POTENTIAL CHANGES IN HYDROPOWER PRODUCTION FROM GLOBAL CLIMATE CHANGE IN CALIFORNIA AND THE WESTERN UNITED STATES

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ABSTRACT

California relies heavily on hydroelectricity. Depending on hydrologic conditions, hydropower represents between 9 and 30 percent of the electricity used in the state. Much of California's hydropower system is part of a broader multi-use system, with power generation facilities at dams that also serve water supply, flood control, recreation, and other beneficial uses. This is the case for the Pacific Northwest and the Colorado River Basin as well, which also supply hydropower to California. Temperature and precipitation effects from global climate change could alter future hydrologic conditions in the West and, as a result, future hydropower generation. To determine how hydropower generation could change, the existing hydropower infrastructure and generation for California, the Pacific Northwest, and the Colorado River Basin were delineated. Climate change studies were reviewed to establish a range of future hydrologic scenarios. These scenarios were then used to determine hydro-power generation impacts on key watersheds in the state. Plan-ning documents and integrated resource plans for the major hydro producers and energy planning agencies were reviewed to determine whether global climate change effects are being considered in future plans. Finally, sea rise and storm surge effects on California coastal power plant operations were evaluated.

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CHAPTER 1 INTRODUCTION AND FINDINGS

The California Energy Commission (Energy Commission) is sponsoring an aggressive level of research into the effects of climate change, as well as taking a leading role in developing strategies to reduce greenhouse gas emissions. These efforts, as well as other statewide studies, have been summarized in two recent Energy Commission reports prepared in support of the *2005 Integrated Energy Policy Report*. The first report, “Climate Change Impacts and Adaptation in California” summarizes the scientific literature and provides a brief overview of the relevant research agenda. The second report, “Global Climate Change” provides background and context to guide the formulation of policy options for reducing greenhouse gas emissions in California. This third report looks at the potential impact of climate change to hydropower operations, as well as impacts to coastal power plants.

California relies heavily on hydroelectricity. On average, hydropower provides 15 percent of the electricity used in the state, although historically this can range from 9 to 30 percent depending on hydrologic conditions. Hydropower’s ability to be dispatched quickly on hot summer afternoons to meet peak load, its low cost, and near-zero emissions are particularly valuable characteristics.

Much of California’s hydropower system is part of a broader multi-use system, with power generation facilities at dams that also serve water supply, flood control, recreation, and other beneficial uses. This is the case for the Pacific Northwest and the Colorado River Basin as well, which also supply hydropower to California. As a result, hydropower production may be preempted by other needs.

In light of California’s dependence on hydropower, the integrated role hydropower plays in complex water systems, and the potential changes to the hydrology of the Western region from climate change, Energy Commission staff are particularly interested in addressing the following questions:

- How will climate change affect those hydrologic parameters critical to hydropower production?
- Is the state of the science sufficient to predict with any level of certainty how hydropower production may change in the future?
- Are there key watersheds that are especially important in terms of hydropower generation, and also especially vulnerable to climate change effects?
- Since California depends on hydropower imports from both the Pacific Northwest and the Colorado River Basin, are the effects of climate change the same in those areas, and how could climate change impact the delivery of hydropower to California?
- Would climate change increase the “competition” between hydropower production and flood control and water supply operations?

- Are entities responsible for the planning, operating, and delivery of hydropower incorporating climate change effects in current or future plans?

- Would sea level rise and increases in storm intensity and/or frequency affect coastal power plants?

Report Organization

In addressing these questions, this report relies on those scientific studies that deal with critical hydrologic parameters and/or specifically identify future changes to hydropower production. It also draws from extensive discussions with hydropower planning, operating, and delivery entities. In addition, staff conducted its own analysis of how specific scenarios might affect key hydro producing watersheds based on the data derived from the studies and discussions.

The report summarizes the hydropower production infrastructure and generation for California, the Pacific Northwest, and the Colorado River Basin. It reviews and summarizes climate change studies which address hydrologic parameters critical to hydropower production, and those studies which have specifically evaluated future hydropower impacts. The report also discusses the state of the science and the uncertainties inherent in predicting future changes. This information is used to establish a range of future global climate change scenarios for assessing hydropower production impacts. The effects of these scenarios on key California hydropower producing watersheds are evaluated. The report then discusses to what extent global climate change effects have been incorporated in planning documents and integrated resource plans for the major hydro producers and energy planning agencies. Finally, potential climate change effects such as sea rise and storm surges on California coastal power plant operations are identified.

Findings

Review of critical climate change studies, a more detailed analysis of climate change effects on specific watersheds, and extensive interviews with hydropower planning and operating entities yielded the following findings.

PIER Program Studies Provide Some Key Insights into Potential Climate Change Scenarios: The studies being conducted under the Public Interest Energy Research (PIER) program provide a comprehensive database for the current and future evaluation of the effects of global climate change on California water and energy supplies.

Key Hydrologic Parameters Will Vary Based on Temperature and Precipitation: The key hydrologic parameters associated with hydropower production are snowfall (especially the snow elevation level); snowpack changes in volume, timing, and density; and snowmelt and unimpaired runoff. The factors determining how these parameters might vary into the future are temperature rise and precipitation (for example, will it be wetter or drier in the future?).

California Is in a Warming Trend: California is experiencing a warming trend; both maximum and minimum temperatures are increasing on a statewide basis. Summer and fall nighttime warming is more pronounced, which could affect air conditioning demands during the night. Temperature is expected to continue to rise.

Climate Change Studies Provide Only Broad Trends: Typically they are global or at best regional, vary in terms of the greenhouse gas scenarios used, and vary as to time periods and geographic focus. The attributes of climate change studies make study comparisons and planning at the watershed or facility level difficult. Coupled with the inherent variability of California's climate, only broad trends in future climate change can be safely assumed from the current studies. PIER is funding further research to explore both the implications of this range and to attempt to better focus the range of estimates.

Precipitation Projections Vary Widely: The available climate change scenarios reveal an extremely wide range of potential variations in Western United States precipitation and runoff. In the wettest scenario, average runoff in California could increase by 77 percent; in the driest, it could decrease by 25 percent.

Higher Temperatures Will Change Snowfall and Runoff Characteristics: Climate change models indicate that higher temperatures could lead to significant changes in snowfall and timing of snowmelt in watersheds now receiving substantial snow. These changes include: an increase in the ratio of rain to snow; a delayed onset of the snow season; a shortened overall snowfall season; an accelerated rate of spring snowmelt; and more rapid and earlier runoff. Runoff would be reduced in spring and summer, and increased in winter. For very high elevation sites, these changes tend to be less significant, since the rain-to-snow ratios are not affected.

Hydropower Production Will Change Based on Future Hydrology: Future hydrological patterns will be different in the future regardless of any other climatic changes. However, climate change is more likely to change hydrology more dramatically. The increase in runoff in winter, and the reduction in summer would correspondingly increase and reduce hydropower production during those times; the hydropower increase would be at a time when demand related to space heating (particularly in the Pacific Northwest) would be decreased due to the warmer temperatures, and the decrease would be during the period when demand would be greater due to increased air conditioning load in California and the Southwest.

Water Diversions May Reduce Hydropower Production: Earlier snowmelts, particularly if coupled with heavy stream flows, could result in water being diverted from hydropower facilities to avoid damage and released from reservoirs to avoid flooding. The already existing conflict between water supply, flood control, and hydropower production would likely be exacerbated under climate change conditions.

Geography and Elevation Will Affect Hydropower Production: California's hydropower capacity is not distributed in the same manner as its water storage capacity, either geographically or by elevation. While the vast majority of storage is located below 1,000 feet, 38 percent of generating capacity and 41 percent of average annual energy comes from facilities located above 2,000 feet. This disparity in distributions implies that the state's hydropower availability may be affected differently than its water supply by potential climate changes.

PIER Study Scenarios Bracket Potential Hydropower Changes. Two scenarios were chosen to reflect the bounding cases on the range of possibilities from two major global climate change models, one being for the very wet HadCM2 (HCM) model and the other, for the very dry PCM model.

Some California Basins Are More Critical Than Others: Hydropower generation in four major river basins are likely to be the most affected by climate changes—the Sacramento, Feather, American and San Joaquin. These rivers generally have a large volume of hydropower generation relative to storage capabilities and projected runoff changes are large relative to storage. This means that the absolute changes in hydropower output would be larger from these river basins than the others. For this reason, further analysis of potential impacts on these river basins is warranted using more complex water system models that specifically incorporate the upper elevations of these basins.

Currently, the existing water system models such as CALSIM II and CALVIN focus almost exclusively on water supply and look at hydropower only as an adjunct function of water storage reservoirs. These models largely ignore the river systems above the major valley-floor reservoirs where the majority of hydropower capacity is installed. The types of models that should be used include those developed for the Pacific Gas and Electric hydropower divestiture environmental impact report for the California Public Utilities Commission (A.99-09-053).

Comparisons Across Regions Are Not Yet Possible Due to the Lack of Comprehensive Modeling: While preliminary results show that the Columbia River Basin may experience less variability than California, and that the Colorado River Basin may experience more, the respective modeling exercises have not been fully calibrated with each other in a manner that allows direct comparison. Such analysis is a necessary next step in looking at potential effects in the West.

Climate Change Is Not Typically Considered in Hydropower Plans: Almost no hydropower planning or operating entities currently incorporate climate change effects in future planning documents, and few changes in operation are underway or anticipated. However, most organizations are tracking the science; their involvement seems to depend on how critical the hydropower resource is to them. The two investor-owned utilities in California with significant hydropower resources are very involved in current research, whereas operators of water systems where water supply and flood control are primary objectives are not as focused on climate change.

The Reasons for Lack of Inclusion Vary: The uncertainties surrounding the science appear to be a major factor limiting incorporation of future climate change effects. In addition, many operators indicated that their current systems are already designed to manage a highly variable water resource, and no near-term changes to facilities are expected. The Pacific Northwest is actively addressing climate change, and the Colorado River Basin less so, again reflecting the energy focus of the Northwest and the water supply focus of the Colorado River Basin.

Climate Change Effects to Coastal Plants Are Limited: Climate change effects may include increased storm frequencies and intensities. These changes are not expected to impact coastal power plants with the exception of Diablo Canyon Power Plant. This facility currently must reduce power when storm debris enters the water intake system, and increased storm events would increase the frequency and duration of power reductions.

CHAPTER 2 HYDROPOWER INFRASTRUCTURE

Hydropower is a major component of California's electricity supply. An understanding of the operations of current hydroelectric facilities is important for identifying the range of potential changes to hydroelectric operations in the Western U.S. that might result from possible climate changes. This section provides a baseline summary related to the hydropower infrastructure that exists in California, the Pacific Northwest, and the Lower Colorado River Basin.

California

A vast inventory of hydroelectric power plants currently exists in California, distributed broadly throughout the state's watersheds and aqueduct systems. The combined total hydroelectric capacity in California is over 14,000 megawatts (MW).[1] This represents about one-quarter of the in-state generation capacity. Hydro-generated energy was about 29,000 gigawatt-hours (GWh), or 13 percent of the in-state generation in 2004, but due to its use predominantly during on-peak periods, hydropower's value outweighs its simple energy contribution.

Of the 14,000 MW of hydropower capacity, approximately 36 percent is controlled by investor-owned utilities (for example, Pacific Gas & Electric and Southern California Edison); approximately 27 percent is controlled by water project operators (for example, the U.S. Bureau of Reclamation's Central Valley Project and Department of Water Resources' State Water Project);and approximately 35 percent is owned by municipalities, such as the Los Angeles Department of Water and Power and the San Francisco Public Utilities Commission, with remaining hydropower capacity owned by irrigation districts and other entities.[2] Power plants with the most capacity in California exist along large river systems such as the Pit, Mokelumne, American, Feather, Stanislaus, and San Joaquin; other medium to small sized plants are distributed throughout the state.

Hydropower can provide peaking reserve capacity as well as load following capacity. Most dams with hydroelectric generation capacity, particularly those with large reservoirs, serve multiple purposes that include power generation, water supply, and flood control. Generally, investor-owned utilities hydropower projects' primary purpose is power generation, while ancillary water supply, flood control, and recreation benefits are also created. These facilities tend to be higher in the Sierra and Cascade watersheds and are managed and dispatched to meet load. For the State Water Project and the federal Central Valley Project, the primary purposes are water supply and flood control; power is generated as an ancillary function as the water is pumped and distributed throughout the system. These hydro facilities, along with those belonging to municipal and irrigation districts tend to be located at lower foothill elevations.

Hydropower in California is categorized as storage, or "pondage", pumped storage, and run-of-river. Storage and pumped storage are particularly valuable for meeting peak demands and maintaining system reliability because water releases can be timed to coincide with peak power demands. The state's major pumped storage projects include the 1,212 MW Helms Project owned by Pacific Gas and Electric, the 1,495 MW Castaic Project which is part of the Los Angeles Department of Water and Power, three smaller projects owned by the Department of Water Resources which collectively provide 1,082 MW, and several smaller facilities.

