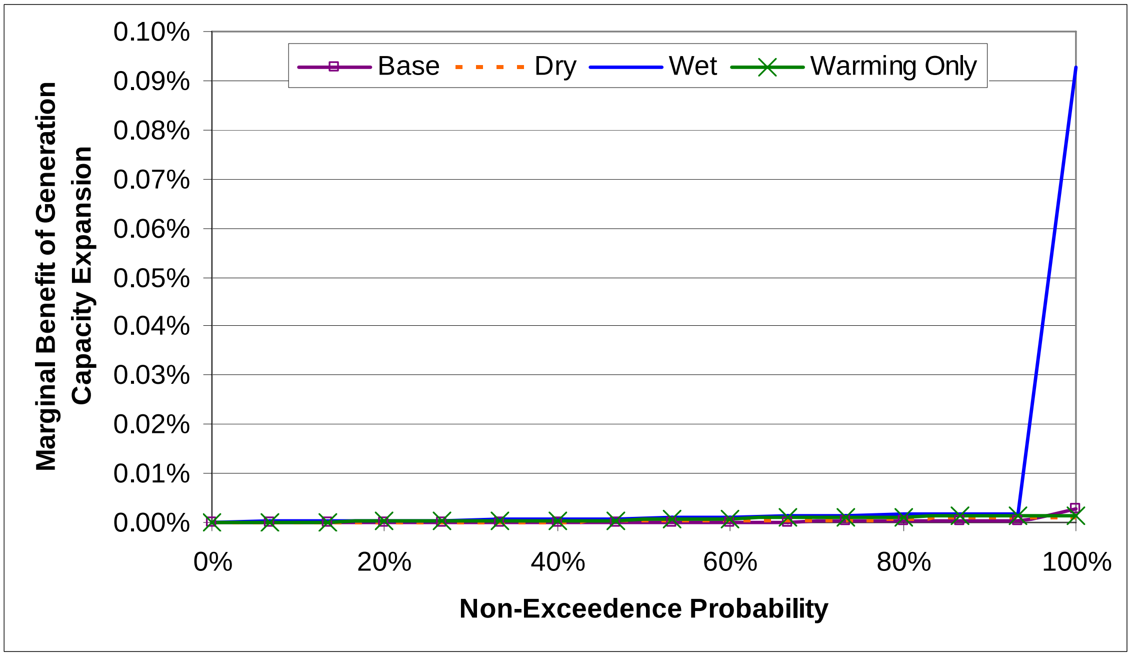

Figure 13a. Frequency of Annual Marginal Benefit of Generation Capacity Expansion* (1984-1998) under Different Climate Scenarios

* The value on the vertical axis shows how much the annual revenue of each unit increases on average, with the addition of one unit of generation capacity at each unit.

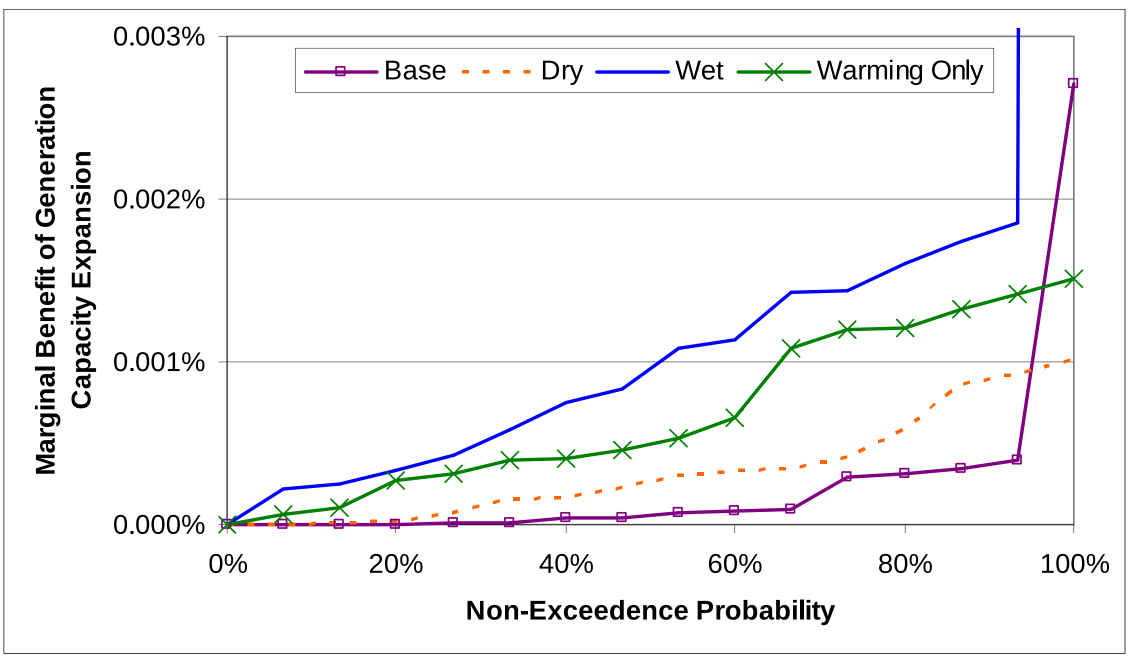

Figure 13b. Frequency of Annual Marginal Benefit of Generation Capacity Expansion* (1984-1998) under Different Climate Scenarios

* The value on the vertical axis show how much the annual revenue of each unit increases on average, with the addition of one unit of generation capacity at each unit.

Limitations

Models are not perfect and optimized results are only optimized to their problem. During model development many simplifying assumptions are made which should be considered when interpreting results. None the less, simulation and optimization models are useful tools for studying resource management problems. Here, optimization results provide insights on how the system works and how it might adapt under different climate warming scenarios. The No-Spill Approach used in this study might under-estimate storage capacities and therefore also underestimate adaptability of the system to climate change.

As a first step in studying the adaptability of Sierra's high-elevation hydropower system to climate warming, this study looks at flexibility of operations without considering environmental constraints. In practice, environmental constraints might restrict the flexibility of operations, because of the trade-off between hydropower generation revenues and ecosystem conservation benefits in some months of the year. However, a large-scale study like this, even if associated with some simplifications, can be useful in exploring whether changes in operations are possible at all. In the next step, environmental constraints should be incorporated in the model to get more realistic results.

California is big and variable in hydrology. Assuming the same hydrologic patterns for a reservoir in the north Sierra as one in the south for a given elevation band will cause some inaccuracies. A 1000-foot elevation range also covers a great variability in hydrologic behavior. Smaller elevation ranges might increase the accuracy of the results. Since many power plants are in the 3000-4000 feet elevation range, it might be worthwhile to study this range in more detail separately. Also, it is more accurate to consider more than a few gauges at each elevation range. The spatially disaggregated and extensively detailed hydrologic modeling of Sierra-wide watersheds and sub-watersheds (in the companion report by Young, et al) provides an opportunity to disaggregate estimates of hydrologic changes for climate scenarios at the individual facility level.

With climate warming, demands are likely to increase in warmer months from higher temperatures. This could have some effect on energy prices. Change in demand and energy prices caused by climate warming should be considered while looking at the relation between monthly generation and energy prices.

Here, the model optimizes generation based on its perfect foresight about the future hydrological pattern. This kind of management is impossible in practice as there is always some risk associated with reservoir operations decisions because of inability to forecast the future hydrological conditions perfectly. A stochastic optimization formulation might help with this limitation in the current study.

The model's results for the base case historical scenario are somewhat different from what has actually happened (recorded observations). Neglect in this preliminary modeling study of non-hydropower operating factors, changes in hydropower prices over the recorded period of record, and non-energy hydropower operations such as spinning reserves, are some of the reasons for the divergence between observed and modeled operational results.

Conclusions

In absence of detailed information about the available energy storage capacity at high-elevation in California, this study explored a simple approach for estimating the adaptability of Sierra's high-elevation hydropower generation to climate warming encompassing virtually all of California's high-elevation hydropower facilities in the study. Substituting the estimated energy content of runoff water inflows for these relatively high-head hydropower units and determining seasonal inflow distribution patterns by elevation band allows preliminary optimization-driven monthly system operations modeling of one hundred thirty-seven hydropower plants with and without climate change.

With climate warming, Sierra loses snowpack which has functioned historically as a natural reservoir, but existing hydropower energy storage and generation capacities at high-elevation provide some flexibility to the system to adapt to hydrologic changes. Lower-elevation reservoirs, constructed primarily for water supply, already have substantial re-regulation capacity for seasonal flow adjustments (Tanaka et al. 2006). However, operating rules would need to change under different climate warming scenarios to adapt the system to different changes in hydrology (Medellin et al. submitted).

Generally, climate warming can cause reductions in high-elevation hydropower generation and revenue which are not only the result of less precipitation, but also the result of changes in seasonal runoff timing. Energy spills increase dramatically under climate warming under existing storage and generation capacities. More storage capacity would increase revenues but may not be cost effective. Storing water in reservoirs helps to shift natural energy runoff reductions to months with lower energy prices to reduce total economic losses. More generation capacity also results in higher revenues by reducing energy spill from the system. However, annual marginal benefits of capacity expansion are higher for storage than for generation, showing the greater gains in revenue from storage over generation capacity expansion to the system.

Nevertheless, current storage and generation capacities give the system some flexibility to adapt to different climate warming scenarios. Although the Dry scenario examined in this study has 20 percent less runoff than the base historical hydrology, system-wide revenues decrease by less than 16 percent through optimally re-operating storage and generation facilities within existing capacity limits. Thus, the current storage and generation capacities are able to compensate for snowpack loss to some extent, and to a greater degree in the Wet and Warming-Only scenarios where revenues decrease very little.

Limited current capacities are unable take advantage of greatly increased energy runoff under the Wet scenario to increase system revenues. Although average annual generation increases by more than 2 percent under Wet climate warming, average annual revenues drop by about 2 percent as a result of a mismatch between monthly generation and monthly energy price patterns and insufficient storage and generation capacities to resolve the mismatch. In a

Warming-Only scenario with unchanged historical precipitation, generation and revenues are expected to decrease by 3.5 and almost 4 percent, respectively.

Although, revenues decrease under all climate warming scenarios, the change may be economically insufficient to justify expanding storage or generation capacity, especially given future uncertainty about the type of climate change likely to occur.

Adaptability of Sierra's high-elevation hydropower system to climate change can be improved by joint operation of hydropower plants. Madani and Lund (2007) showed how hydropower system adaptability in California can be improved and overall energy generation quantities, seasonal patterns, and revenues could be better preserved when facility operations are optimized jointly across the region and across elevation bands rather than independently and separately for each system. This insight supports the broader notion that a more regional approach to FERC re-licensing could help minimize negative impacts on Sierra hydropower generation caused by runoff shifts to, or reductions in streamflow, as well as by mitigation option implementation. By integrating operations of individual hydropower systems that span different watersheds and elevation bands, greater operational flexibility to respond to changes in climate, streamflow, and runoff is created.

This study required some simplifying assumptions. For example, this study ignores constraints imposed on the system for ecosystem management. Nevertheless, the goal of this study was to explore an approach which makes the study of the Sierra's large multi-facility hydropower system possible. This study gives valuable insights about the system and suggests some degree of adaptive capability to climate warming. Future studies should address environmental and other constraints, include demand and price impacts of climate change, and apply refined estimates of varied hydrologic changes from climate change across the Sierras.