Storage plants typically generate energy throughout the spring snowmelt or runoff season and on through the summer until minimum reservoir pools are reached. Low-volume, high head plants that produce large amounts of energy with relatively small amounts of water typify this part of the state's hydropower system. Water is channeled from high elevation reservoirs down steep penstocks over vertical drops of hundreds of feet. This system contrasts with the low head, high capacity powerhouses on the Columbia and Snake Rivers that typify hydropower in the Pacific Northwest.

Run-of-river is the most variable of the three hydro categories. Hydroelectricity production from these units varies in direct proportion to the seasonal and annual hydrology. The highest run-of-river production occurs during spring snowpack melt and run-off.

One concern about potential climate change is that along with a general warming, the precipitation and snowmelt patterns may change. The lack of a clear relationship between temperature and precipitation patterns adds more uncertainty about hydropower production on top of the uncertainty about temperature trends. The analysis presented here is intended to help establish (along with the climate change information presented in the next section) the range of possible runoff scenarios to identify what further analysis might assist policymakers and system designers to adapt to these potential changes. Establishing such a range of possibilities can help determine the "option value," (the value of choosing a certain action at a point in time) for various policy choices.

A discussion of the potential effects of global climate change is facilitated by the presentation of hydroelectric infrastructure baseline data by elevation range: hydrologic changes that may occur as a result of global climate change would likely be sensitive to differences in elevation. Table A-1 (presented in Appendix A) presents a summary of hydropower capacity and usable reservoir storage data by elevation range[3] and river basin.[4] As the effects of climate change likely will vary by both geographic area and elevation, Table A-2 (also in Appendix A) presents a summary of the average annual California hydropower energy production by watershed. The data presented in the tables draw from the Energy Commission's Hydroelectric Power Plant Inventory database.[5] The tables provide a compilation of hydroelectric data for over 120 hydropower plants that was provided by various hydroelectric generators in 2003. The tables include data for facilities with generation capacity of at least one MW.

The information provided in Table A-1 is meant to provide only a general understanding of the existing hydroelectric infrastructure setting in California; it should not be relied upon for detailed technical studies or evaluations. The rivers with the largest nameplate capacity are the following (note that the Sacramento River includes the Pit River system):

- American River: 1,158 MW
- Feather River: 1,661 MW
- Kings River: 1,609 MW
- Sacramento River: 1,506 MW
- San Joaquin River: 1,089 MW
- Stanislaus River: 724 MW

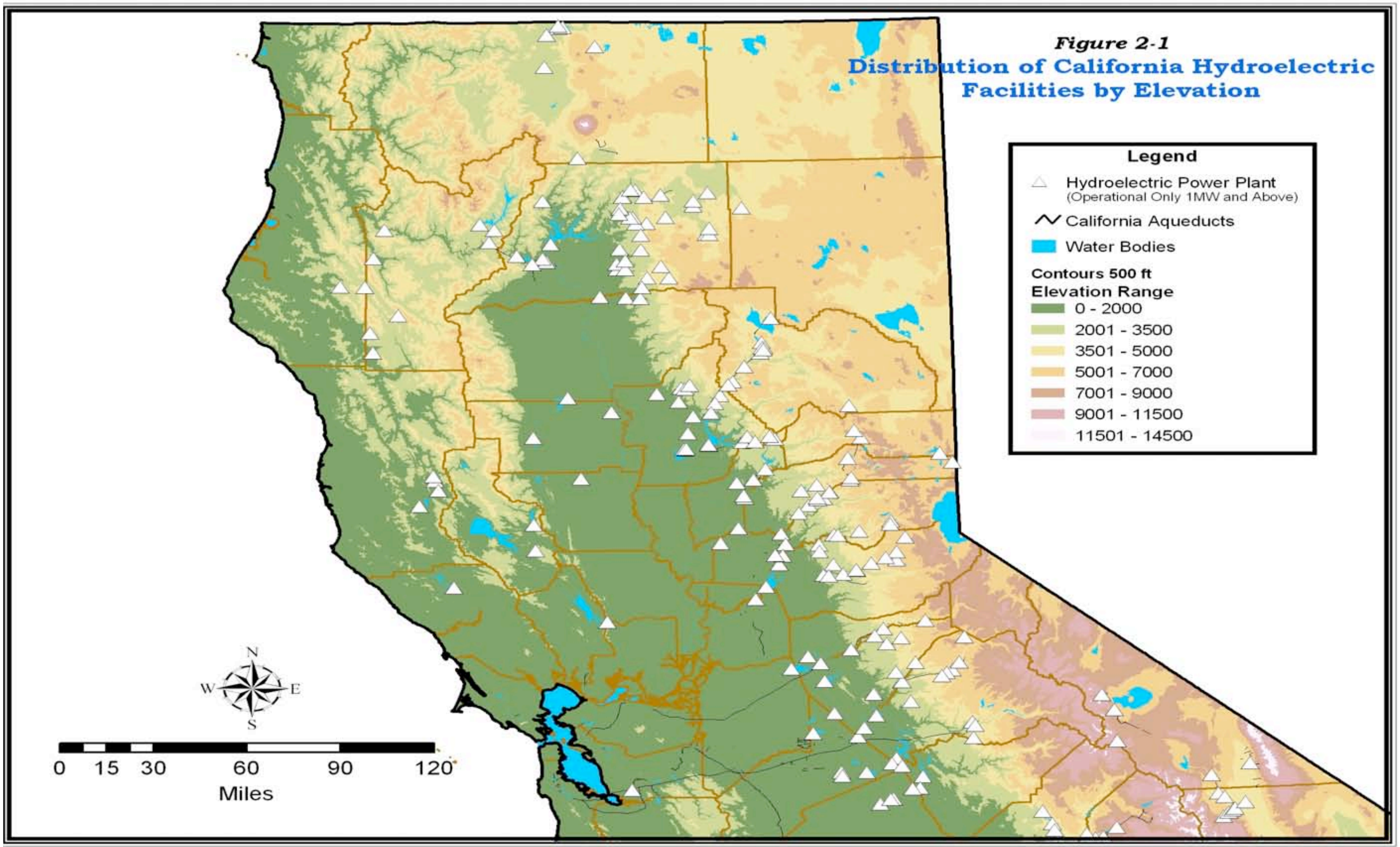
Capacity data are presented in terms of nameplate capacity and dependable capacity. The nameplate capacity refers to the equipment rating of the power plant. In simple terms, it is the generation capacity of a power plant established under standard conditions by the manufacturer. The actual rating can vary by location and usage. Due to the high hydraulic heads on many of California's penstocks, the actual output for these units often significantly exceed the nameplate ratings. Dependable capacity refers to the capacity that can be relied upon for a specified time interval during the peak load period of the relevant electricity system. For California, the dependable capacity is measured during August when the system peak occurs most often. Dependable capacity definitions vary by utility, but it is the utility reported data that are shown here.[6]

As identified in Table A-2 in Appendix A, the rivers with largest annual production are as follows:

- American River: 2,771 GWh
- Feather River: 5,533 GWh
- Kings River: 1,483 GWh
- Sacramento River: 5,779 GWh
- San Joaquin River: 4,076 GWh
- Stanislaus River: 1,938 GWh

Figure 2-1 illustrates the elevations and locations of hydroelectric facilities in California.

Figure 2-1:Distribution of California Hydroelectric Facilities by Elevation



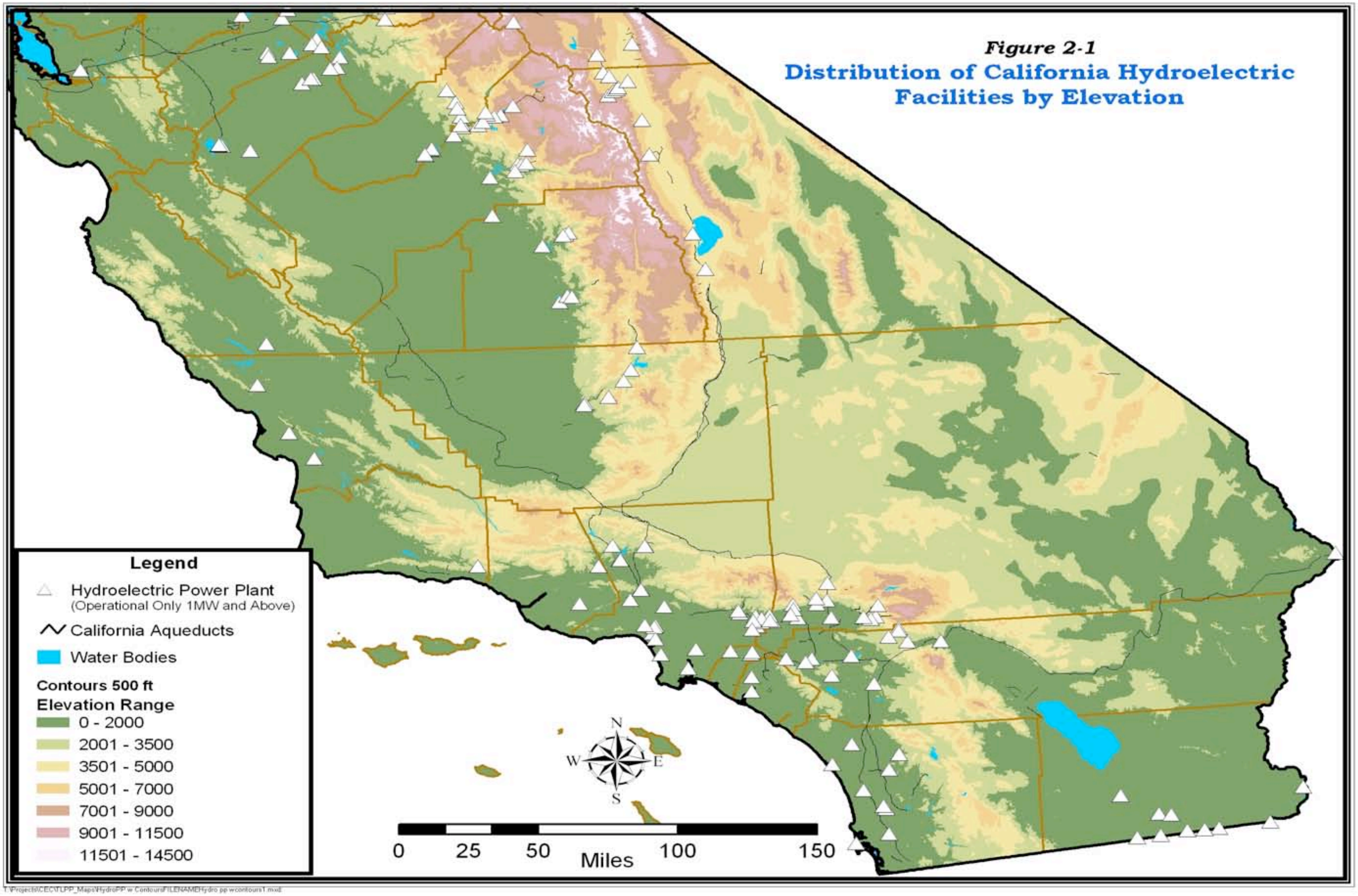


Figure 2-1
Distribution of California Hydroelectric Facilities by Elevation
Legend
Hydroelectric Power Plant
(Operational Only 1MW and Above)
California Aqueducts
Water Bodies
Contours 500 ft
Elevation Range
0 - 2000
2001 - 3500
3501 - 5000
5001 - 7000
7001 - 9000
9001 - 11500
11501 - 14500
0
25
50
Miles
100
150
N
S
E
W

Pacific Northwest

Pacific Northwest hydropower is an important source of power for California because surplus hydropower from the region is often sold to the state. Hydropower imports from the Pacific Northwest provide between 4,000 to 7,000 MW of power to California on high load days.[8] The region produces an immense amount of hydropower. The Pacific Northwest relies on local hydropower for approximately two-thirds of its electricity requirements, and approximately 40 percent of all hydropower in the United States comes from the region.[9] The U.S. Bureau of Reclamation (USBR), U.S. Army Corps of Engineers (USACE), Grant County Public Utility District No. 2, Chelan County Public Utility District No. 1, Douglas County Public Utility District No. 1, City of Seattle (City Light), and the Idaho Power Company are the primary hydropower operators in the region.

Table 2-1 provides a summary of the existing nameplate capacity of major hydroelectric facilities in the Pacific Northwest by river watershed. As conveyed in the table, the Columbia River provides by far the most hydropower capacity in the Pacific Northwest. For the purpose of this report, only data from Oregon, Washington, and Idaho hydroelectric power plants are included in the table.[10]

Table 2-1 Capacity of Major Facilities in the Pacific Northwest

River Watershed	Nameplate Capacity (MW)
South Fork, Boise River	40.0
Columbia River	19,181
Pend Oreille River	1,050*
Snake River	4,200
Clearwater River (North Fork)	400

*Indicates maximum capacity.
Source: NWPCC.[11]

Lower Colorado River

Hydroelectric energy produced on the Colorado River is available to the Western United States, including California; Hoover Dam provides 626 MW to California.[12] The USBR operates Glen Canyon, Hoover, and Davis, which are the major hydropower plants along the Lower Colorado River.

Table 2-2 provides a summary of the nameplate capacity, generation, and storage of the three main hydroelectric power plants along the Lower Colorado River. For the purposes of this study, the Lower Colorado River extends up to the Glen Canyon Power Plant, which is sometimes characterized within the Upper Colorado River watershed.[13]

Table 2-2 Capacity, Generation, and Storage Along the Lower Colorado River

Plant	Nameplate Capacity (MW)	Generation for FY 2004 (GWh)	Total Storage (acre-ft)
Glen Canyon	1,296.0	3,320.2	27,000,000
Hoover	2,078.8	4,020.7	28,537,000
Davis	251.3	1,168.8	1,818,300

Source: USBR.[14]

CHAPTER 3 REVIEW OF CLIMATE CHANGE STUDIES

Extensive research is ongoing regarding the projected effects of climate change. Much of the work specific to California has been sponsored by the California Energy Commission through the Public Interest Energy Research (PIER) program.

This section provides a review of the Energy Commission's efforts to identify climate change effects on the state's water and energy resources and studies by other entities that provide additional detail on site-specific effects within the state. Particular focus is directed to those scientific studies that deal with critical hydrologic parameters and/or specifically identify future changes to hydropower. Because California also relies substantially on hydropower generated out of state, this section identifies the potential effects of global climate change on watersheds in the Pacific Northwest and the Colorado Basin.

Climate Change Research on Hydrologic Parameters and Hydropower Production in California

A number of key reports form the basis for the analysis in this section.
In addition to the two Energy Commission reports highlighted at the beginning of this report, other particularly salient Energy Commission reports include:

- "Climate Change and California Water Resources: A Survey and Summary of the Literature".[15] This 2003 report reviews over 150 articles and identifies the consequences of climate change for water resources and water systems in California.
- "Global Climate Change in California: Potential Implications for Ecosystems, Health and the Economy."[16] This report, also prepared in 2003, evaluates climate change in the context of increased populations, economic growth, and technological change. Multiple climate change scenarios were modeled. Sixteen appendices by researchers throughout the state provide supporting material; selected studies are discussed further below.
- "The Effects of Global Climate Change on California Water Resources."[17] As part of the PIER Climate Change Research Plan produced in 2002, background information on climate change effects is provided in order to shape research needs.
- "From Climate-Change Spaghetti to Climate-Change Distributions for 21st Century California."[18] This 2005 report, updated from its initial distribution as a PIER document in 2004, evaluates the various modeling scenarios to determine if basic projections can be made in light of multiple layers of uncertainties.

In addition to these reports, more than 150 peer-reviewed scientific articles on climate and water in California have been published. Many of these reports and articles discuss the application of General Circulation Models (GCMs) to determine water-related effects of increases in ambient temperature due to global warming. GCMs are used to look at large-scale changes in climate parameters. Because of their global nature, GCMs are often supplemented with regional models that are more able to identify changes on a localized basis. Due to the very large scale of these models (both global and even regional), the results cannot be automatically attributed to a specific watershed, which makes planning at the watershed or facility level difficult at this time.

Study uncertainties and the inherently variable nature of climate compound the problem. Climate change studies vary in terms of which greenhouse gas emissions scenarios are considered, what models are used (for example, there are multiple GCMs), the scale of the model (global, regional, local), the time periods examined, and the geographical area. This hampers comparisons of study results. Also, uncertainties abound, especially relating to what emissions scenario can be expected at future timeframes; the aggressiveness of emission reduction strategies would certainly play a role here. Finally, California's climate is inherently variable.

With these caveats, presented here are the key studies providing information on hydrologic parameters and hydropower production in California.

As part of the report "Global Climate Change in California: Potential Implications for Ecosystems, Health, and the Economy," the possible effects of climate change on the long-term performance and management of California's water system were evaluated. Twelve different climate warming scenarios were examined to determine the change in the amount of water available to the California water system. Six of these scenarios were different combinations of changes in temperature and precipitation. Six scenarios were from two widely used GCMs which could produce more extreme scenarios (the particular PCM version being drier and less warm, and the HADCM2 model being warmer and wetter).

These scenarios were used to evaluate inflows to the overall water system. Mountain rim inflows, which represent 72 percent of inflows to the system and would be the major source for hydropower, were one of four inflow components analyzed. The others - local accretions to surface water, groundwater recharge, and reservoir evaporation - are less critical to hydropower operations. Streamflow and snowmelt were also evaluated.

Mountain Rim Runoff: Estimates of changes in rim inflow were based on Lawrence Berkeley National Laboratory (LBNL) studies of six index basins which represent a range of snowmelt- and rainfall-dominated catchments: Smith River at Jed Smith State Park, Sacramento River at Delta, Feather River at Oroville Dam, American River at North Fork Dam, Merced River at Pohono Bridge, and Kings River at Pine Flat Dam. The results from these six basins were then used to develop rim inflows for each of 37 major inflows to California's water supply system. These 37 inflows were ultimately used in the CALVIN model, which was used to evaluate the effect of climate change on water operations.

LBNL found that for most cases, inflows were greater with climate warming, driven by accompanying precipitation increases. Except for the very wet HadCM2 GCM results, the increases in annual runoff occurred only during the wet winter months (October through

March). For all scenarios, a larger proportion of the annual streamflow volume occurs earlier in the year because of fewer freezing days during the winter months. The amount and timing depends on the portion of drainage above the elevation of the freezing line.

Snowpack and Snowmelt: These parameters were assessed by Miller, Bashford, and Strem in their evaluation of how climate change might affect a representative set of rivers in California.[19] Using the same six major watersheds identified, the Miller et al. study found that the sensitivity of snowmelt to temperature increases depended on how many degrees the baseline temperature was below freezing. The high elevation Kings and Merced basins were less sensitive to small temperature increases. The snow-to-rain ratios varied significantly with latitude and most importantly with the level of the lower and upper basins. Both the HadCM2 and PCM model projections showed a significant reduction of the snow-to-rain ratio. The snow water equivalent (SWE, or the depth of water the snowpack would produce if melted) decreased for most basins, except for the very high Kings basin. Peak snowmelt month was earlier for the low-elevation basins and remained unchanged for the high ones. With the exception of the Kings basin, SWE decreased as temperature increased. For all cases, there were fewer freezing days during peak snowpack storage months with climate change than in the present.

Hayhoe et al.[20] used the HadCM3 and PCM GCMs in conjunction with two greenhouse gas emissions scenarios, one lower (B1) and one higher (A1fi) to evaluate change in hydrologic parameters. These two scenarios reflect emissions pathways that could result from aggressive greenhouse gas emissions (low end-B1) and from pathways that would result in the absence of aggressive reductions (high end-A1fi). By the end of the century, projected temperature increases under A1fi are nearly twice those under B1. The resulting combinations reflect extreme ends of the spectrum as to what could occur under future climate change conditions.

Inflows to seven major dams and reservoirs in the Sacramento-San Joaquin water system were evaluated. These included three in the northern Sierra (Shasta, Oroville, and Folsom) and four in the Southern Sierra (New Melones, New Don Pedro, Lake McClure, and Pine Flat). None are at particularly high elevation.

Results from Table 3-1 indicate that rising temperatures produce substantial reductions in snowpack in the Sierra Nevada. The table clearly shows how SWE is affected more at lower elevations; reductions are more pronounced at elevations below 3,000 meters (or 9,840 feet). Results from the HadCM3 model, coupled with the high emissions scenario reductions, showed the greatest change in snowpack SWE, which would be expected since they represent the more extreme case. All changes were greater in the latter part of the century.

The Hayhoe study also found that under this more extreme case, warmer temperatures brought about by the high emissions scenario (A1fi) and more precipitation falling as rain as a result of the wetter HadCM3 GCM cause snowmelt runoff to shift earlier under all simulations. Stream inflows decline because of diminished snowpack and increased evaporation.

Table 3-1 Summary of Midcentury (2020–2049) and End-of-Century (2070–2099) Climate and Impact Projections for the HadCM3 and PCM B1 and A1fi Scenarios

		1961 to 1990	2020-2049				2070-2099			
			PCM		HadCM3		PCM		HadCM3	
	Units		B1	A1fi	B1	A1fi	B1	A1fi	B1	A1fi
Change in April 1 snowpack SWE										
1,000-2,000 m elevation	%	3.6 km^3	–60	–56	–58	–66	–65	–95	–87	–97
2,000-3,000 m elevation	%	6.5 km^3	–34	–34	–24	–36	–22	–73	–75	–93
3,000-4,000 m elevation	%	2.3 km^3	–11	–15	4	–16	15	–33	–48	–68
All elevations	%	12.4 km^3	–38	–37	–26	–40	–29	–73	–72	–89
Change in annual reservoir inflow*										
Total	%	21.7 km^3	–18	–22	5	–10	12	–29	–24	–30
Northern Sierra	%	15.2 km^3	–19	–22	3	–9	9	–29	–20	–24
Southern Sierra	%	6.5 km^3	–16	–23	10	–14	17	–30	–33	–43
Change in April-June reservoir inflow*										
Total	%	9.1 km^3	–20	–24	–11	–19	–1	–46	–41	–54
Northern Sierra	%	5.5 km^3	–21	–24	–16	–19	–6	–45	–34	–47
Southern Sierra	%	3.6 km^3	–18	–24	–2	–19	5	–47	–52	–65

SWE = snow water equivalent.

* Results are for inflows to seven major dams and reservoirs in the Sacramento–San Joaquin water system, including three in the Northern Sierra (Shasta, Oroville, and Folsom) and four in the Southern Sierra (New Melones, New Don Pedro, Lake McClure, and Pine Flat).

Water storage volume is reflected as cubic kilometers (km^3). 1 m^3 x 0.0008107 is an acre-foot; for example, 3.6 km^3 is 2.92 acre-feet.

Source: Hayhoe et al.

Many of the climate change studies, including those discussed above, use emission scenarios and models that tend to produce more extreme, outlier results. Dettinger has reevaluated studies where multiple scenarios (combination of emissions projections and particular GCM used) have projected certain trends, but with significant deviation by outlier projections. He terms the figures depicting these results as “spaghetti,” and by using projection-distribution functions, changes the spaghetti into more realistic distributions. His results suggest that temperatures will warm but precipitation will change very little overall, and that the warmest projections tend to yield a moderately drier California while the cooler projections yield a somewhat wetter future.

Studies on Changes in Hydropower Production

A number of climate change studies have directly addressed hydropower production. The Energy Commission lists 386 licensed hydropower facilities in the state, ranging from the 1,495 MW Castaic pumped-storage facility to local facilities of less than 100 kW. Most of the facilities that capitalize on falling water from mountain runoff are located in Northern California and the Sierra Nevada and Coast mountain ranges. Most of the larger storage facilities are located at lower elevations. However, much of the generation capacity is located at higher elevations.

Since most of the studies that have evaluated hydropower have done so as part of a broader water supply focus, they have tended to look at systems that are at lower elevations. To put this in context, Table 3-2 shows the types of hydropower facilities in California and their primary purpose.