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Appendix A. No-Spill Method

In month *i*, the runoff percentage (*runPercent(i)*) and generation percentage (*genPercent(i)*) can be calculated by dividing the average monthly runoff in month *i* (*average runoff (i)*) and the average monthly generation in month *i* (*average generation (i)*) to the average annual runoff and the average annual generation, respectively.

$$runPercent(i) = \frac{average\_Runoff(i)}{average\_Annual\_Runoff} \qquad (1)$$

$$genPercent(i) = \frac{average\_generation(i)}{average\_Annual\_generation} \qquad (2)$$

In percentage terms, the total difference between the two curves for a year period (12 months) should be zero.

$$\sum_{i=1}^{12} (runPercent(i) - genPercent(i)) = 0 \qquad (3)$$

In the 12 month period there are months *i* when the runoff percentage exceeds the generation percentage value (e.g. when runoff is stored in the reservoir) and months *j* when the generation percentage value exceeds the runoff percentage value (e.g. when hydropower is generated by releasing stored water).

$$\sum_i (runPercent(i) - genPercent(i)) - \sum_j (genPercent(j) - runPercent(j)) = 0 \qquad (4)$$

Therefore, the storage capacity as a percent of total inflow is:

$$StorCapPercent = \sum_i (runPercent(i) - genPercent(i)) \qquad (5)$$

or:

$$StorCapPercent = \sum_j (genPercent(j) - runPercent(j)) \qquad (6)$$

Multiplying the storage capacity by the average annual generation gives the energy storage capacity. Multiplying the storage capacity percentage by the average annual runoff gives the volumetric water storage capacity which is directly used for hydropower generation. This study performed all calculations in terms of energy.

Appendix B. Energy Generation and Energy Price Correlation

If fixed monthly energy prices are fed into the model, while maximizing the revenue, the model suggests no generation in months when the price is low and generation in months with higher prices (Madani and Lund, 2007). The model assumes that there is enough electricity demand and all generated power can be sold at the same price. In practice this operation might not be possible and electricity price will not be constant when supply is changing. Typically, in reality, as energy generation increases, marginal benefit of generation decreases. In order to improve the model, we should define a relation between generation and price. We use real-time hourly energy prices from California ISO to find the correlation between generation and price, assuming that the price gets lower as the generation increases. Figure B-1 shows the frequency of real-time market hourly price of energy in October 2005, including on-peak and off-peak prices. Based on our assumption, for a given power plant, maximum energy price corresponds to the lowest nonzero generation and lowest price corresponds to maximum generation which is equal to the generation capacity of the plant. Integration over the price curve (given in Figure B-1) can give us the revenue as follows:

$$Revenue = \int_{0}^{Generation} Price(Generation)dGeneration \qquad (7)$$

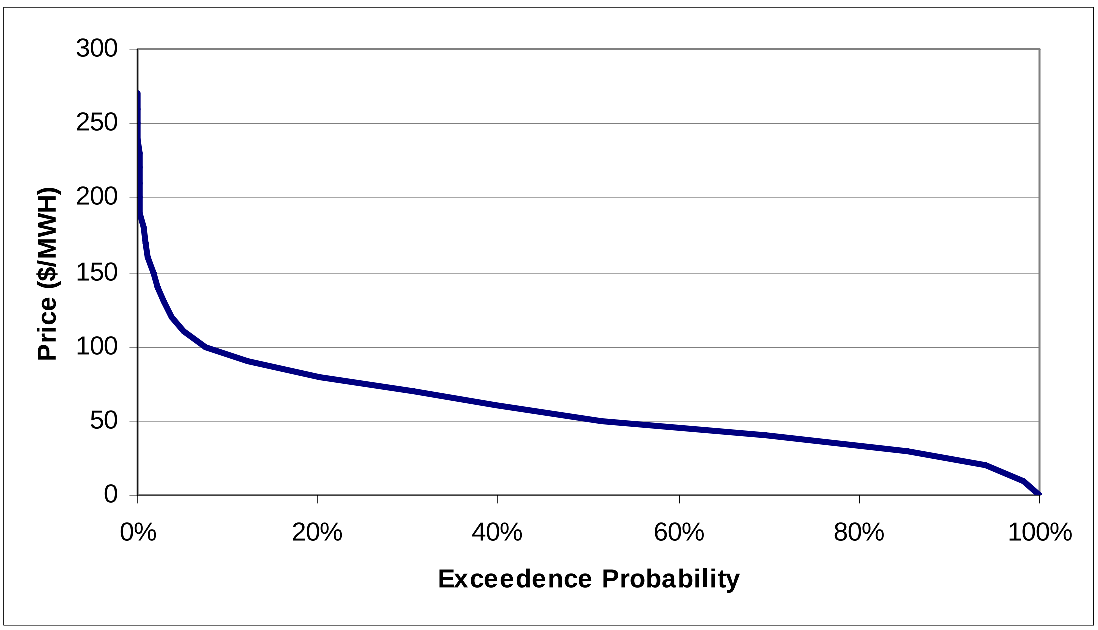

Figure B-1. Frequency of hourly energy price in October 2005 (Cal-Iso)

Using Equation 7, revenue curve for October can be derived as shown in Figure B-2. In this figure, the horizontal axis shows the portion of the generation capacity which is used in October, and the vertical axis shows the corresponding revenue divided by the generation capacity of the power plant. For instance, if a given power plant generates at its full capacity in October, the revenue at that power plant is 48 times of its generation capacity. Revenue curve for a given hydropower plant in October can be derived by multiplying both axes of Figure B-2 by generation capacity of that power plant.

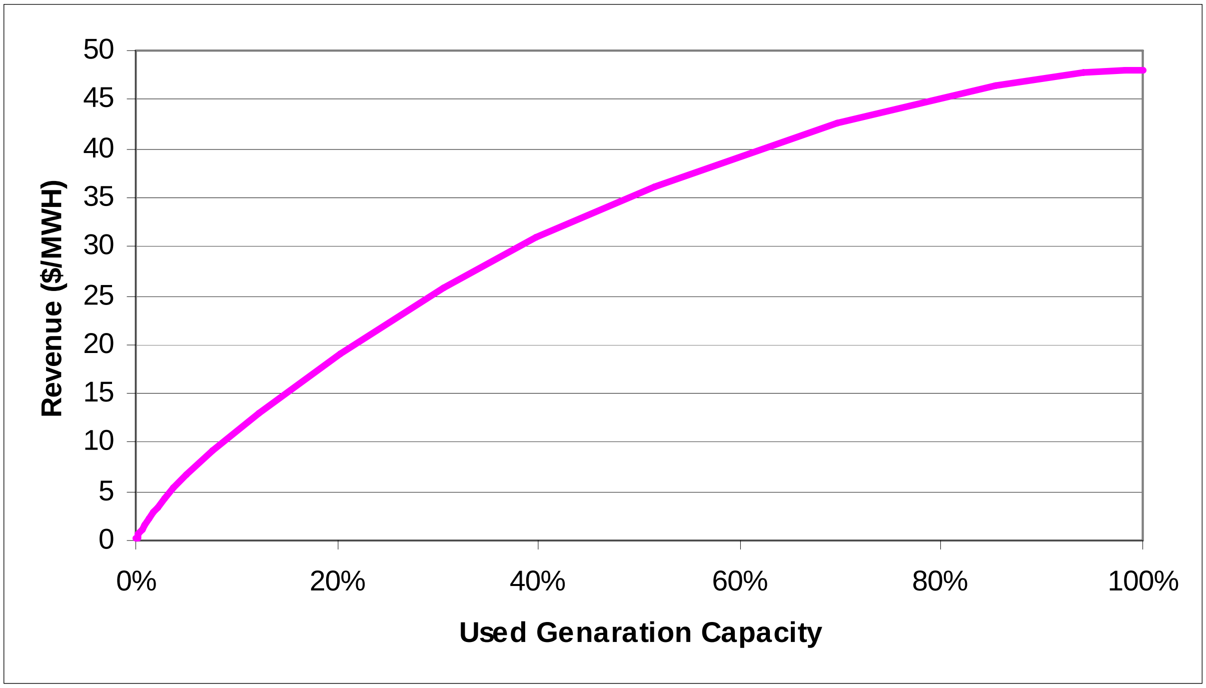

Figure B-2. Revenue-Generation Relationship in October 2005 (California ISO)

Monthly revenue curves were found in this study based on the information obtained from California ISO. Based on the curves, the correlation between generation and revenue was defined for each month either by piecewise linearization in the linear model or by the polynomial found by Excel in the nonlinear model.

Here, we assume that the revenue-generation correlation does not change by climate warming. However, since energy demand will be affected by climate warming, there will be changes in energy prices. For instance, energy prices might get higher in summer months in California, as more energy is needed for cooling. In future studies, different revenue curves can be defined for various climate warming scenarios to be fed into the model.

Appendix C. High-elevation Hydropower Plants in California

The following table shows the names of 156 power plants identified at high-elevation in this study as well as their estimated storage capacities, generation capacities and historic annual generation for the study period (1982-2002). Instead of using the name-plant capacity of each hydropower plant during the study, to more realistically estimate the generation changes, the maximum value of monthly generation during this period is reported as the monthly generation capacity.

Table C-1. High Elevation Hydropower Plants in the Sierra Nevada, Estimated Capacities and Historical Annual Generation (1982-2002)

Plant Name	Storage Capacity (MWh)	Monthly Generation Capacity (MWh/month)	Historic Annual Generation (MWh/year)
ALAMO	8,743	10,112	37,936
ALTA	1,481	809	4,312
ANGELS CAMP	2,024	1,440	6,645
AZUSA	1,899	2,295	8,370
BALCH 1	26,388	26,868	102,625
BALCH 2	81,288	80,161	503,824
BEAR VALLEY	1,340	5,793	3,608
BEARDSLEY	20,896	8,227	56,783
BELDEN	139,080	88,345	403,358
BIG CREEK 1	179,756	75,958	450,639
BIG CREEK 2	157,879	53,401	384,764
BIG CREEK 3	123,473	170,232	848,902
BIG CREEK 4	68,867	74,016	455,184
BIG CREEK 8	74,399	59,719	313,746
BIG CRK 2 A	179,497	81,964	471,389
BIG PINE	5,007	7,094	13,810
BISHOP CR 2	16,408	6,137	41,153
BISHOP CR 3	14,912	5,935	37,727
BISHOP CR 4	20,718	6,254	50,568
BISHOP CR 5	8,379	3,386	20,839
BISHOP CR 6	5,089	2,296	12,407