Table 3-2 Types of Hydropower Facilities in California

Owner Type	Owner	Capacity (MW)	Primary purpose
Investor-Owned Utilities	PG&E	3,896	Power generation
	SCE	1,163	Power generation
Water Projects	Central Valley Project (USBR)	2,355	Water supply, flood control
	State Water Project (DWR)	1,520	Water supply, flood control
Municipal Utilities	Los Angeles DWP	1,761	Water supply, power generation
	Sacramento MUD	688	Power generation, recreation
	San Francisco PUC	385	Power generation
	Other Municipal Utilities	513	Water supply
Water Districts	multiple	921	Water supply
Irrigation Districts	multiple	704	Water supply
Others	multiple	210	

Hydropower production was evaluated as part of the CALVIN modeling effort referenced above. Figure 2 below presents monthly hydropower generation from California's major reservoirs under various climate modeling scenarios. Using the mountain rim inflows developed by LBNL and the streamflow data from Miller et al., Lund et al.[21] calculated statewide changes in runoff. The CALVIN model was used with several statewide scenarios to evaluate climate changes with and without population growth and adaptation of the water system. Changes to hydropower production were included in the evaluation. The five modeled scenarios include:

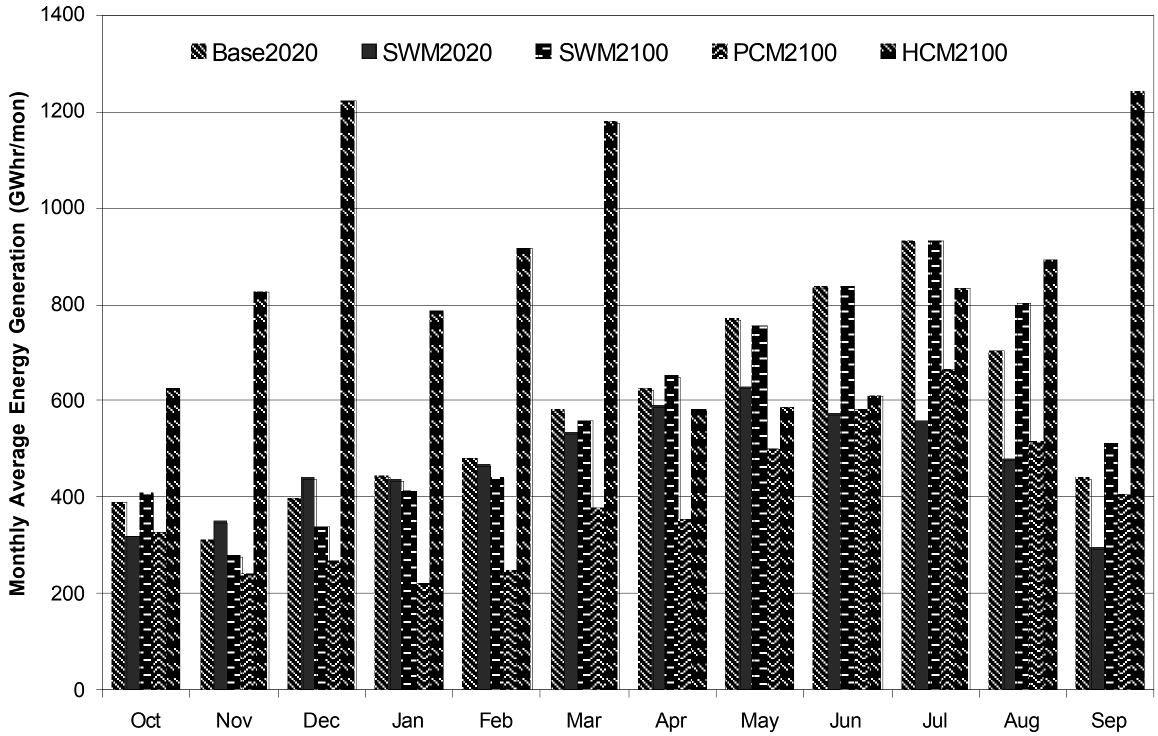
- **Base 2020**: Uses water supply operations and allocations in 2020 under current operating practices and using historical climate data.
- **SWM 2020**: Uses historical climate but optimizes operation in 2020 in response to allocations.
- **SWM 2100**: Uses historical climate but extends the model to 2100.
- **PCM 2100**: Uses the same 2100 water demands as SWM 2100 but uses the dry and warm PCM 2100 climate warming hydrology.

- **HadCM2 2100**: Uses the same 2100 water demands as SWM 2100 but uses the wet and warm HadCM2 2100 climate warming hydrology.

CALVIN hydropower facilities totaled about 6,100 MW of capacity and included those operated as part of the Central Valley Project, State Water Project, and by the Los Angeles Department of Water and Power, the San Francisco Public Utilities Commission and several irrigation districts. Because the CALVIN study focused on water supply, it limited analysis to those facilities that had large water storage reservoirs. As discussed below in further detail, substantial amounts of hydropower capacity is installed at higher elevations which may be more affected by changes in the timing of snowmelt because this generation does not have the storage capacity to retain significantly more water into the summer.

As shown in Figure 3-1, hydropower production was estimated to decrease in the cooler and drier scenario and to increase in the warmer and wetter scenario. Figure 3-1 shows a “base” case, SWM 2100, that assumes an economically-optimal allocation of water supplies that differs from those that would occur under today’s laws, regulations, and allocations. However, the changes in overall generation are not significant based on a comparison of status quo and optimized allocations in 2020, also shown in Figure 3-1. This result is then compared to the two GCM scenarios in 2100. Monthly hydropower energy generation would fall in all months under the drier PCM scenario while under the wetter HCM scenario generation would increase in winter months but decrease in summer months.

Figure 3-1 Monthly Hydropower Generation from Major Reservoirs



Source: Lund et al.

Vanrheenen et al.[22] evaluated hydrologic effects to the Sacramento–San Joaquin River basins from global climate change. The study used PCM simulations for the time periods 2010 to 2039, 2040 to 2069, and 2070 to 2098. This same modeling approach was used by Payne et al.[23] for the Columbia River basin and Christensen et al.[24] for the Colorado River Basin. These two other studies are discussed below.

Snowpack, snowmelt, and streamflow changes in the Sacramento–San Joaquin River basin were consistent with the findings of previous studies. Hydropower production was evaluated for the Central Valley reservoirs associated with the State Water Project (SWP) and the Central Valley Project (CVP). More detail on the SWP and the CVP is presented in subsequent sections. Hydro production (a function of reservoir storage) for this collective system generally decreased with the climate altered hydrologies; for example, Lake Shasta hydro production decreased by 8, 4 and 11 percent, respectively, for the three periods studied.

PG&E owns and operates the nation's largest privately held hydropower system. It includes 68 powerhouses, 110 generating units, and 99 reservoirs with 3,896 MW of generation capacity and 2.3 million acre-feet of storage capacity. These powerhouses are located in California's Sierra Nevada and the southern Cascade range, extending from the Kern River east of Bakersfield, north to the Pit River, with headwater drainage just south of the Oregon border. The system tends to have upper elevation small- and mid-sized reservoirs and high head systems that produce significant MWh per unit of water. An exception is the Lake Almanor reservoir located on the Feather River. Its

1,409 x10^6 m^3 or 1,143,000 acre-feet of storage capacity has approximately ten times the storage capacity compared with PG&E's next largest storage reservoir.

PG&E has examined global climate change effects to its system.[25] Historically, runoff powering these facilities has been derived from aquifer outflow resulting from absorption of rain into porous volcanic rock, such as, the Pit-McCloud Rivers (38 percent), snowpack (37 percent) and rainfall (25 percent). Snowmelt produced runoff has decreased over the last 50 years as compared to 1900-1950. The reduction is attributed to the decreasing trend in the low elevation snowpack, with a corresponding increase in rainfall from lower elevations. The April 1 SWE equivalent for the Lake Spaulding snow course (at 1,609 meter elevation) declined 19 percent from earlier periods, while no significant decline was observed at a nearby snow course at Meadow Lake, 610 m higher in elevation.

The Pit-McCloud and North Fork Feather River Projects, which comprise 55 percent of PG&E's annual hydro production, are both at lower elevation, and a relatively large portion of the total watershed could be affected by a slight elevation shift in freezing weather. However, the Pit-McCloud Rivers benefit from extensive volcanic drainage and would be less affected from a shift in precipitation patterns.

The Feather River, which is the prime summer peaking resource for PG&E, is more reliant on snow melt (less volcanic drainage) but has substantial reservoir capacity at Lake Almanor as noted above. Spills past diversion dams may possibly increase in frequency and quantity in the future. In addition, high runoff events during the winter and early spring can require shut down of the Feather River facilities to prevent facility damage. This is an important finding. An increase in stream flows affects not only the ability of the facility to operate but also, depending on timing, can affect whether water is retained (and used for future hydropower) or released for flood control purposes.

At this time, PG&E's water management team has not observed any significant change in hydroelectric production that could be specifically tied to global climate change, and no significant generation impact is anticipated for the near future.[26] PG&E's systems were designed to accommodate a large wetness variance, and most of its reservoirs are located at mid-to-high elevations, which, as noted previously, could face fewer effects depending on how the snowmelt timing changes by elevation. In contrast, CVP and SWP reservoirs were designed principally for water supply and are sited at lower elevations, which collectively could lead to greater hydropower impacts at those facilities.

Columbia River Basin Global Climate Change Research

About one-third of the hydropower production used by Californians is imported from the Pacific Northwest (including Canada). The Columbia River, a snowmelt-driven river, is the region's primary provider of electricity, with more than 250 reservoirs and 100 hydroelectric plants. Total hydropower capacity on the river system is almost 20,000 MW. The total storage on the river represents 44 percent of the annual average flows, which allows for significant smoothing of interseasonal and interyear variations.

U.S. Global Change Research Program's (USGCRP) publication "Climate Change Impacts on the United States"[27] includes a section addressing the potential consequences of climate variability and climate change for the Pacific Northwest. Over the last 100 years, temperatures in the U.S. Pacific Northwest increased 1 to 3°F (0.6 to 1.7°C), with nearly equal warming in summer and winter. Annual precipitation increased by 11 percent on average, with about a 50 percent increase in northeastern Washington.

In British Columbia, average annual temperatures warmed during the 20th century by 0.6 to 1.7°C, depending on location. Average spring temperatures are warmer than 100 years ago. Precipitation increased by 2 to 4 percent in southern British Columbia.[28]

Projections of Pacific Northwest climate change (through 2100) were presented in the USGCRP report. Using the Canadian Centro model, temperature changed from 1.05 to 5°C (1.9 to 9°F) and using the Hadley-Version 2 model, temperature changed from 0.4 to 2.5°C (0.8 to 4.7°F) for the 20th and 21st century, respectively.

These projections were similar to those projected for British Columbia. By the end of the 21st century, average temperatures in the province will likely be 1 to 4°C higher, depending on the region. Other future impacts may include an increase in annual precipitation by 10 to 20 percent and the disappearance of many small glaciers in southern British Columbia.

USGCRP projected that warmer, wetter winters would likely increase flooding; however, the adequacy of existing management systems on the Columbia River would reduce this threat. Year round warming would increase the risk of summer shortages in both rainfed and snowfed rivers because of smaller snowpack and earlier melt. Modeling also indicated significant recurrent patterns of multi-year variability. Warm years would tend to be dry with less rain and snowpack, and cool years would be wetter, with high streamflow and heavy snowpack.

Reduced summer flows would reduce hydropower, although reliability of firm energy would remain near 100 percent. Using the Hadley model, 100 percent of firm demand could be met in 2020 and 99 percent met in 2090. Non-firm energy production would change from a base case of 94 percent to 98 percent in 2020 and 90 percent in 2090.

The potential effects of climate change on the hydrology and water resources of the Columbia River basin were assessed by Payne et al.[29] Using the same three future scenarios discussed above for the Sacramento–San Joaquin study, climate warming produced a gradual shift toward diminished snowpacks, earlier snowmelt runoff, and reduced summer and fall flows. Lower storage at the end of the summer would reduce the ability of the system to meet present firm hydropower production ("safe yield") during the winter months. In autumn, firm power reliability decreased and sustainable firm power decreased by 3 percent in 2010-2039, 5 percent in 2040-2069, and 7 percent in 2070-2098.

The Northwest Power and Conservation Council (NWPPC) evaluated global climate change in its Fifth Power Plan.[30] The council modeled different warming scenarios to determine the effects on the Columbia River. Although the modeled scenarios differed in projected annual river volume, they showed greater winter period runoff (and subsequent flows) and lower summer runoff. The increase in winter flows would be greater in 2020 than in 2040.

Current annual hydroelectric generation for the Columbia River system is about 16,000 average MW (MWa) or 140,000 GWh (average year) and 11,000 average MW or 96,000 GWh in the driest years. Table 3-3 shows the projected change in annual energy (MW) using the different warming scenarios. The results indicate that any hydropower reductions would be within the normal variation range for existing production.

Table 3-3 Change in Annual Energy (Hydropower Production) (average megawatts)

Year	HC Model Warm and Wet	COMP Model Combination of Model Runs	MPI Model[31] Warm and Dry
2020	1982 MWa	164 MWa	–664 MWa
2040	333 MWa	447 MWa	–2033 MWa

Source: NWPPC, 2005. Historical average is 16,000 MWa.

Increased winter flows and greater hydroelectric production would be a benefit to the Northwest since the greatest demand for electricity is during the winter. However, winter power benefits would be offset by summer problems. The Northwest, which currently has surplus capacity in the summer, may be forced to compete with the Southwest for resources during that period. For California, this would mean that there would be reduced sales of surplus hydroelectric energy available to the state. The report concludes that at some point the Northwest may have to plan for both winter and summer peaks due to expected warmer temperatures. The NWPPC report states that the difference between winter and summer peak loads is getting smaller each year.

Colorado River Basin Global Climate Research

The Colorado River provides water supply, flood control and hydropower to the Southwest through 12 major reservoirs. The largest reservoirs are Lake Mead (formed by Hoover Dam) and Lake Powell (formed by Glen Canyon Dan). Lake Mead is especially sensitive to reduced streamflow and storage. High elevation snowpack in the Rocky Mountains provides over 70 percent of the river's flow. However, the storage capacity in Lakes Mead and Powell represent about three times the annual average flows on the Colorado. This storage tends to even out year-to-year variations, and almost fully mitigates any seasonal fluctuations.