Plant Name	Storage Capacity (MWh)	Monthly Generation Capacity (MWh/month)	Historic Annual Generation (MWh/year)
BOREL	11,998	8,352	64,928
BOWMAN	2,733	2,730	8,094
BUCKS CREEK	118,647	45,007	244,547
BUTT VALLEY	46,501	31,958	155,772
CAMINO	113,100	75,778	384,681
CARIBOU	61,458	54,798	176,720
CARIBOU 2	146,274	89,111	436,790
CHICAGO PRK	49,230	27,208	142,022
CHILI BAR	7,086	6,871	33,484
COLGATE N	259,321	247,308	1,225,709
COLLIEVILLE	124,779	127,296	465,344
COMBIE NO	361	1,002	1,467
COMBIE SO	610	1,200	3,254
COPCO NO1	43,497	18,512	103,765
COPCO NO2	59,787	127,270	137,143
COTTONWOOD	3,288	1,945	6,721
CRANE VALLY	1,219	657	3,249
CRESTA	99,113	53,824	336,859
D R HOLM	257,780	123,852	739,044
DE SABLA	41,038	14,858	109,449
DEER CREEK	8,721	14,171	21,591
DEVIL CANYN	132,136	108,663	547,027
DIV CREEK	2,444	2,642	5,150
DONNELS	138,500	54,909	314,959
DRUM NO 1	57,138	25,243	123,986

Plant Name	Storage Capacity (MWh)	Monthly Generation Capacity (MWh/month)	Historic Annual Generation (MWh/year)
DRUM NO 2	125,598	38,754	268,854
DUTCH FLAT	42,685	19,132	87,763
EASTWOOD	63,535	109,411	225,301
EL DORADO	17,742	15,064	50,180
ELECTRA	108,561	57,530	431,244
F MEADOWS	20,134	13,374	65,440
FALL CREEK	3,624	1,424	11,505
FARAD	3,204	1,701	6,401
FISH POWER	506	982	1,688
FONTANA	1,776	1,273	6,443
FOOTHILL	12,122	7,306	49,860
FOOTHILL F	11,201	44,461	36,184
FORBESTOWN	43,687	28,366	161,997
GRIZZLY	11,895	12,732	51,336
HAAS	102,372	106,265	497,409
HAIWEE	9,407	3,011	21,051
HALSEY	14,640	8,191	61,261
HAMILTON BR	11,401	3,902	21,978
HAT CREEK 1	19,210	5,579	39,863
HAT CREEK 2	17,914	8,712	55,625
HELL HOLE	923	578	2,812
INSKIP	14,165	5,760	53,340
IRON GATE	44,711	14,132	114,147
J B BLACK	193,726	99,688	669,868
JAYBIRD	238,249	105,794	550,955
JDGE F CARR	127,700	107,161	459,289

Plant Name	Storage Capacity (MWh)	Monthly Generation Capacity (MWh/month)	Historic Annual Generation (MWh/year)
JONES FORK	8,742	7,786	20,556
KAWEAH NO1	2,939	1,456	12,271
KAWEAH NO2	2,615	2,814	11,785
KAWEAH NO3	5,353	3,317	22,717
KERN RIV 3	66,143	28,832	168,939
KERN RIVER	52,718	19,554	178,291
KILARC	6,956	2,474	18,488
KINGS RIVER	48,543	38,735	194,056
L MATHEWS	10,254	37,442	30,248
LEWISTON	853	455	2,514
LIME SADDLE	2,550	2,100	8,846
LOON LAKE	48,633	38,383	104,550
LUNDY	4,117	2,286	10,239
LYTLE CREEK	866	3,830	3,188
MAMMOTH	228,798	140,163	631,725
MIDDLE FORK	217,106	100,360	540,543
MIDLE GORGE	42,512	26,655	114,277
MILL CRK 1	1,438	866	4,762
MILL CRK 3	3,104	2,061	10,612
MOCCASIN	206,400	104,510	443,434
MOCCASIN LW	4,623	2,100	7,403
MOJAVE SIPH	10,310	7,298	33,122
MURPHYS	5,926	2,672	20,518
OAK FLAT	2,545	2,321	6,191

Plant Name	Storage Capacity (MWh)	Monthly Generation Capacity (MWh/month)	Historic Annual Generation (MWh/year)
ONTARIO 1	1,826	608	3,877
ONTARIO 2	341	286	1,612
OXBOW	6,198	6,249	29,452
PERRIS	2,481	13,194	10,458
PHOENIX	3,205	1,687	10,746
PILOT KNOB	31,084	25,938	65,231
PIT NO 1	150,185	45,404	306,455
PIT NO 3	152,499	53,295	426,578
PIT NO 4	201,151	93,502	547,431
PIT NO 5	291,254	119,206	940,541
PIT NO 6	115,718	59,074	377,074
PIT NO 7	279,173	82,206	516,391
PLEASANT VL	3,528	1,626	9,304
POE	177,043	93,576	587,050
POOLE	15,715	22,370	32,767
PORTAL	17,047	9,948	43,762
POTTER VAL	17,126	8,132	48,804
RALSTON	74,966	63,512	385,181
RINCON PWR	76	248	550
ROBBS PEAK	30,245	17,021	50,835
ROCK CREEK	182,829	86,931	527,010
ROLLINS	18,949	9,367	63,070
RUSH CREEK	20,483	8,644	51,336
S FERNANDO	7,987	4,503	33,450
S GORGNIO	619	1,052	2,368
S JOAQUIN 2	3,097	2,829	11,622
S JOAQUIN 3	4,066	7,427	15,404

Plant Name	Storage Capacity (MWh)	Monthly Generation Capacity (MWh/month)	Historic Annual Generation (MWh/year)
S JOAQUN 1A	385	275	1,451
SALT SPGS	83,159	34,019	214,825
SAND BAR	27,623	18,840	75,636
SANTA ANA 1	5,684	5,729	11,402
SANTA ANA 2	1,345	1,111	5,801
SANTA ANA 3	1,242	1,320	4,363
SCOTT FLAT	1,465	2,920	4,696
SF PR PL 1	66,443	41,468	258,094
SF PR PL 2	24,330	12,897	96,025
SIERRA	657	517	3,122
SLAB CREEK	347	319	1,060
SLY CREEK	17,890	10,730	35,152
SOUTH	14,692	6,081	52,933
SPAULDING 1	15,199	6,937	35,909
SPAULDING 2	6,211	2,893	12,856
SPAULDING 3	15,978	4,925	36,338
SPRING GAP	14,254	5,280	39,632
STAMPEDE	5,004	2,813	9,055
STANISLAUS	96,246	42,924	388,505
TEMESCAL	5,525	20,298	15,368
TIGER CREEK	122,196	38,865	302,880
TOADTOWN	2,468	1,141	6,027
TRINITY	87,664	99,356	467,397
UNION VALLY	52,311	33,505	125,244
UPPER GORGE	38,877	24,634	107,455

Plant Name	Storage Capacity (MWh)	Monthly Generation Capacity (MWh/month)	Historic Annual Generation (MWh/year)
VOLTA	18,441	6,887	53,754
VOLTA 2	2,124	1,138	6,424
W E WARNE	81,336	57,447	236,349
WEST POINT	25,094	10,913	92,522
WHISKEYTOWN	5,698	5,402	15,142
WHITEROCK	117,483	164,733	597,811
WISHON	18,125	13,137	64,569
WOODLEAF	90,181	45,520	263,201

OPTIMAL HOURLY OPERATIONS OF A HYDROPOWER RESERVOIR-AFTERBAY SYSTEM UNDER VARIABLE ENERGY PRICES IN CALIFORNIA

PROJECT REPORT

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Abstract

Requirements of minimum instream flows and maximum ramping rates are often imposed on hydropower generation operations. Re-regulation facilities (afterbays or reservoirs) can mitigate this reduction in flexibility by dampening or eliminating the connection between hydropower operations and releases to the stream. Hydropower reservoir-afterbay system release operations were modeled for a range of physically possible minimum instream flow and ramping rate requirements using a linear program. Results show that an afterbay can effectively reduce the effect of instream flow constraints on hydropower revenues and operations.

Keywords: California, hydropower reservoir, afterbay operations, hydropeaking, MIF, ramping rates

Introduction

Hourly operations of hydropower reservoirs often involve sudden changes in releases associated with the hourly fluctuations in energy prices. This release pattern, known as hydropeaking, affects stream ecosystems by changing flow conditions on short time scales (Flug, 1997). Within the Federal Energy Regulatory Commission (FERC) licensing process, operations are often restricted by limiting rates of change of reservoir releases and by setting minimum releases to the stream. These restrictions limit the ability of the system to follow the pattern of energy prices and potentially reduce the economic value of daily generation.

An alternative to direct constraints on hydropower operations is to re-regulate the release pattern with a water storage facility downstream of the power house (Richter and Thomas, 2006). Such an alternative typically exists in cascade hydropower systems, where the most downstream reservoir can be used for this purpose. In some systems, afterbays have been created for this purpose.

It is important to distinguish between facilities used solely to mitigate hydropeaking operations by an upstream reservoir by re-regulation and those used for both re-regulation and power generation. In the first case (Fig. 1), which typically corresponds to a regulation facility at the downstream end of a hydropower reservoir system, all releases from the re-regulation facility are discharged directly into the stream. In this case, the re-regulation facility has to mitigate the hydropeaking operations and provide lower and upper bounds to instream flows.

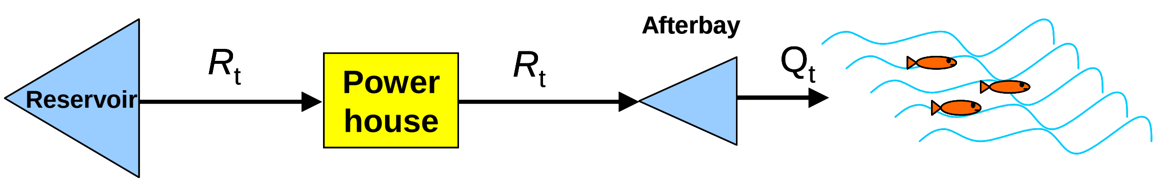

Figure 1. End-of-system afterbay schematics showing releases from the hydropower reservoir R_t and afterbay Q_t.

In the second case, which is not considered in this report, water releases from the re-regulation facility can be allocated either for power generation or for instream flows in the downstream reach.

This document begins with the mathematical formulation of end-of-system afterbay operations as an optimization problem—a linear program. The behavior of solutions to this problem are then explored numerically and discussed in terms of hydropower and instream flow performance, afterbay capacity and operations, and turbine capacity.

Mathematical Formulation

For daily operations on an hourly time-step, reservoir storage and elevation head can usually be considered fixed (for small rates of daily release relative to water stored and inflows for the immediately-upstream reservoir). Linear program formulations for maximizing the economic value of hydropower subject to capacity and instream flow and flow ramping constraints are developed for cases without and with an afterbay.

No Afterbay

As a first step, the effects of minimum instream flow (MIF) requirements will be examined for a simple system, where hydropower releases are directly discharged into the stream.

The objective is to maximize the total daily value of energy generation

$$Max \quad z = \sum_{t=1}^{24} p_t \cdot E_t \tag{1}$$

where p_t is the energy price and E_t is the energy generated at time t.

$$E_t = \eta \cdot \gamma \cdot h \cdot R_t \tag{2}$$

where η is the combined turbine and generation efficiency, γ is the specific weight of water, h is the (constant) water head, and R_t is the water release through the turbines at time t.

Hydropower operations are constrained by physical and regulatory restrictions. First, hydropower releases are bounded by turbine capacity.

$$R_t \le R_{MAX} \quad t = 1,...,24 \tag{3}$$

The mass balance in the hydropower reservoir can be simplified at this time scale by defining a total daily target release volume. This eliminates the need to consider inflows to the reservoir. Therefore, the total daily hydropower release is constrained by the total daily release target:

$$\sum_{t=1}^{24} R_t \le R_{TOT} \tag{4}$$

The regulatory constraints on stream releases are:

Minimum instream flow: $R_t \ge Q_{MIN}$ (5)

Maximum up-ramping rate: $R_{t+1} - R_t \le \Delta Q^{UP}$ (6)

Maximum down-ramping rate: $R_t - R_{t+1} \le \Delta Q^{DOWN}$ (7)

This formulation can be summarized by the following linear program:

$$
\begin{aligned}
&\underset{R_t}{Max} \quad z = \sum_{t=1}^{24} p_t \cdot \eta \cdot \gamma \cdot h \cdot R_t \\
&s.t \quad R_t \le R_{MAX} \qquad t = 1,\ldots,24 \\
&\qquad \sum_{t=1}^{24} R_t \le R_{TOT} \\
&\qquad R_t \ge Q_{MIN} \qquad t = 1,\ldots,24 \\
&\qquad R_{t+1} - R_t \le \Delta Q^{UP} \qquad t = 1,\ldots,24 \\
&\qquad R_t - R_{t+1} \le \Delta Q^{DOWN} \qquad t = 1,\ldots,24 \\
&\qquad R_t \ge 0 \qquad t = 1,\ldots,24
\end{aligned}
$$

With Afterbay

This formulation corresponds to the case of an end-of-system afterbay, whose sole purpose is to re-regulate the operations of an upstream hydropower reservoir. The problem is to operate both the hydropower reservoir and its re-regulation facility hourly to maximize total daily economic value of energy subject to constraints on the releases to the stream. A one-day time horizon is considered.

The operational decisions are the hourly releases from each storage facility (hydropower reservoir and afterbay) during the day.

The operational objective, turbine capacity constraint and daily water availability constraint are those of Eqs. (1) through (4).

The mass balance in the afterbay, neglecting evaporation for such short time periods, is:

$$S_{t+1} = S_t + \left(R_t - Q_t\right) \cdot \Delta t \qquad t = 1,\ldots,24 \qquad \Delta t = 3{,}600 \text{ sec} \tag{8}$$

where S_t is the storage at the beginning of hour t and Q_t is the flow discharge from the afterbay during period t.

The following constraints (9a, 9b, 9c, and 9d) set storage bounds without imposing a timing phase or hour of minimum storage on the drawdown-refill cycle. First, initial storage is set as a large positive number:

$$S_1 = S_{ref} \tag{9a}$$

Then define the maximum and minimum reference storages:

$$S_t \ge S_{MIN} \text{ and } S_t \le S_{MAX} \tag{9b}$$

Restrict storage range by afterbay reservoir capacity:

$$S_{MAX} - S_{MIN} \le S_{CAP} \tag{9c}$$

Real storages can be recovered by subtracting the lower bound:

$$S_t^{REAL} = S_t - S_{MIN} .$$

To ensure temporal continuity in the problem, the final storage must be equal to the initial storage:

$$S_{24} + \left(R_{24} - Q_{24}\right) \cdot \Delta t = S_1 \tag{10}$$

The regulatory constraints on stream releases are now imposed on the releases from the afterbay:

Minimum instream flow: $Q_t \geq Q_{MIN}$ (11)

Maximum up-ramping rate: $Q_{t+1} - Q_t \leq \Delta Q^{UP}$ (12)

Maximum down-ramping rate: $Q_t - Q_{t+1} \leq \Delta Q^{DOWN}$ (13)

The problem can be summarized by the following linear program:

$$\begin{array}{lll}
\underset{R_t, Q_t}{Max} & z = \sum_{t=1}^{24} p_t \cdot \eta \cdot \gamma \cdot h \cdot R_t & \\
s.t & R_t \leq R_{MAX} & t = 1,\ldots,24 \\
 & \sum_{t=1}^{24} R_t \leq R_{TOT} & \\
 & S_{t+1} = S_t + \left(R_t - Q_t\right) \cdot \Delta t & t = 1,\ldots,24 \\
 & S_t \geq S_{MIN} & t = 1,\ldots,24 \\
 & S_t \leq S_{MAX} & t = 1,\ldots,24 \\
 & S_{MAX} - S_{MIN} \leq S_{CAP} & \\
 & S_1 = S_{ref} & \\
 & S_{24} + \left(R_{24} - Q_{24}\right) \cdot \Delta t = S_1 & \\
 & Q_t \geq Q_{MIN} & t = 1,\ldots,24 \\
 & Q_{t+1} - Q_t \leq \Delta Q^{UP} & t = 1,\ldots,24 \\
 & Q_t - Q_{t+1} \leq \Delta Q^{DOWN} & t = 1,\ldots,24 \\
 & R_t \geq 0, \quad Q_t \geq 0 & t = 1,\ldots,24
\end{array}$$

Model Parameters

Model parameters define infrastructure and instream flow regulatory constraints, daily hydropower release targets, and energy prices. Turbine capacity (R_{MAX}), set at 50 m^3/s. Afterbay storage capacity (S_{MAX}) values of 180,000 m^3 and 360,000 m^3 are modeled, besides the No Afterbay case. These capacities are equivalent to a continuous flow of 50 m^3/s (turbine capacity) during one and two hours, respectively. Other fixed parameters are: $h = 100\ m$, $\eta =$ 0.80, and $\gamma = 9.8\ kN/m^3$. Hourly energy prices p_t are based on average August 2005 prices for the California ISO system (Fig. 2). In general, higher energy prices are between noon and midnight, with local peaks at 4 PM, 5 PM and 9 PM. The lowest prices are between 3 AM and 8 AM.

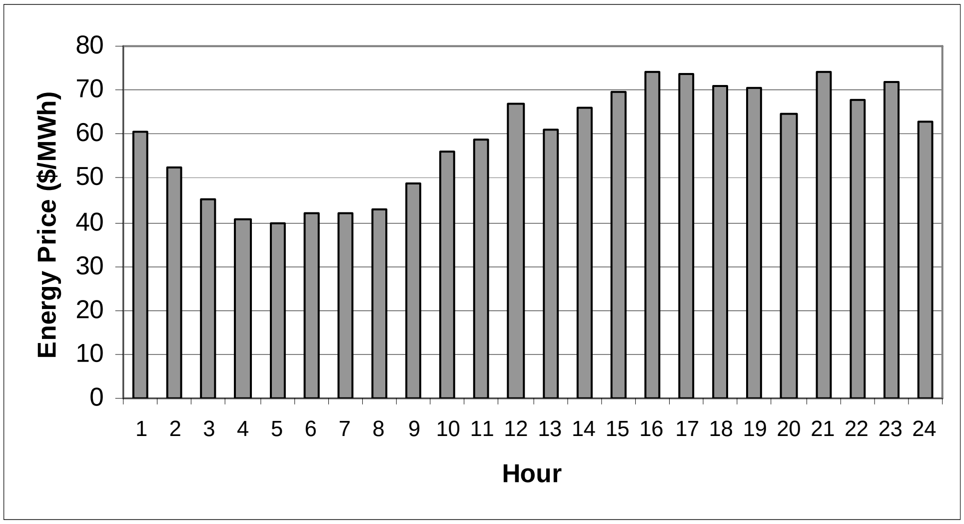

Figure 2. Hourly Energy Price August 2005 (Source: Cal-ISO)

Values of regulatory-constraint parameters and daily hydropower release targets originate from various policy scenarios for hydropower operations. These scenarios are described in the next section.

Regulatory Scenarios

Different regulatory scenarios can be explored by changing the parameters Q_{MIN}, ΔQ^{UP}, and ΔQ^{DOWN}. The two latter ramping parameters are assumed equal for ease of analysis. Daily operational scenarios can be defined by different daily hydropower release targets, R_{TOT}. Ranges for these parameters can be defined based on the fixed turbine capacity, R_{MAX}, by the following inequalities.

Total daily hydropower release must be within the range defined by turbine capacity times hours of the day: $0 \le R_{TOT} \le 24 \cdot R_{MAX}$.

Minimum instream flow must be within the range defined by the average hourly release target: $0 \le Q_{MIN} \le R_{TOT} / 24$.

Ramping rates ranges are defined by the difference between turbine capacity and minimum flow: $0 \le \Delta Q^{UP} \le R_{MAX} - Q_{MIN}$ and $0 \le \Delta Q^{DOWN} \le R_{MAX} - Q_{MIN}$.

Model Results

The results of the optimization models under different scenarios allow for analysis of several economic and operational aspects of the system. The effects of regulatory policies (i.e., instream flow constraints) on hydropower revenues and on how the system is operated are examined. Operational results include the optimal daily pattern of hydropower releases and releases to the stream.

Effects of Instream Flow Constraints on Hydropower Revenues

Operations with unconstrained instream flows define a base case for subsequent comparison. Figure 3 shows the optimal revenue for the relevant range of total daily hydropower releases, with no constraints on releases to the stream. The curves are identical for all three afterbay storage capacities (including the No Afterbay case). This means that a re-regulation facility has no economic value if hydropower operations are not constrained by instream flow restrictions. The daily revenue the system can generate when it operates at full capacity the entire day is about $56,000. The revenue from increasing daily release is somewhat non-linear, with preference given to maximizing release during hours when energy prices are highest. With limited turbine capacities, larger daily release target volumes force larger releases during off-peak times, when energy prices are lower. The marginal revenue (slope of the curve) therefore decreases as larger amounts of water are available.

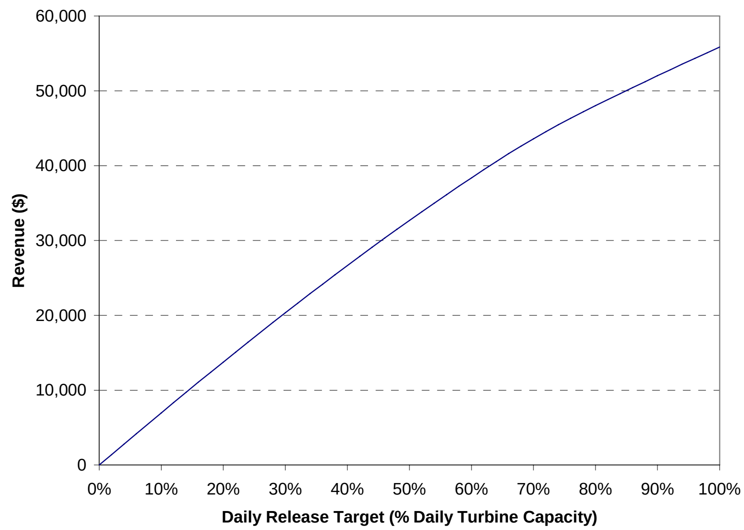

Figure 3. Optimal Daily Hydropower Revenues with Unrestricted Instream Flow

The effects of varying minimum instream flow (MIF) levels with no ramping constraints are shown in Figure 4, for the afterbay storage capacity of zero, and storage capacities equivalent to one and two hours of operation at turbine capacity, respectively. Series represent daily hydropower release target as a percentage of the maximum usable level, defined by 24 hours of operation at turbine capacity. For all three storage capacities revenues decrease as the minimum instream flow requirement increases. However, the effect is clearly milder as storage capacity increases. For example, for a daily release target set to 50% of maximum daily release, with no afterbay the revenue decreases from $32,685 to $27,923, a 15% loss. With an afterbay, revenues fall to $29,614 and $30,743, or 9% and 6% losses for the smaller and larger capacity, respectively. The reductions in revenue losses—$1,691 and $2,820 for the smaller and larger, respectively in this example—represent the economic value of afterbays for the system. Another interesting observation is that the slope of each curve tends to become more negative as the minimum instream flow requirement increases. In other words, the marginal decrease in revenues increases with the minimum flow requirement. This can be explained by the fact that as the MIF increases, more of the available water is released during hours with lower energy prices.