Christensen et al. used scenarios from the PCM analysis, coupled with a macroscale hydrologic model, to assess the sensitivity of the Basin's reservoir system to projected climate changes.[32] This study used future climate ensembles that were also used by Vanrheenen et al. for the Sacramento–San Joaquin River basin and by Payne et al. for the Columbia River basin. Results indicated that precipitation generally decreased for the future scenarios, averaged over the entire basin. Snowpack, reported as snow water equivalent (SWE), decreased by about 30 percent for the future scenarios.

As in California, snow levels remained mostly unchanged in the high elevation Rockies but were reduced in the high plains of western Colorado. Runoff was reduced almost 10 percent which, although appearing low, had major effects on reservoir system performance. Streamflow timing was shifted as a result of earlier spring snowmelt. Future climate scenarios decreased hydropower production by 56, 45, and 53 percent (for the time periods 2010–2039, 2040–2069, and 2070–2098, respectively) compared to simulated historical hydropower. Table 3-4 identifies the climate scenarios and the projected hydrologic effects.

These hydropower reductions are much greater as compared to the California and Pacific Northwest changes, which were evaluated using the same methodology. This is due to the high sensitivity of the Colorado River system where current demands are not much less than mean inflows. Therefore, decreasing the mean inflow even slightly results in substantial degradation of system performance (including hydropower production).

Comparing results from the similar (but not calibrated) studies of California, Columbia River Basin, and Colorado River Basin (see Table 3-4) shows that, for the most part, impacts to hydrologic parameters are fairly similar. However, as noted above, the reduction in hydropower production from the Colorado River Basin is the most significant difference.

Table 3-4 Comparison of Relative Climate Change Impacts for California, the Columbia River Basin, and the Colorado River Basin

	California (Lake Shasta)	Columbia River Basin	Colorado River Basin
Temperature	Warms by 0.5, 1.2, and 1.9 Degrees C	Warms by 0.5, 1.3 and 2.1 Degrees C	Warms by 1.0, 1.7, and 2.4 Degrees C
Precipitation	Winter and spring amounts reduced from 10 to 25%	Decreases by 3%, then increases by 5, 1%	Decreases by 3, 6 and 3%
Snowpack (SWE)	Declines by 26, 38 and 52%	Declines by 22, 23 and 39 %	Declines by 24, 29, and 30%
Runoff	Decreases by 16, 11, and 20%	Decreases by 5, 0 and 3 %	Decreases by 14, 18, and 17%
Hydropower	Decreases by 8, 4, and 11%	Decreases by 7, 5, and 7 %	Decreases by 56, 45, and 53%

Note: Results are shown for the three time periods (2010-2039, 2040-2069, 2070-2098) and are in comparison to historical levels.

CHAPTER 4 RANGE OF CLIMATE SCENARIOS

Due to the uncertainty associated with global climate change, particularly at the regional scale, analyses at best can only identify the range of possibilities rather than develop forecasts with predictions that can be acted upon. The analysis of how climate change may impact California's hydropower resources necessarily falls into this category. It highlights the potential increase in climate variability by examining two scenarios, one in which runoff nearly doubled and another in which runoff was reduced by a quarter on average. No probabilities can yet be attached to either of these scenarios, nor any others that have been developed, so no predictions can be made yet. But results such as these can be used to assess the value of choosing among different resource-planning options that arise from anticipating potential changes that will be required in the state's water supply and generation infrastructure.

Further analysis shows that flood control, hydropower, and water supply decisions could be closely linked as the trade-offs between each become more readily apparent. The increased uncertainty about future conditions may undermine the various "rules" used to operate the facilities to meet these objectives under various conditions. Storage space is maintained through the winter in many reservoirs for flood control purposes, but this rule is contingent on sufficient moisture being stored in the snowpack into the late spring so that the state's water demands can be met. Similarly, hydropower generation is dependent on the late release of snowmelt. If precipitation amounts are more varied or runoff increases in a small period of time, increasing water storage for supply and later power generation will inherently decrease flood protection from these facilities. Reexamining priorities and coordinating policies in these areas, as well as in associated environmental protections, is an important step in accommodating risks associated with future climate change.

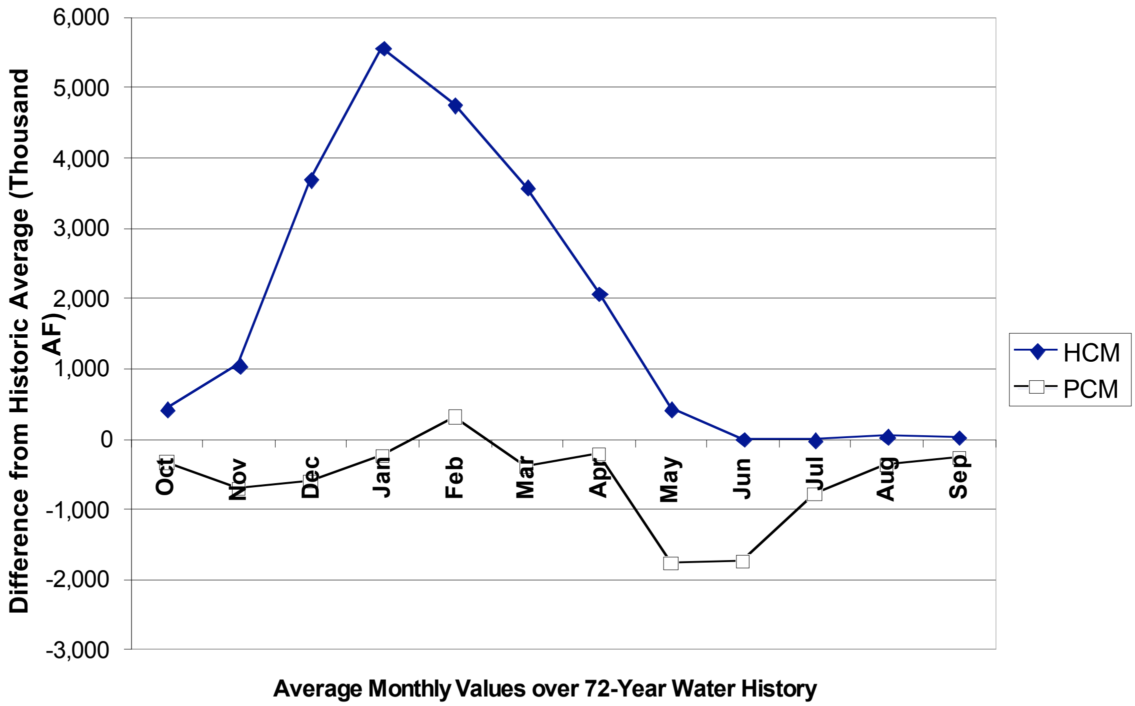
As discussed previously, Lund et al. looked at the potential effects of climate change on the long-term performance and management of California's water system. For the analysis presented below, two scenarios were chosen to reflect the bounding cases on the range of possibilities from two major GCM models, one being for the very wet HadCM2 (HCM) model, and the other for the very dry PCM model. The runoff projections were derived for the year 2100. Further scenarios are under development under PIER contracts to reflect updated model runs, but those were not available for this analysis.

An important missing component in the analyses done to date is to assess how runoff timing and amounts may vary by elevation. As pointed out below, patterns of generation capacity by elevation differ significantly from those for reservoir storage capacity. Since previous studies have focused largely on water supply issues and only tangentially address hydropower, the fact that most of the storage is at the bottom of the river basins has diminished the importance of the elevation distinction. But for hydropower, this is an important question yet to be answered.

Figure 4-1 shows how the monthly rim inflows changed in the two scenarios. Rim inflows represent the portion of flows that produce hydropower. In the HCM scenario inflows increase by 76.5 percent on average compared to the historic 72-year trace from

1922 to 1993 across the basins studied. Note that this increase is commensurate with the difference between a normal year and all but the wettest years historically. Almost 70 percent of the increased flows occur in the December to April period. The increases in January and February are disproportionately higher than the other months, consistent with a warmer climate that accelerates snow melt at lower elevations during the winter. In the PCM scenario, inflows decrease by an average of 25.5 percent. This would bring the average down to what is now considered a dry, but not critically dry, level. The decrease is most pronounced in May and June and there is even a slight increase in the mid winter months. Again, this reflects the accelerated snowmelt that reduces the available snowpack in the late spring.

Figure 4-1 Comparison of Northern California Runoff Change for Year 2100 GCM Scenarios: HCM (Wet) vs. PCM (Dry)



In both of these scenarios, the increased winter flows and relatively decreased spring and summer flows could have significant impacts on the state's hydropower infrastructure. Currently, the snowpack stores the large amounts of precipitation that arrives during the winter and slowly releases it to streams and aquifers during the late spring and summer. The effect is that the snowpack acts as an above-ground reservoir that releases water at a fairly constant, predictable rate during the period when hydropower is most valuable to California. The utilities' smaller surface reservoirs act not as seasonal carry over storage, but rather as regulating reservoirs for releases from the snowpack. A decreased snowpack going into the spring would mean that the "reservoir" of snow that the state has counted on to provide water for hydropower during the summer could be depleted earlier than under the conditions for which the system was originally designed. As a result, less hydropower would be available to meet peak load demands during July and August. The increased winter flows also imply that increased flooding could be an issue. If the existing reservoirs are used for flood protection rather than water retention and the flood control space is increased, they will more likely be further diminished going into the summer as the probability of fully refilling will decrease. In the dry PCM scenario, the accelerated runoff in March and April could accentuate this condition by making it more difficult to retain sufficient flows to carry over through May and June into the peak load season. This situation highlights the importance of coordinating flood control, hydropower, and water supply policies going into this period of increased uncertainty.

CHAPTER 5 CLIMATE CHANGE EFFECTS ON SELECTED KEY HYDROPOWER WATERSHEDS

The effects from climate change may not be evenly distributed. The changes in flows may vary both across geography and by elevation. If snowmelt occurs earlier at higher elevations, facilities that rely on the snowpack as an effective reservoir for spring and summer flows will see those flows diminished. The result would be reduced summertime hydropower availability.

Figure 5-1 shows the usable reservoir storage capacity statewide segmented by elevation. The vast majority of the capacity, over 17 million acre-feet (MAF), is situated below 1,000 feet. This dwarfs the amount of capacity at higher elevations. The lower capacity is used for water storage and flood control, and was not constructed to maximize hydropower output as its first objective.

Figure 5-1 Usable Reservoir Capacity by Elevation Segments

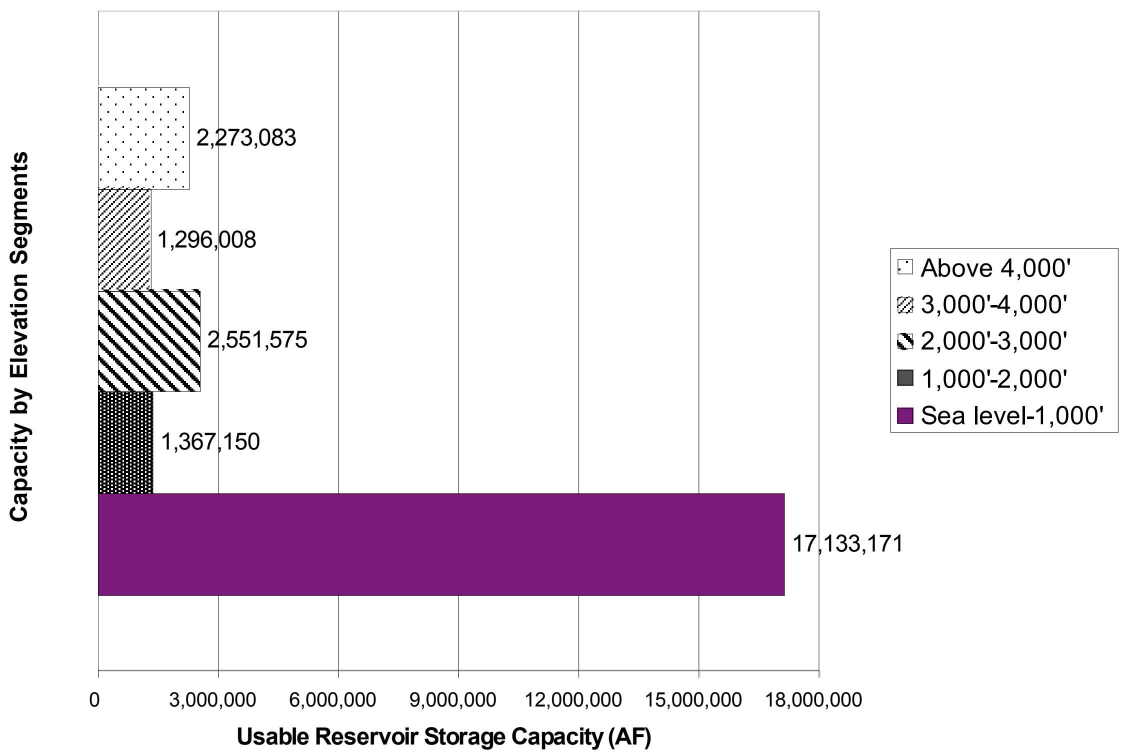


Figure 5-2 shows the dependable hydro capacity segmented by elevation. While the largest block is situated below 1,000 feet, the amounts from 1,000 to 2,000 feet and above 4,000 feet are substantial. Figure 5-3 shows the distribution of energy production by elevation. The higher elevation plants produce more than the lowest-elevation facilities. Figure 5-4 shows how the energy production per unit of capacity increases with elevation up to 4,000 feet. This results from the increasing hydraulic heads at the higher facilities, which are more effective than the larger water volume that flows through the lower facilities. The decreased water flows at the highest elevations counterbalance this effect beyond 4,000 feet.