The effects of ramping constraints on revenues are shown in Figure 5. Series represent combinations of daily hydropower release target as a percentage of the level defined 24 hours operating at turbine capacity, and afterbay capacity levels. As the allowed maximum ramping rate (MRR) increases, operations are less constrained and therefore revenues increase, eventually reaching unconstrained levels. The reduction in revenues due to restricted ramping is greater for the case with no afterbay. For a daily hydropower release target of 50% the total capacity, a 17% reduction in daily revenue occurs between the unconstrained and zero ramping case. The reduction is 10% and 6% for afterbay storage capacity equivalent to one and two hours operating at turbine capacity, respectively.

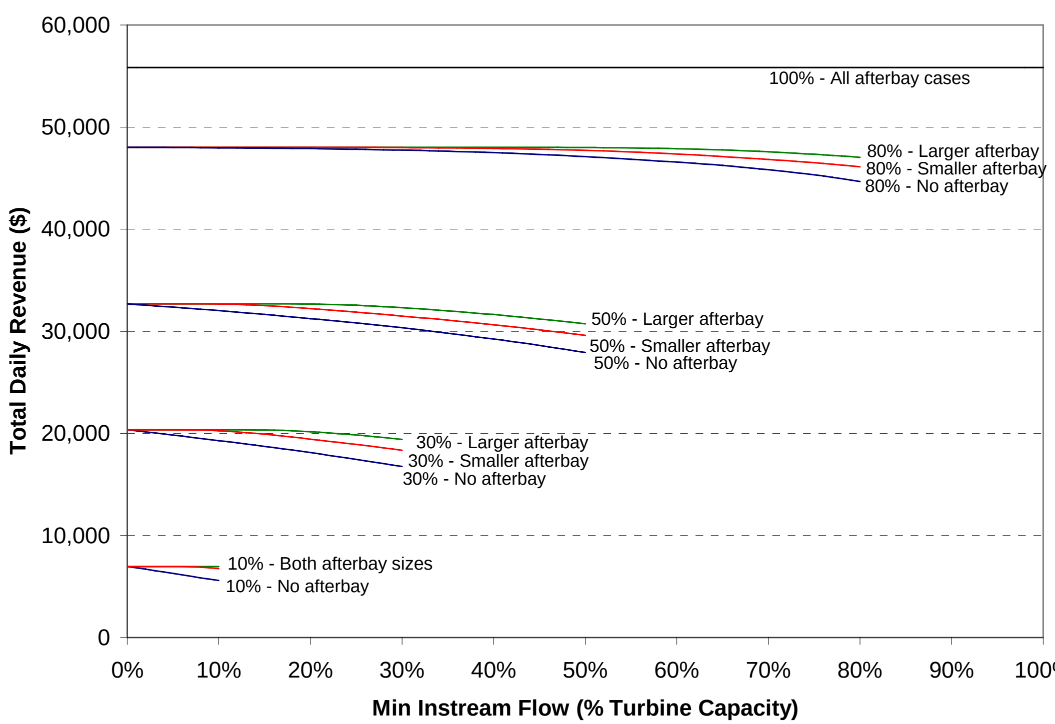

Figure 4. Effect of Minimum Instream Flows on Daily Revenues for Different Daily Release Targets and Afterbay Sizes

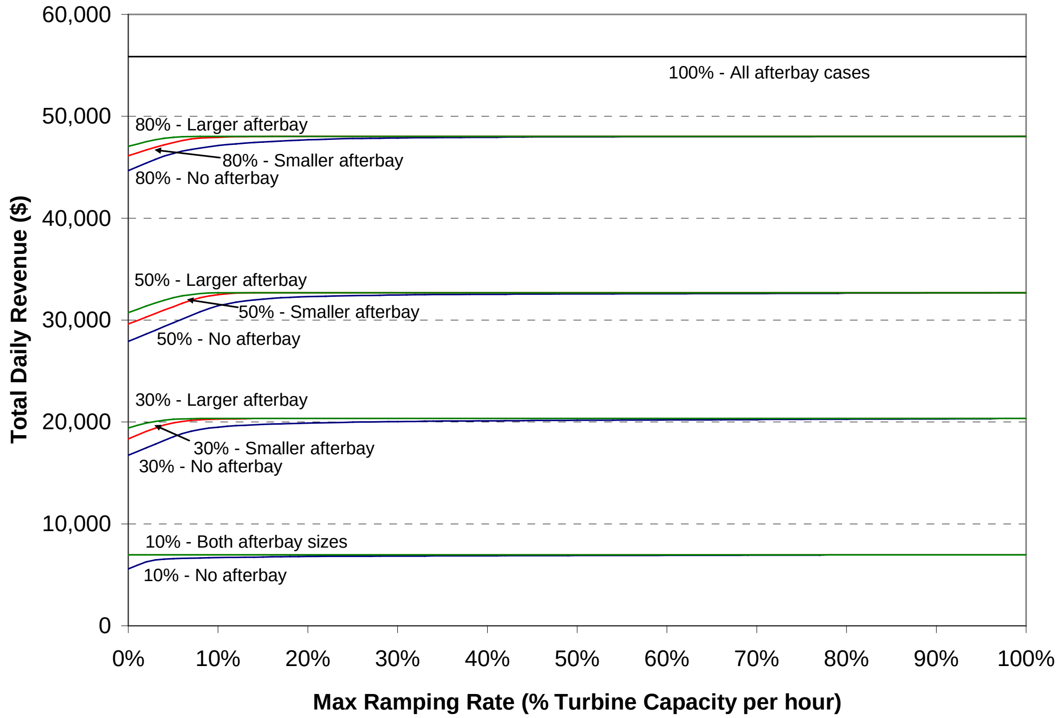

Figure 5. Effects of Ramping Constraints on Daily Revenue for Different Daily Release Targets and Afterbay Sizes

The effect of ramping constraints on revenue is strongest for intermediate daily water availability levels. Ramping rate constraints have little effect when very little or very much water is available for the day. For the curves where revenues are affected by ramping constraint levels, the marginal effect of limiting ramping rates decreases as higher ramping rates are allowed. Thus, the reduction in revenues due to ramping constraints is greatest for relatively small ramping rates. When higher ramping rates are allowed, the revenue approaches rapidly that of the unconstrained case. The range of ramping rates affecting the revenues is influenced by the existence and size of the re-regulation reservoir. Without re-regulation, revenues are affected by a wide range of allowed ramping rates. The unconstrained revenue levels are reached only for ramping rates beyond 90% of turbine capacity per hour. Afterbay capacity reduces the range of ramping rates that affect revenues. For an afterbay able to store an hour of operation at turbine capacity, revenues are only affected when allowed ramping rates are below 15% of turbine capacity per hour. This range decreases to 10% for an afterbay twice as large. This is the range where a conflict exists between the goals of avoiding sudden streamflow fluctuations and maximizing hydropower revenues. Restrictions outside this range will not affect revenues. Identifying this range is important for FERC licensing negotiations.

The combined effect of minimum flow and ramping constraints on hydropower revenues is shown in Figure 6. The graph shows how the optimal daily revenue changes for different levels of minimum release to the stream, when ramping rates are restricted to less than 10% the turbine capacity per hour. The effect is similar to that observed in Figure 4, although in this case the curves without an afterbay are further apart from those with afterbay, in particular for low MIF requirements. This is due to the additional effect of the MRR. This situation, with relatively low MIFs (compared with turbine capacity) and relatively stringent ramping rates, will likely be encountered during FERC licensing negotiations for hydropower systems in the Sierra Nevada. Without an afterbay, revenue levels are lower for all daily hydropower release target (series) and for small required instream flow. As the MIF increases, the revenue becomes closer to (even coincides with) that with MIF but unconstrained ramping. So, when large MIFs are required, ramping rates can be as stringent as 10% of turbine capacity per hour, without additional effect on revenues. This is reasonable, since increasing MIFs reduces the range of physically possible ramping rates, as seen in Section 4.0. With a re-regulation reservoir, the curves practically coincide with those obtained when ramping is unconstrained. In this case, limiting ramping rates to 10% of the turbine capacity per hour has no additional effect on revenues to that attributed to minimum required releases to the stream. Again, the existence of an optimally operated afterbay reduces the degree of conflict between hydropower generation and instream flow goals.

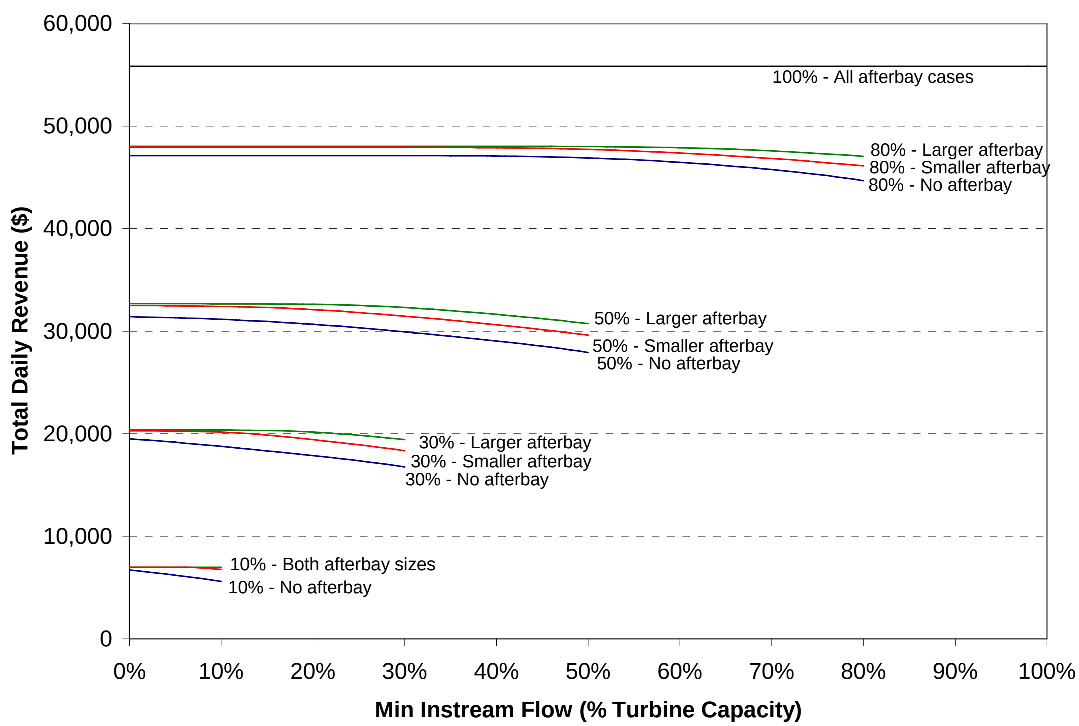

Figure 6. Combined Effect of MIFs and Ramping Constraints on Revenues for a Ramping Rate of 10% of Turbine Capacity per Hour

Hydropower Generation Pattern

Daily hydropower generation is expected to follow the pattern of energy prices. Thus, in the unconstrained case, the water available for the entire day would be allocated first for generation when energy is most valuable, and then to increasingly less valuable hours as turbine capacity is reached. This would continue until the day's allocation of water to release was exhausted, leaving no discharge in any remaining off-peak hours.

MIF and ramping rate constraints reduce the flexibility of the system to allocate water this way. If no re-regulation reservoir is available, such constraints are imposed directly on the hydropower generation pattern. In this case, releases to the stream coincide in magnitude and timing with those of hydropower generation. All the results shown in this section are for a daily hydropower release target equal to 50% the maximum usable daily water volume, as defined by turbine discharge capacity. In other words, the daily release target is enough to operate during 12 hours (50% of the day) at turbine capacity, although the actual allocation can consider intermediate releases (less than capacity) during some hours.

Figure 7 shows the effect of MIF requirement on the hydropower release pattern. Each series represents an hour during the day. For the case without an afterbay (top graph), under no minimum flow requirement the hydropower release equals turbine capacity for twelve hours in the day (those when energy price is highest) and zero for those hours when energy is least valuable. This is expected, since the daily hydropower release equals 50% of the maximum volume defined by turbine capacity. As the required release to the stream increases, hydropower releases during less valuable hours make up the required MIF and, since only a fixed amount of water is available for the day, generation decreases during some of the more valuable hours (in order of increasing energy price). When the MIF matches the average hourly water availability (50% of turbine capacity in this case), hydropower releases are steady all day.

With an afterbay, the unconstrained hydropower release pattern, i.e. generation at turbine capacity during the twelve more valuable hours and zero during the rest of the day, is observed when relatively small instream flows are required. For instream flow requirement up to 9% of turbine capacity, hourly hydropower generation releases are the same as if no minimum release to the stream was imposed. This MIF level up to which hydropower revenues are not affected increases to about 18% for an afterbay twice as large. Beyond this range, generation gradually increases during the off-peak hours and decreases during the peak hours. With re-regulation storage capacity, even when MIF is the highest possible, hydropower releases are uneven during the day, with some (most valuable) hours generating at turbine capacity, with no generation at times when energy prices are low. Interestingly, hydropower releases during hours 20 and 22 go from turbine capacity to zero as the MIF requirement increases. Also, releases during hour 12 remain at turbine capacity for all MIF levels, whereas generation during hours with higher energy prices is smaller.

The effect of ramping constraints on hydropower releases is shown in Figure 8. With no afterbay, hydropower releases are steady and unchanging if no ramping is allowed. As allowable ramping rates are increased, releases tend to increase during the most valuable hours and decrease when energy is cheapest, as expected. A similar behavior is observed when hydropower releases can be re-regulated by an afterbay. However, as the ramping constraint's effects are dampened or eliminated by the afterbay, releases reach the optimal unconstrained zero-100% pattern (twelve hours operating at capacity and the other twelve with no generation), even with more stringent MRRs. This optimal pattern can be achieved with ramping rates

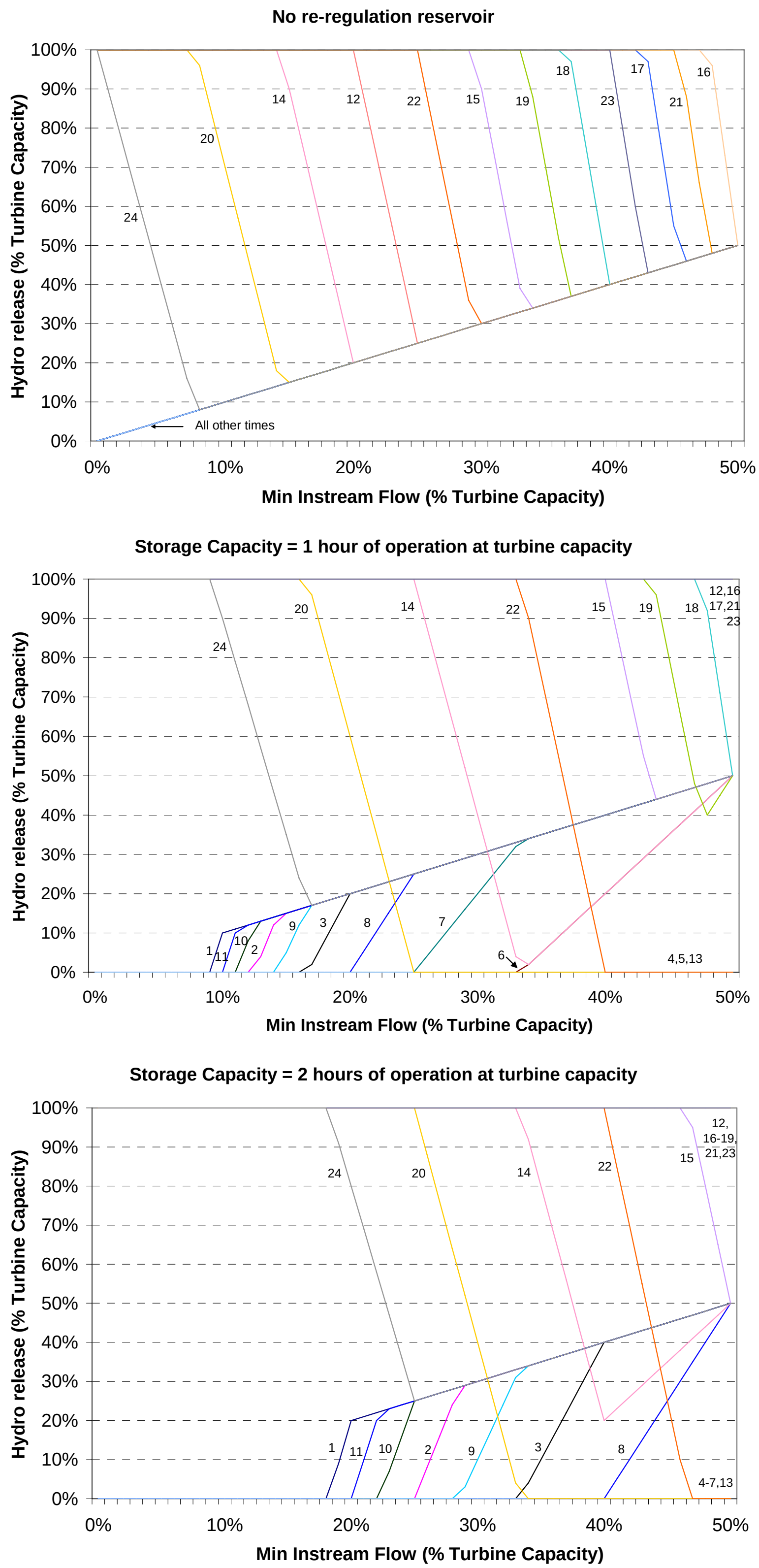

Figure 7. Hourly Hydropower Release Pattern under MIF for Daily Hydropower Release of 50% of Maximum

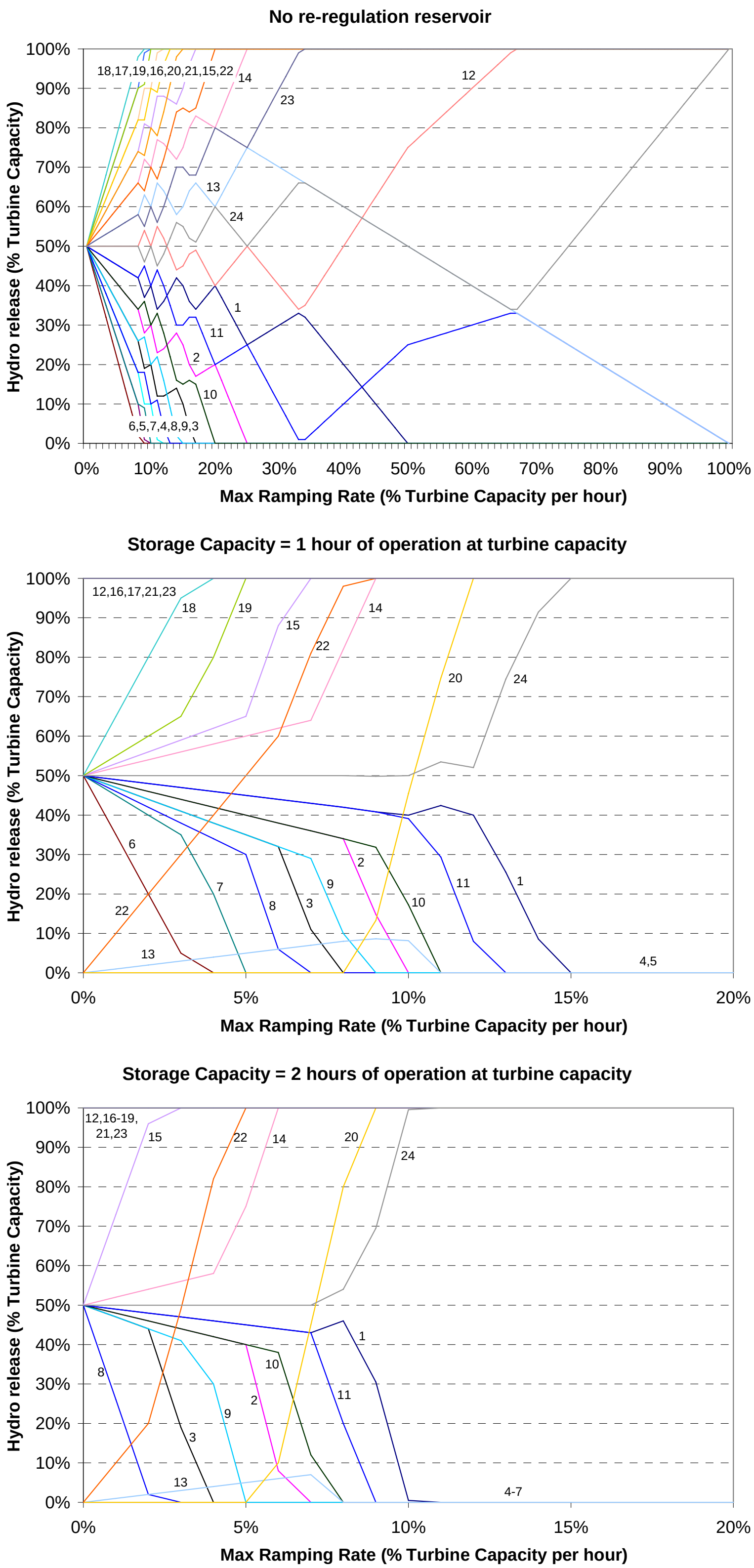

Figure 8. Hourly Hydropower Release Pattern under Ramping Constraints for Daily Hydropower Release of 50% of Maximum