Figure 5-2 Dependable Hydro Capacity by Elevation Segments

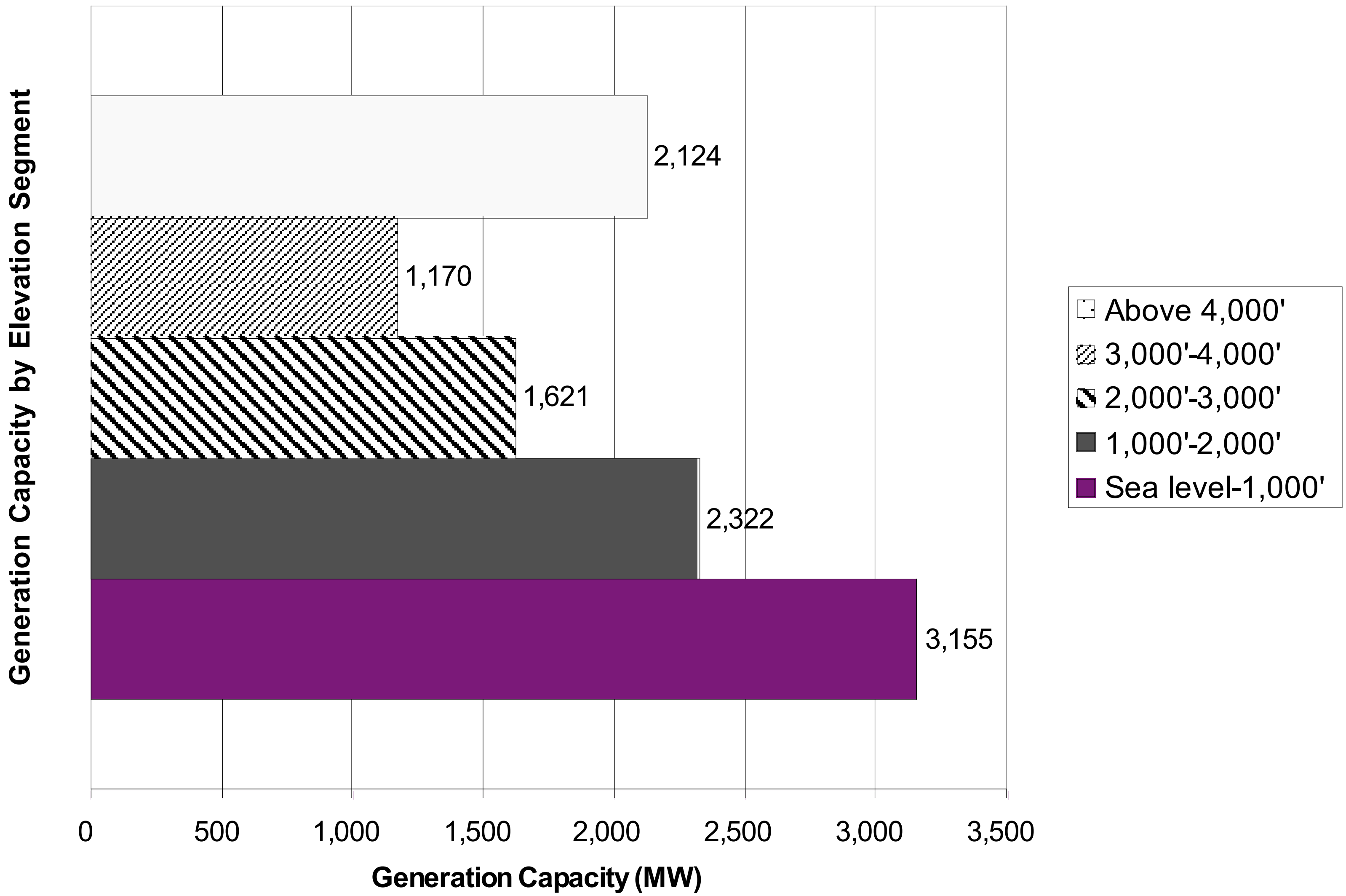


Figure 5-3 Average Annual Energy Production by Elevation Segments

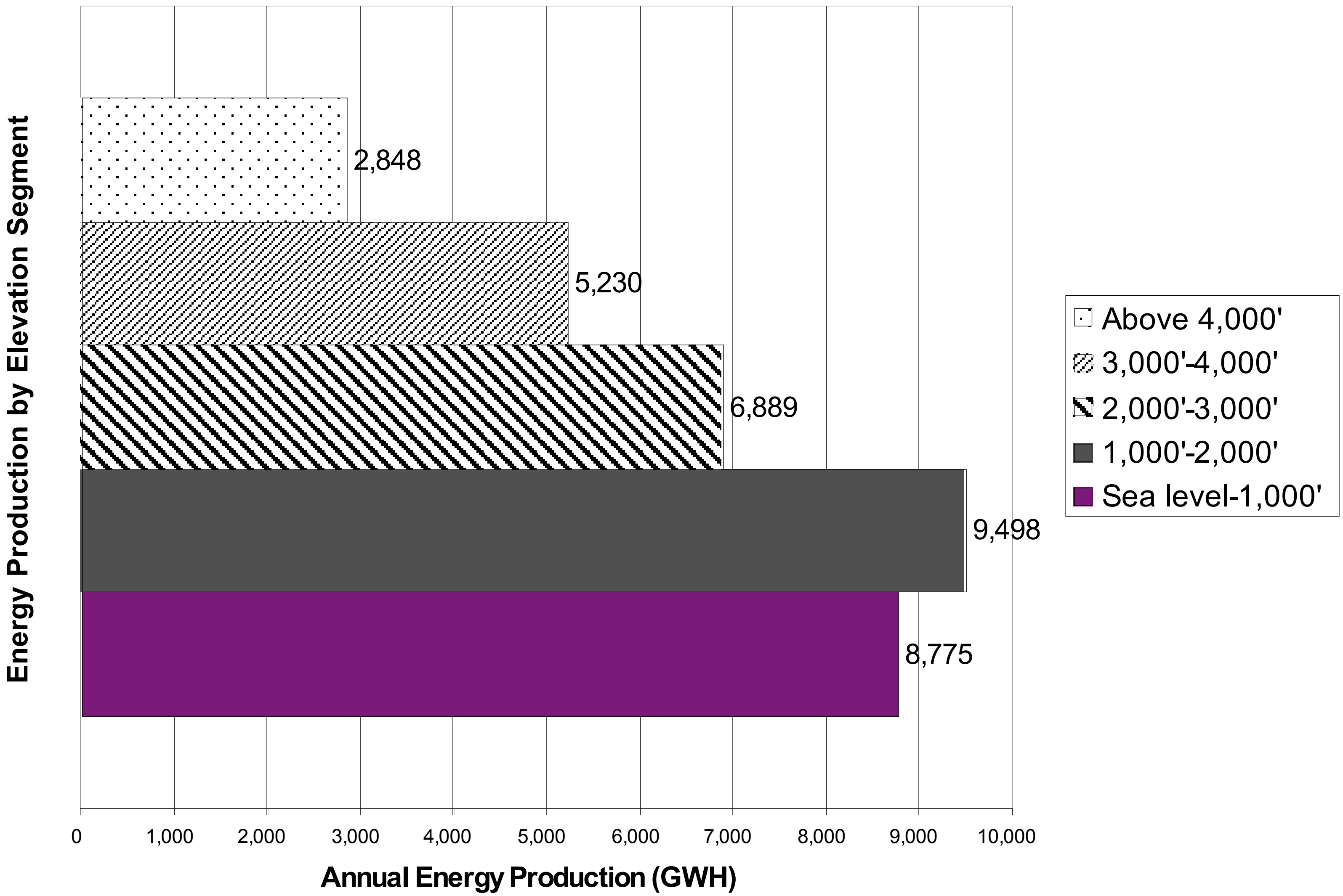
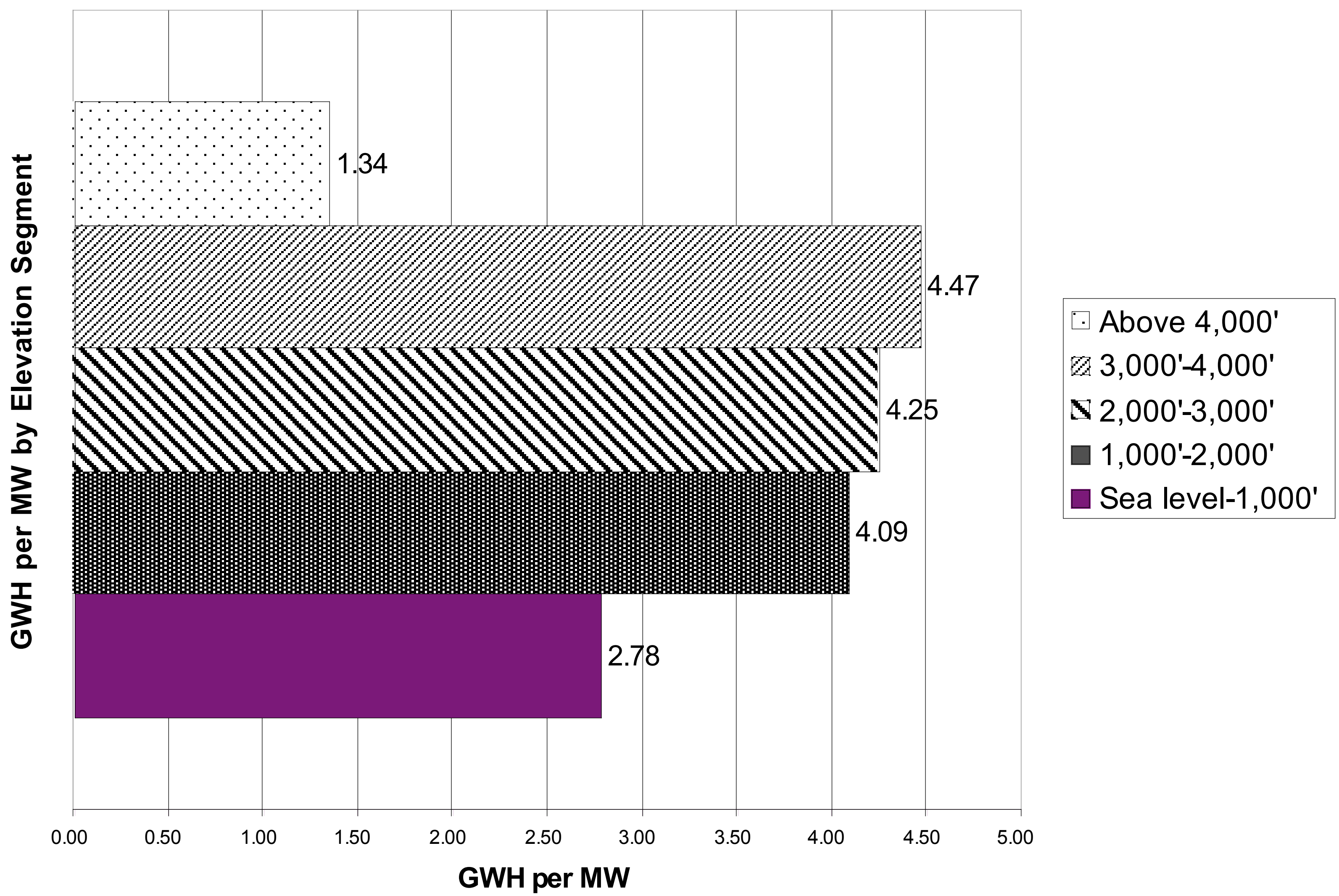


Figure 5-4 Energy Production per MW of Capacity by Elevation Segments



The rather even distribution of capacity and energy across elevation segments contrasts with the reservoir capacity distribution which is heavily concentrated at the lowest segment. This reflects how the higher hydro plants were designed to exploit the snowpack as a reservoir. Large surface water reservoirs are not necessary to deliver water to the plants during the early summer under current conditions. In contrast, the water supply storage facilities only needed to capture the runoff at the lowest point before it was collected and shipped south to the San Joaquin Valley and Southern California. However, this configuration with the existing reservoir capacity well below the majority of generating capacity has important implications for how hydropower plants may be operated in a climate regime in which runoff occurs earlier in the season. Snow that melts in the late winter rather than the late spring more likely will bypass the turbines before the period when that water is most valuable in the summer. What are now considered important peaking pondage facilities may become more like run-of-river facilities which have depleted reservoirs in August and September.