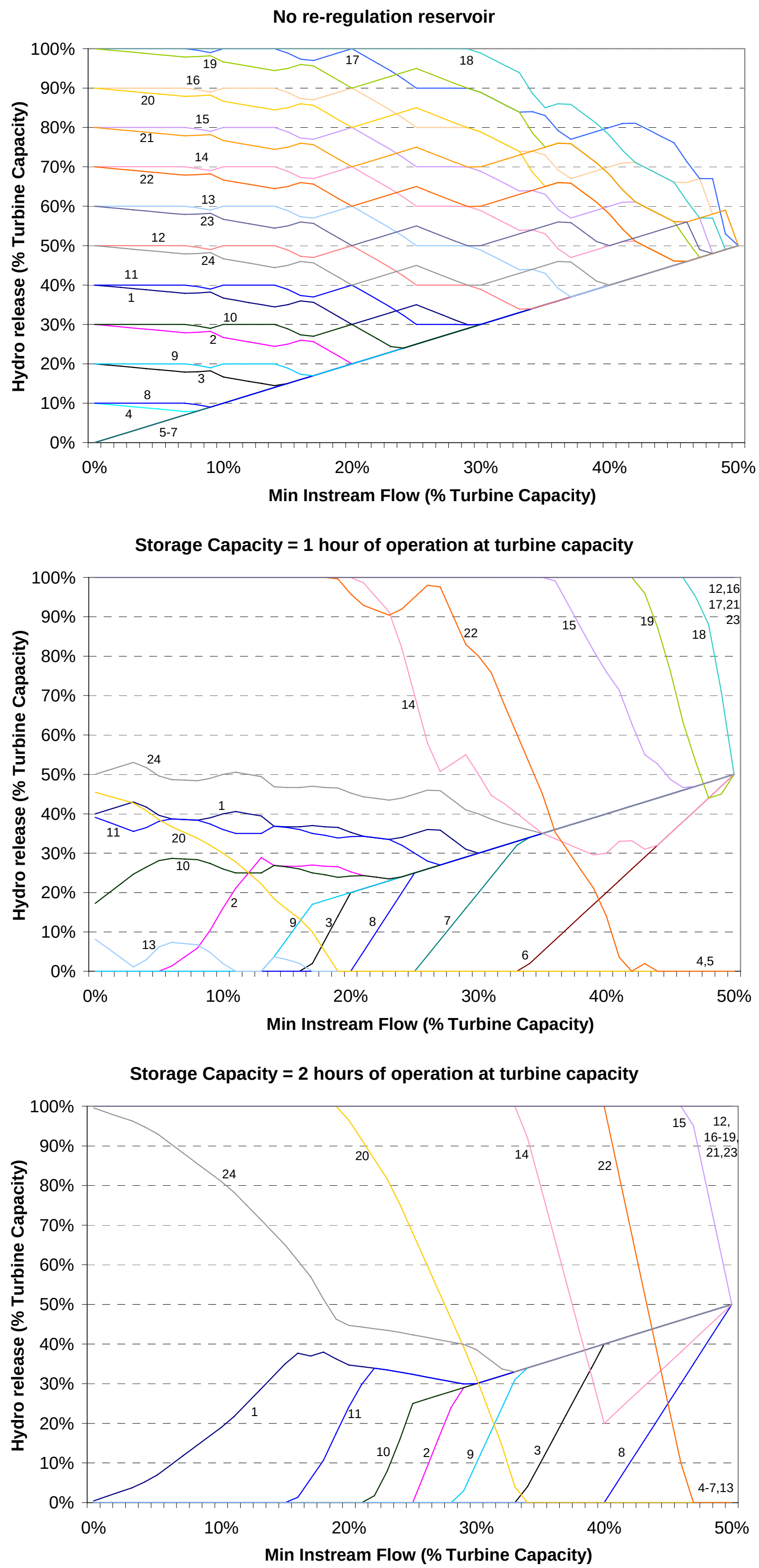

Figure 9. Hourly Hydropower Release Pattern under Combined Constraints (Ramping rate 10% and Daily Hydropower Release of 50% of Maximum)

greater than 18% and 12% with the smaller and larger afterbay, respectively. Constrained ramping affects the revenue only for smaller allowable ramping rates. Similar to what was observed for MIFs, releases during hours 20 and 22 can vary from zero to turbine capacity as the restriction becomes less stringent, in this case as allowed ramping rates increase.

The combined effect of minimum flow and ramping constraints on hydropower release decisions is shown in Figure 9, for a MRR of 10% of turbine capacity per hour. Without re-regulation, the MRR eliminates the possibility of zero-100% generation releases. Even if no minimum flow is required, hydropower releases cover the entire spectrum (from zero to 100%), with increases of 10% of turbine capacity (allowed MRR) between hours. This is in contrast with the corresponding result in Figure 7, where the zero-100% release pattern was observed when no MIF was required. Of course, more water is released during hours of high energy price. When releases are re-regulated through an afterbay, for low MIFs the system operates at full capacity during some hours, at intermediate levels during others, and not at all at other times. For an afterbay twice as large, the hydropower releases follow a pattern closer to that with unconstrained ramping. If no minimum flow is required, the zero-100% pattern is observed. For relatively high required releases to the stream, the patterns observed in this case almost coincide with those observed in Figure 7, without a ramping constraint.

Instream Flow Pattern

The hourly instream flow pattern is important for the ecosystem (Moog, 1993). This section presents the results obtained for a daily hydropower release target of 50% the maximum usable water volume defined by turbine capacity. Fig. 10 shows the daily time sequence, for MIF requirements between 0% and 50% (maximum possible in this case) and unconstrained ramping. With no afterbay, releases to the stream coincide with hydropower releases. Only the minimum releases occur during the midnight to 11 AM off-peak period. During the rest of the day, water is allocated to the hourly periods when water is more valuable, within the total daily release volume. In this case, releases to the stream cannot exceed the turbine capacity. For a required minimum flow equal to 50% of turbine capacity (the same as our daily release volume), the same flow is released to the stream during the entire day. A similar pattern occurs with releases to the stream from an afterbay. However, during the peak period strong hourly fluctuations are observed, which can be explained by the lesser peaks in energy prices. The peak instream flows during the peak period reach values of twice the turbine capacity for small MIFs, probably to ensure the afterbay empties before the next day’s peak period. This behavior is interesting, since the existence of low minimum flow constraints with no restriction on ramping rates seem to cause these high releases to the stream in presence of an afterbay. Maximum releases to the stream were not imposed in this study.

The effects of ramping constraints with no MIF on the hourly instream release pattern are shown in Figure 11. Without an afterbay, releases to the stream are those of generation. Releases to the stream tend to be small (even zero) during the night and morning, and high during the afternoon and evening, when turbine capacity is reached. For allowed ramping rates up to 40% of turbine capacity per hour, releases to the stream are zero somewhere during the off-peak period, and tend to reach turbine capacity during peak hours, with a linear behavior in