To determine whether the potential impacts on certain hydro facilities warrant further study, the possible impacts were separated by river basin. Unfortunately, runoff scenarios have not yet been segmented by elevation so the importance in seasonal timing at different elevations cannot yet be studied.[33] As an alternative, this analysis identifies which river basins support substantial amounts of hydropower capacity which would be most affected by changes in annual flows and the timing of those flows.

Figure 5-5 shows the annual runoff changes for the two scenarios by major river basin overlaid on the amount of generating capacity within that river basin. The largest capacities are on the Kings (with the Helms Pumped Storage plant most of that), the Feather, and the Sacramento Rivers.[34] For the HCM scenario, the incremental flows increase more moving south through the basins. In other words, the proportional increases are larger farther south. The largest amounts of capacity tend to be toward the north, so on net, the increases in total hydropower generation will tend to be less than the increase in runoff. For the PCM scenario, the incremental decrements tend to be larger going farther south, although the differences are not as large as in the HCM scenario. Overall, the changes in flows are relatively evenly distributed across the river basins.

Figure 5-5 Comparison of Runoff Changes to Generation Capacity for Notable River Basins for Year 2100 GCM Scenarios: HCM (Wet) vs. PCM (Dry)

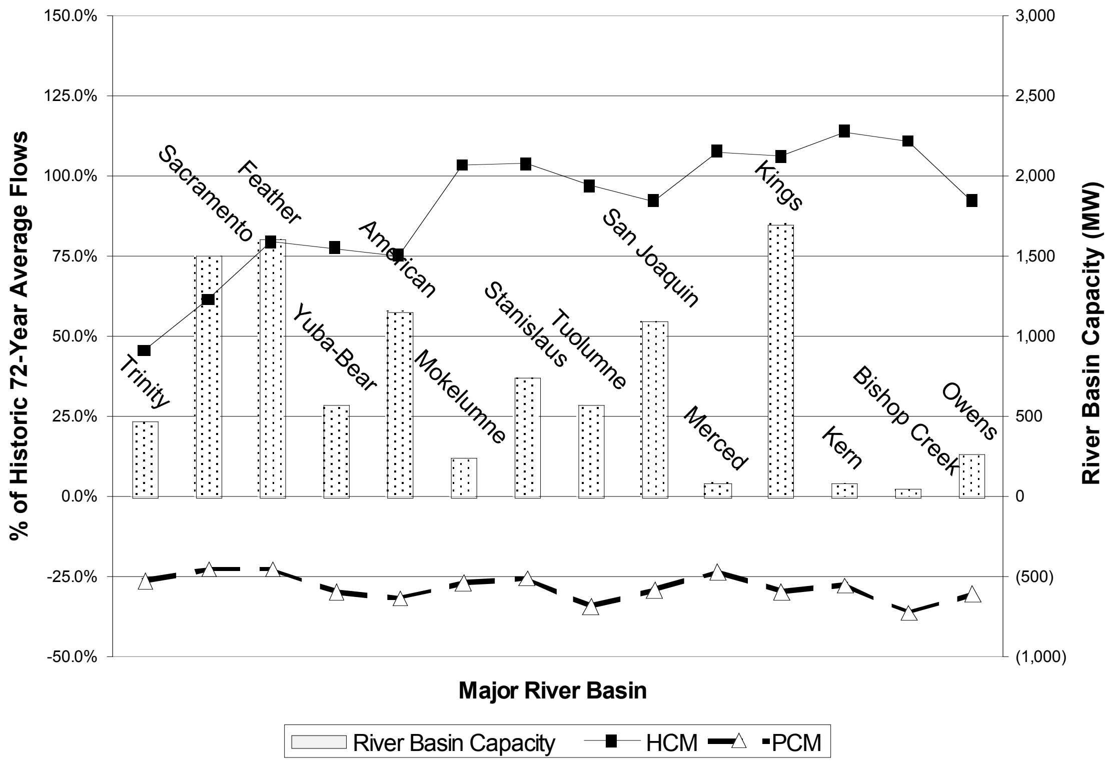
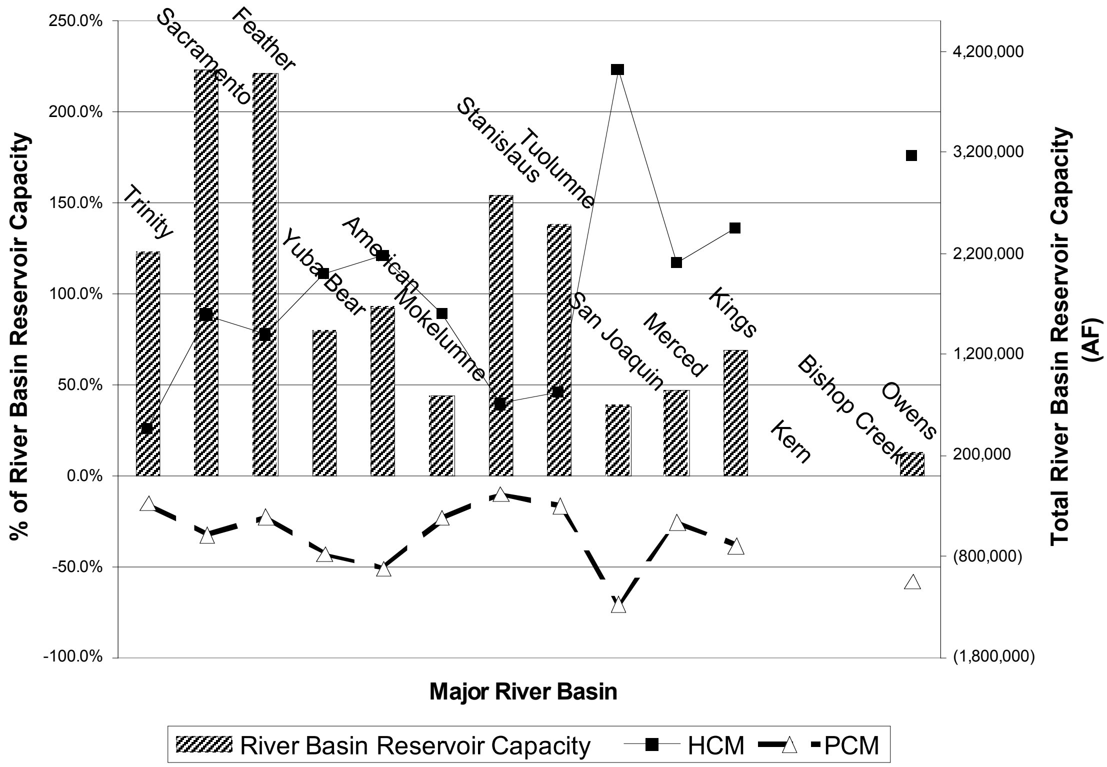


Figure 5-6 shows a different way of viewing the variation in runoff. It assesses the changes as a percentage of the usable reservoir capacity in the river basin and compares that to the reservoir capacity of each basin. A small change may be easily accommodated by the existing facilities. A large change may require re-operation and estabilishing new objectives, and perhaps even physical changes to existing or new structures. In the HCM scenario, the increases exceed 50% of reservoir capacity in all but three of the basins. The Yuba-Bear, American, Mokelumne, and Kings basins see the largest changes relative to capacity for those rivers with significant storage. Changes of these magnitudes could induce substantial changes such as re-operation with different priorities on flood control, water supply and power generation, or physical modification or additions to facilities.

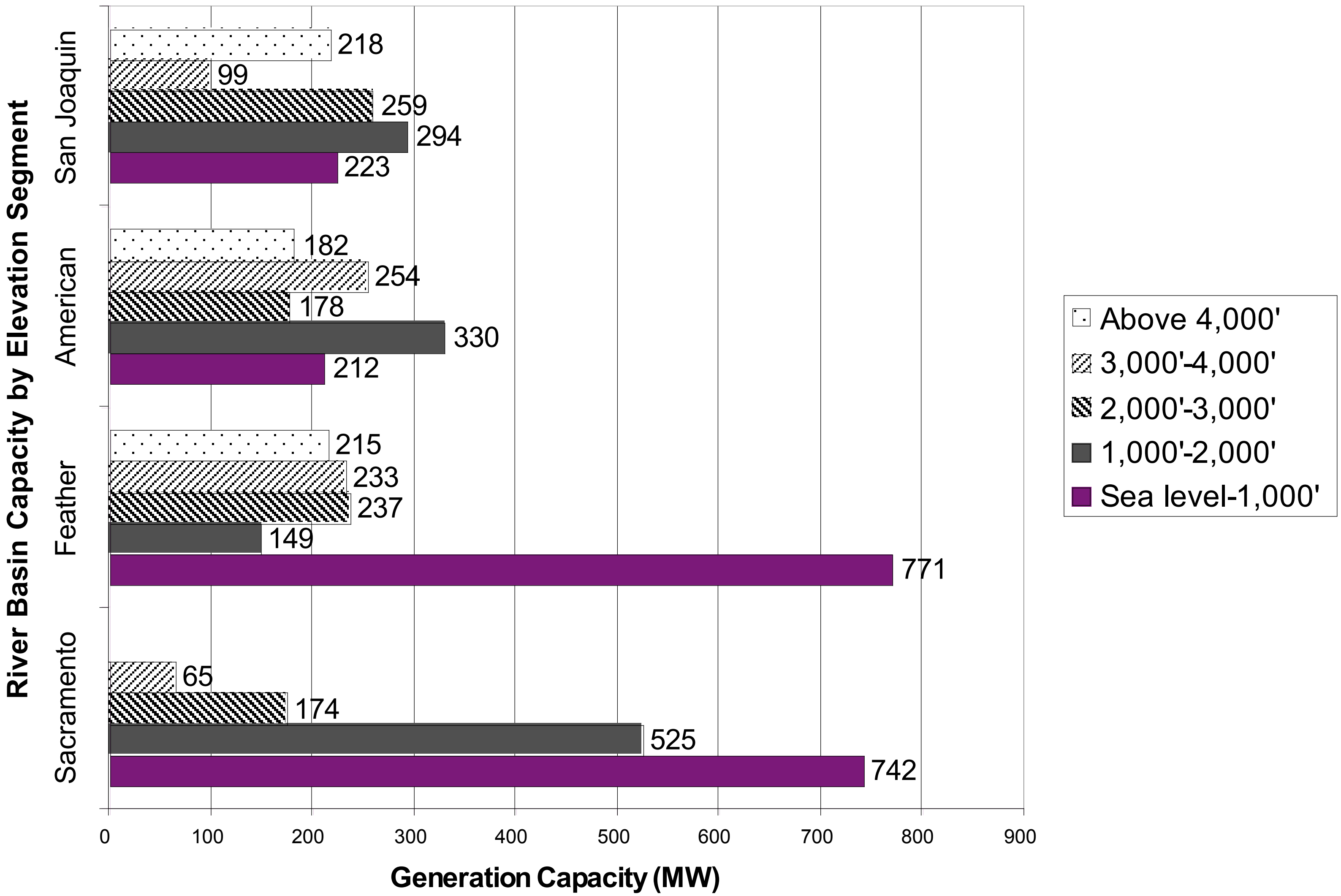
Figure 5-6 Comparison of Runoff Changes in Proportion to Reservoir Capacity for Notable River Basins for Year 2100 GCM Scenarios: HCM (Wet) vs. PCM (Dry)



In looking at both Figures 5-5 and 5-6, we see that the Sacramento, Feather, and American Rivers have relatively large amounts of both generation and storage capacity. The potential fluctuations as a proportion of reservoir capacity are large for these three, particularly the American. These three river basins are of primary interest for these reasons. The San Joaquin and Kings have large amounts of generation capacity, but not much storage, and the potential changes relative to storage capacity also are large. However, the Kings is dominated by the Helms pumped storage plant. Pumped storage output is largely independent of flow amounts, so generation on the Kings should not change much in absolute terms. This leaves the San Joaquin as the remaining river basin for which changes in the runoff regime may have significant impacts on California's electricity system.

Figure 5-7 shows how the generation capacity is distributed across elevation for these four major river basins, the Sacramento, Feather, American, and San Joaquin. While the Sacramento's capacity is concentrated in the lower 2,000 feet, the capacity is distributed relatively evenly for the other three river basins. This situation indicates that those river basins may be at particular risk for experiencing a substantial shift in generation timing toward the winter months if runoff timing is accelerated.