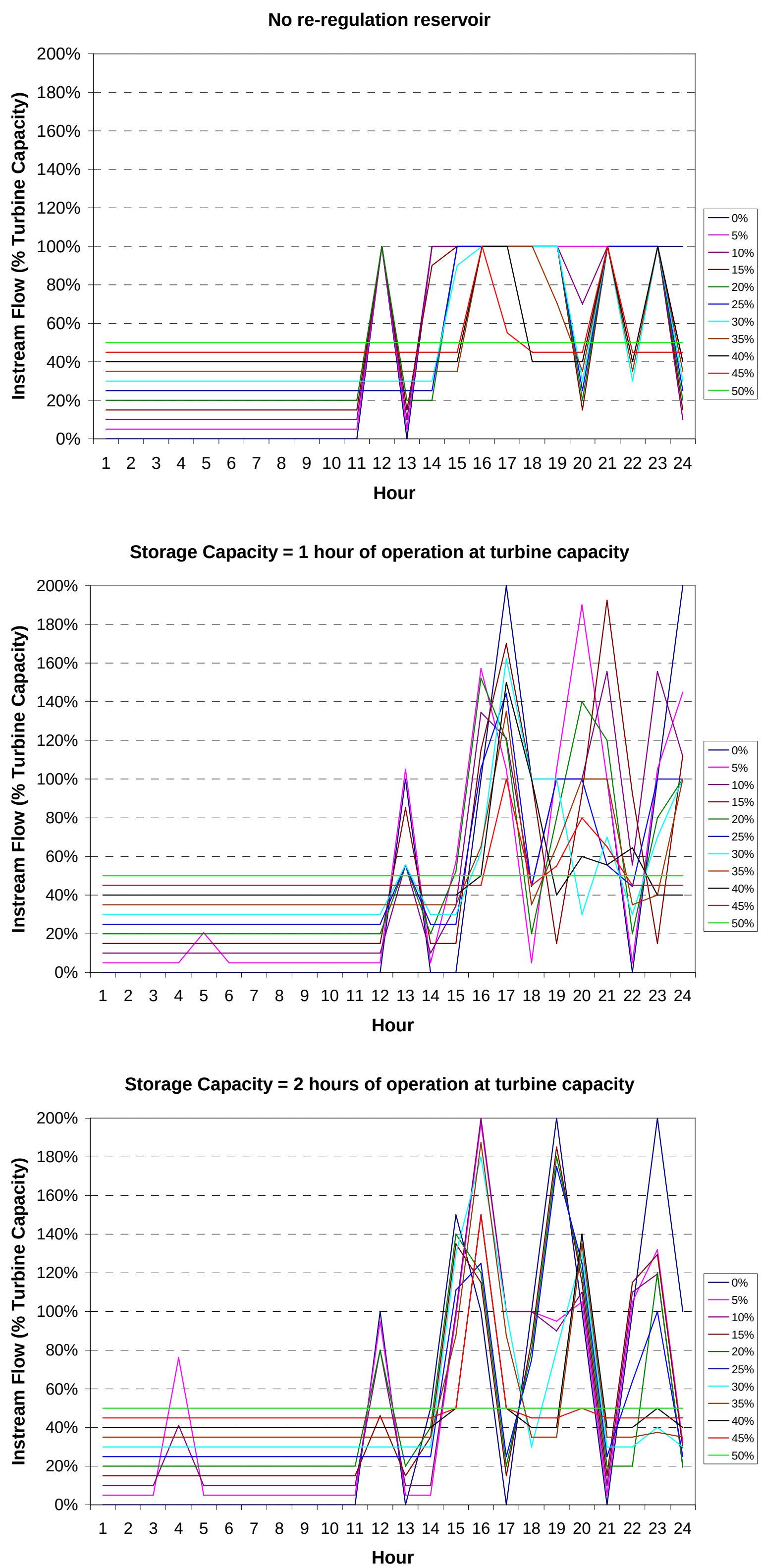

Figure 10. Instream Flow Hourly Pattern under Different Levels of MIF

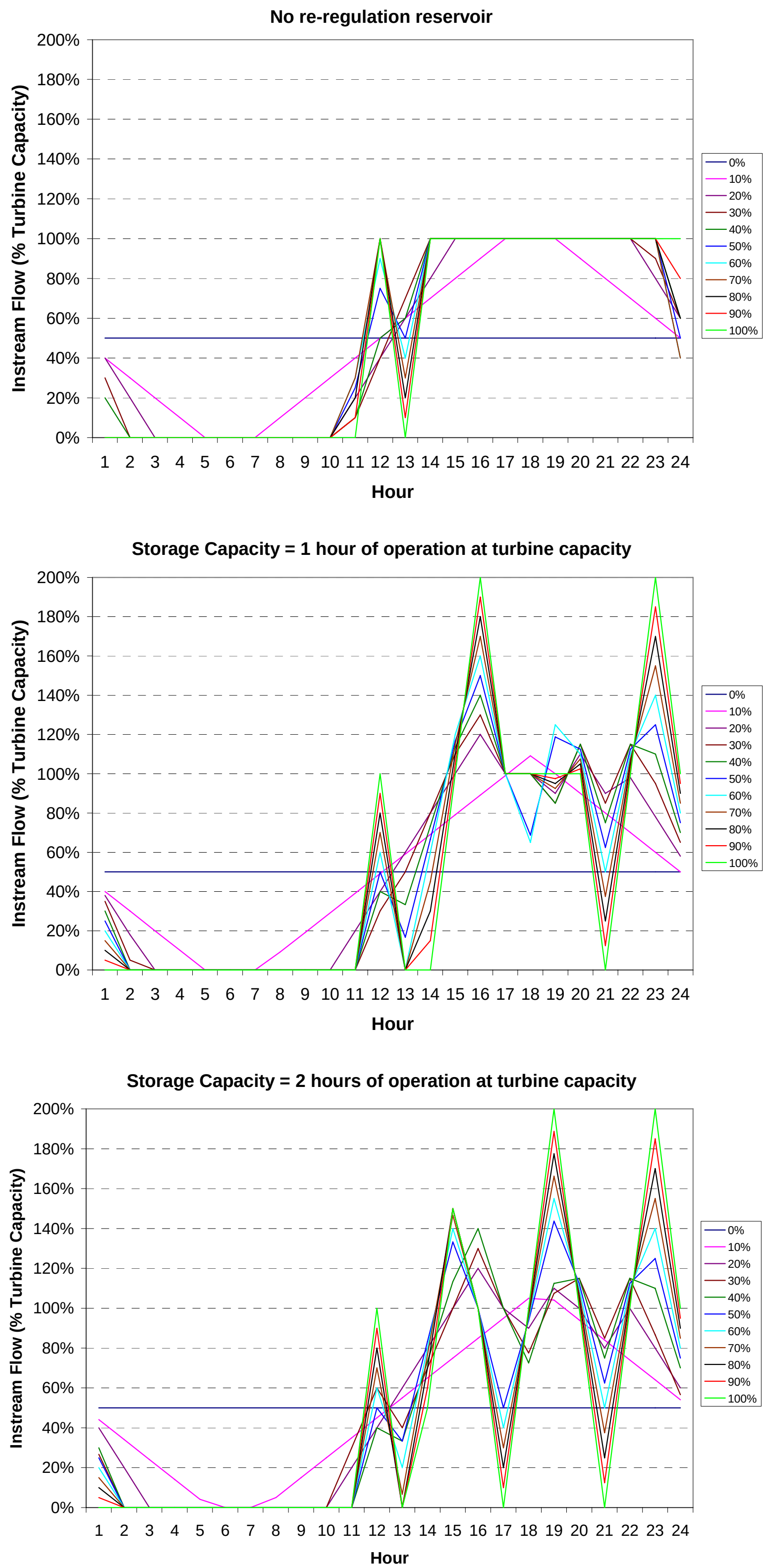

Figure 11. Instream Flow Hourly Pattern under Different Levels of Ramping Rates

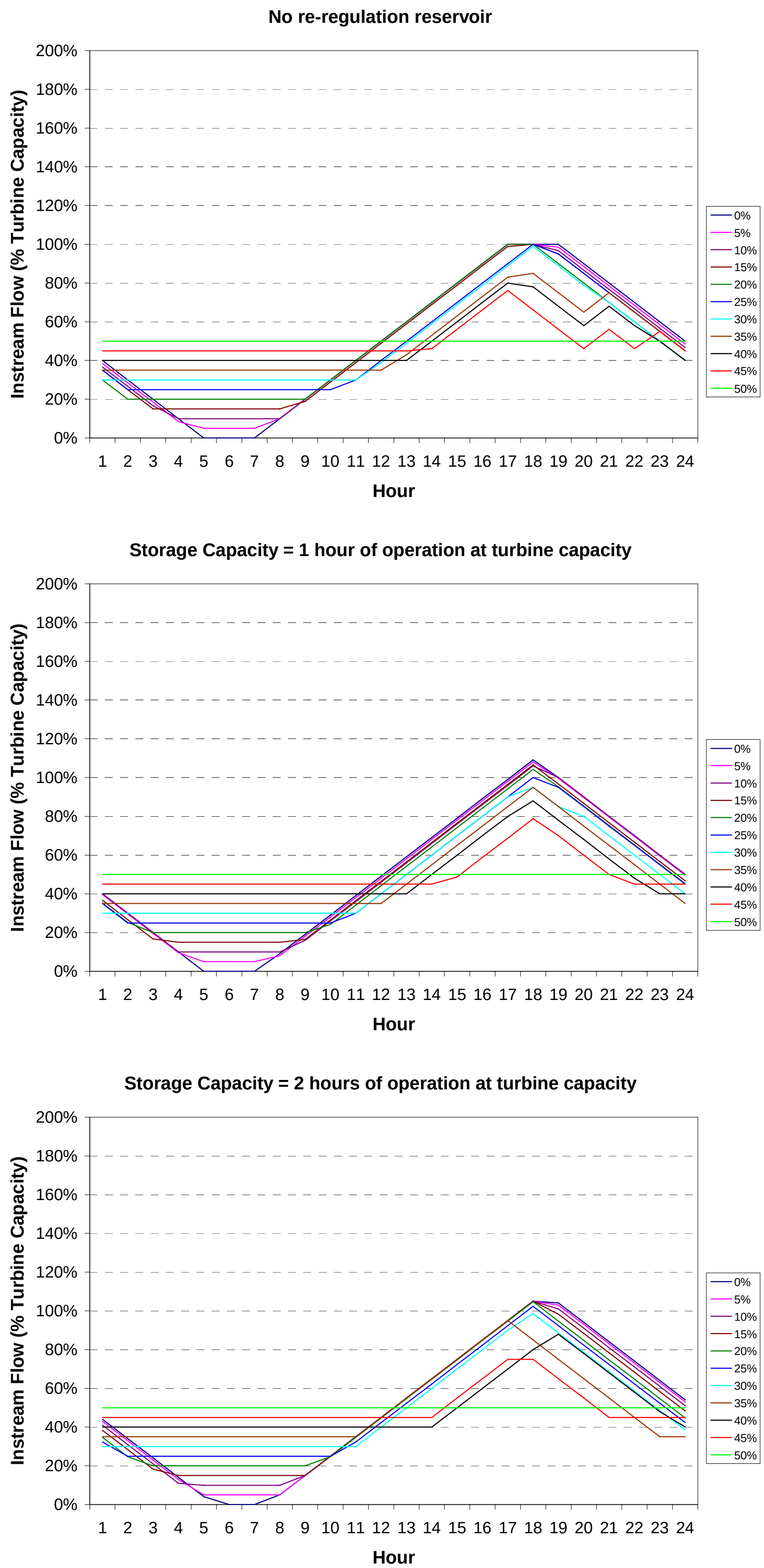

Figure 12. Instream Flow Pattern under Combined Constraints

between. When ramping beyond 50% of turbine capacity is allowed, a peak streamflow is observed at noon. With an afterbay, a similar pattern is observed, although with more fluctuations during the peak period. For large MRRs (i.e. when large ramping rates are allowed), instream flows reach 200% of turbine capacity when generation is more valuable. Once again, it seems that when the unconstrained case is approached, large releases to the stream are induced.

Figure 12 shows the pattern of releases to the stream for a combination of MIFs and a MRR of 10% the turbine capacity per hour. In this case, a similar, much more regular pattern is observed for all three afterbay sizes. In general, the instream flow equals the minimum requirement during off-peak hours and reaches about turbine capacity during the peak period. As the required release to the stream increases, the maximum released observed during peak hours decreases, because only a finite amount of water can be released in total during the day. Interestingly, unlike the case without ramping constraints (Fig. 10) releases to the stream barely exceed turbine capacity during peak hours. Imposing a restriction on ramping also limits the maximum flows released to the stream. These results show that combinations of MIF and MRR restrictions can induce very regular patterns of releases to the stream.

Conclusions

This report presents the results of an optimization model that simulates the operation of a reservoir-afterbay hydropower complex, under regulatory constraints defining minimum releases to the stream and the maximum rates of release change between consecutive hours. Modeling has proven a useful tool to study a reservoir-afterbay complex under parametrically varying instream flow constraints and daily hydropower release targets.

Tradeoffs between economic benefits and instream flow requirements were explored. Constraints on releases to the stream have an economic impact on hydropower revenues. However, a re-regulation reservoir, such as an afterbay, can mitigate this effect by dampening the connection between hydropower generation flows and releases to the stream. Stringent MIF requirements alone can reduce revenues by 15% when no re-regulation capacity is in place. If a re-regulation reservoir is introduced, the revenue reduction is decreased to 9% and 6% for afterbay capacities equivalent to one and two hours of operation at turbine capacity, respectively. Similar effects where observed for restricted ramping rates alone. However, it was observed that, for the cases with an afterbay, only very stringent ramping rates, below 15% of turbine capacity, affect hydropower revenues. When higher hourly fluctuations of instream flows are allowed, revenues reach the unconstrained levels. The effect of combined minimum flow and ramping constraints was studied for a MIF of 10% turbine capacity and varying levels of minimum required releases to the stream. The results are very similar to those obtained for MIF alone. Therefore, limiting ramping rates to 10% of the turbine capacity per hour has no additional effect on revenues to that attributed to minimum required releases to the stream.

The magnitude and timing of hydropower generation flow releases were also studied. In general, releases tend to follow the price pattern characterized by high prices during the afternoon and evening hours and lower prices during the rest of the day. These two periods can be considered peak and off-peak, respectively. Constraints on releases to the stream restrict the ability of the system to follow the daily pattern of energy prices. Minimum required releases to the stream force the system to generate electricity during less valuable hours, when no afterbay is available. With an afterbay, operations are not affected for MIFs up to 10% and 20% of turbine capacity, for the smaller and larger storage capacity, respectively. Constraints on ramping rates tend to equalize hourly releases. As larger ramping rates are allowed, more generation is observed during peak hours. When re-regulation is possible, only very severe constraints on ramping (less than 20% of turbine capacity) have an impact on hydropower release decisions.

Releases to the stream match the minimum required during off-peak hours and are higher and fluctuate more during peak hours, even twice turbine capacity when re-regulation is available. These fluctuations can be attributed to the lesser peaks in energy prices during the peak period, requiring the afterbay to be empty before a new peak hour. However, this can also be due to the fact that releases to the stream do not affect the revenues, and therefore several alternative instream flow patterns can yield the same revenue. An extension to this work, which is currently in progress, explores this aspect by introducing penalties to the revenues associated with potentially undesirable instream flow patterns. The most desirable instream flow pattern among those can be identified for the particular needs of the ecosystem of interest.

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