Figure 5-7 Dependable Hydro Capacity for Four Major River Basins by Elevation Segments



CHAPTER 6 INCORPORATION OF GLOBAL CLIMATE CHANGE IN HYDROPOWER PLANNING AND OPERATIONS

The previous analyses have shown that there is intense research interest in global climate change and how it may affect hydrologic parameters and hydropower production. While uncertainties exist, the Energy Commission is interested in knowing whether the key hydropower planning agencies and utility operators in California, the Pacific Northwest, and the Colorado Basin are evaluating climate change research and addressing the issue in long-term plans (such as integrated resource plans or IRPs), and whether any operational changes to hydropower facilities are contemplated. To this end, the Energy Commission personally contacted over two dozen organizations, many of which have both planning and operations staff, to determine how the organizations were addressing climate change. The results of this survey are presented below.

The number of energy planning agencies in the West is fairly large, and no one central organization is responsible for determining how global climate change may affect hydropower operations and how current and future planning and operations documents should take such changes into consideration, in spite of the fact that the systems may all react in somewhat similar fashion. The large number of players occurs in part because operators may not be the actual marketers of the power; for example, federal power in the Pacific Northwest is marketed by the Bonneville Power Agency, while in the Colorado River Basin, the Western Area Power Administration markets the resource.

The extent to which climate change is incorporated in hydro planning and operations is variable. The West as a whole has a fairly aggressive program of research (as noted in previous sections) that tends to be reviewed by most entities. However, the many uncertainties that surround the science limit the extent to which climate change effects actually are translated into future planning or operational changes. The two IOUs in California with significant hydropower resources are tracking the issue and participating in research efforts. Many of the smaller operators in California are more concerned with flood control. The Pacific Northwest is also taking a leading role. Whether global climate change would affect hydropower in the Colorado River Basin does not appear to be a significant issue at the time, although climate change gets attention in terms of how it might affect the hotly disputed area of water allocation.

Many of the individuals contacted noted that temperatures have been increasing overall, but were hesitant to attribute this change to global warming because of the overall significant variation in climate routinely experienced. A good many indicated that their current systems are already designed to manage a highly variable water resource, and no near-term changes to facilities are expected.

Western United States

California is part of an interconnected western grid, which includes most of the territory of the eleven western states, as well as portions of British Columbia, Alberta, and Baja California. A number of entities have responsibilities relating to planning and operations of western utilities.

The **Western Electricity Coordinating Council** (WECC) is responsible for coordinating and promoting electric system reliability. It has not specifically evaluated global climate change. WECC does look at the capacity of hydro facilities in times of drought or other changes in weather that affect water flow and storage.[35]

The **Western Interstate Energy Board (WIEB)** is an organization of 12 western states and three western Canadian provinces, which are associate members of the Board. The purpose of the Board is to provide the instruments and framework for cooperative state efforts to "enhance the economy of the West and contribute to the well-being of the region's people." The Board serves as the energy arm of the Western Governors' Association. WIEB's **Committee on Regional Electric Power Cooperation (CREPC)**, which consists of the public utility commissions, energy agencies, and facility siting agencies in the western states and Canadian provinces in the western electricity grid, has been working to improve the efficiency of the western electric power system. The **Westwide Resource Assessment Team** (WRAT), a subgroup to CREPC, prepared a consensus draft report in January, 2004, that reviewed resource assessment and resource adequacy in light of continuing challenges and the need for enhanced regional cooperation. A risk assessment framework was proposed to CREPC that included impacts of global climate change as one of seven risk factors. The report stated that change in rainfall amounts, patterns, and timing that affects snowpack could reduce hydro generation both in the Pacific Northwest and in California and could increase summer peak temperature, in combination magnifying summer peak loads.[36] No next steps were identified, however.

California

As noted previously, the **California Energy Commission** (Energy Commission) is taking a leading role in the research and analysis of climate change. PIER is also sponsoring several analytic research projects on adaptation to climate change. For example, in a three-year project, the Energy Commission and Hydrologic Research Center will implement an integrated management system for reservoir operation that incorporates global climate model forecasts at the Folsom, Oroville, Shasta, and Trinity reservoirs.[37] Researchers will then demonstrate and quantify the improved efficiency of water management for hydropower production, water supply, and flood control in California.

On the planning side, the Energy Commission annually prepares an assessment of California's electricity system as part of its ongoing responsibilities to evaluate California's electricity demand and supply and to assess electricity system issues. The most recent report, the *2002-2012 Electricity Outlook Report*, does not include the projected effects of global climate change. The Energy Commission has no independent capability to assess hydropower changes since it lacks the hydro system simulations models and the assumptions that populate them.[38] Rather, it relies on information submitted by the utilities. This information may or may not include forecasts of hydro generation under conditions of climate change. The Electricity Analysis Office (EAO) nevertheless has been working with the PIER group at the Energy Commission to coordinate efforts regarding ongoing climate change studies.

The **California Independent System Operator (Cal ISO)** acts as the impartial operator of the state's wholesale power grid, maintaining reliability and overseeing transmission. Cal ISO would be generally concerned with global climate change both from the standpoint of reduced hydropower generation and also increased demand from higher temperatures. However, because Cal ISO operates the grid on a day-to-day basis, long-term trends are not factored into daily forecasting.[39] Hydro forecasting is generally based on previous year data and late winter/early spring snowpack conditions; the 2005 Summer Operations Assessment includes the actual average hourly output of hydro generating resources in 2004 and indicates how 2005 hydro generation would vary.[40]

The **California Public Utilities Commission (CPUC)** has requested that its regulated energy utilities address key issues pertaining to climate change as part of their long-term energy procurement planning. This includes internal planning and measurement of greenhouse gas emissions (GHGs), an assessment of the utilities' current GHG emissions profile, and any steps the utilities have taken to minimize the release of these gases. The CPUC is now requiring that the IOUs employ a "greenhouse gas adder" when evaluating competitive bids to supply energy. This adder is designed to capture the financial risk to IOU ratepayers of emitting GHGs, recognizing the likelihood that these emissions will be limited by regulation in the future. The CPUC is also investigating the creation of a "carbon cap" to be applied to each IOU's resource portfolio.[41]

In addition to energy planning agencies, there are a variety of hydro operators in the state.

Investor-Owned Utilities

The three regulated utilities in the state serve the bulk of California's energy users and either operate and/or contract for the largest amount of hydropower production. While all three — Pacific Gas and Electric (PG&E), Southern California Edison (SCE) and San Diego Gas and Electric (SDG&E) — have aggressive greenhouse gas emission reporting and reduction programs, the degree to which they are addressing operational effects of climate change varies.

The physical attributes of the **PG&E** hydroelectric system were discussed earlier. The design and placement of the system took elevation into consideration as it relates to precipitation type and timing of runoff.[42] PG&E routinely reviews global climate change studies such as Scripps studies of climate change along the Sierra and Pacific Coast. PG&E's water management team is planning for how to work with runoff change in terms of best hydroelectric scheduling practices.

Currently, observed changes over the last few decades, such as increased frequency of earlier snowmelt and greater climate variability, are subjectively considered in run-off forecasting and hydroelectric scheduling.[43] In light of the greater variability and more intense storms, PG&E now tends to keep reservoirs at a higher level.

SCE owns, operates, and maintains the Big Creek Hydroelectric System within the Sierra National Forest. The system produces hydropower and additionally supplies water for municipal and agricultural purposes throughout the San Joaquin Valley. The Big Creek System produces up to 1,056 MW of hydroelectricity.[44]

Because it generates about 1,000 MW of hydro, SCE is concerned with how precipitation may change.[45] It currently conducts 13 cloud seeding programs in the state, which on average increase precipitation by 5 percent. SCE is actively participating with the Energy Commission on two climate change studies: one is evaluating how anthropogenic (man-made) particles from areas such as the Central Valley and Los Angeles Basin affect precipitation; and a second one, in the planning stages, will study how precipitation processes (cloud physics) change as temperature increases and how those altered processes could impact the SCE's cloud-seeding program.[46]

SDG&E does not rely on hydropower for a significant amount of electricity.[47]

Water Projects

The **California Department of Water Resources (DWR)** operates and maintains the State Water Project, including the California Aqueduct. The department's divisions also provide dam safety and flood control services, assist local water districts in water management and conservation activities, promote recreational opportunities, and plan for future statewide water needs. Both planning and operations staff were contacted regarding climate change.

The State Water Project (SWP) is the nation's largest state-built water and power development and conveyance system. Its power plants generate on average 7600 GWh of electricity annually,[48] but the SWP uses about 5 billion kWh annually to pump and deliver water throughout the state. The SWP watershed encompasses the mountains and waterways around the Feather River.

DWR Division of Operations and Maintenance, Operations Control Office, Project Operations Branch, typically works on short-term rather than long-term plans for the SWP.[49] Although not evaluated per se by the Operations Center, climate change would get factored into water supply forecasting. Because the pattern of runoff has been different over the past 50 years as compared to the historical record, DWR uses the former in its planning. Climate change effects (for example, more runoff in winter) would be considered as DWR looks at flood control changes and operating rules. However, the variability of climate and resulting water availability is so great that it could well mask any trends.

DWR's Statewide Planning Branch is, however, tracking climate change issues in general.[50] The department is already observing sea-level rise, some evidence of temperature rise, and a change in runoff characteristics for the Sacramento River watershed. For the near future, DWR plans to focus on uncertainty issues, what analytical tools to use, and how to best direct planning and research.

Climate change is specifically addressed in the *2005 Update to the California Water Plan*.[51] Background information is provided in *Volume 4 – Reference Guide*, with an extensive review of climate change information specific to California (Kiparsky and Gleick, 2003) and a description of how climate change may affect DWR resources and next steps.[52] Section 3 of the draft plan identifies future hydrologic scenarios, but these are based on historical conditions and do not consider future hydrologic conditions that might occur due to climate change.

DWR hosted a technical workshop on Climate Change and Its Impacts on Water Supply and Water Quality in California in November, 2003, and is a co-sponsor of the PIER's California Climate Change Research Center (CCCRC). DWR plans to continue to work closely with the Energy Commission and to partner with Cal Fed on future climate change analyses.[53] Activities underway at the CCCRC in support of future updates of the California Water Plan include:

- The development and maintenance of a comprehensive climatic data base for the state and the analysis of meteorological and hydrological trends.
- The monitoring of meteorological and hydrological parameters in some key remote locations using remote sensing devices.
- The development of climate projections for the State using regional climate models at levels of resolution appropriate for water resources impact analyses.
- The study of water resources impacts under different climatic projections.

The **U.S. Bureau of Reclamation (USBR)** runs the Central Valley Project (CVP), comprised of some 20 reservoirs with a combined storage capacity of more than 11 million acre-feet, 11 powerplants, and more than 500 miles of major canals and aqueducts. Project purposes include water supply (its primary purpose), flood control, navigation, fish and wildlife protection/restoration/enhancement, and power generation. As its Chief of Power Operations states, "We move water first and foremost."[54] Water management is performed using over 70 years of history as a guide. Climate change is not being addressed prospectively at this time.[55]

The **U.S. Army Corps of Engineers (ACE)** oversees flood control operations and so is therefore concerned with the timing and amount of runoff into reservoirs. The Sacramento District oversees 7 million acre feet of variable flood control space within its boundaries, which include the areas drained by the Sacramento and San Joaquin Rivers, most of Utah, and parts of Colorado, Wyoming, Arizona, and New Mexico. The district has noted a trend in less winter snowpack and earlier runoff,[56] and in anticipation that such trends could continue, reviewed operations at Folsom Lake to determine if the USBR could store more water in the space typically reserved for flood control. The decision to encroach on flood control space is based on snowpack conditions, upstream storage availability, and precipitation and temperature forecasts; these are all the elements that could be impacted by global climate change. The district determined that it could increase flexibility in reservoir management, and increase storage, by incorporating forecast information.[57]

Municipal Utility and Water/Irrigation Districts

In discussions with several municipal utilities and irrigation districts across the state, it appears that some, but not all, are tracking the climate change issue. However, in almost no cases are effects being incorporated into planning documents and decisions. The principal reasons are the lack of specific data and the great uncertainties regarding future weather conditions.

Los Angeles Department of Water and Power's (LADWP) electrical load is served by a variety of resources, including hydroelectric generating facilities located in the Owens River gorge and the Owens Valley and along the LA aqueduct. LADWP did not respond to requests for information from Energy Commission staff.

In 2003, large hydroelectric projects provided 34 percent of the **Sacramento Municipal District's (SMUD)** power mix. Its Upper American River Project includes 11 reservoirs and 8 powerhouses and totals 688 MW. Power production averages 1,800 GWh and ranges from 800 GWh to 2,800 GWh, depending on hydrologic conditions.

SMUD has been proactively and intensively following the global climate change issue.[58] It included the general issue of greenhouse gases in its IRPs done in the early 1990s. SMUD believes that although there appear to be trends in regional climate change, the tools to determine regional or local impacts are still too unrefined to include results in any operational models. During the next 20 years, other factors are more likely to affect operations more than climate change. SMUD is working with University of California Irvine to develop better temperature maps. The utility is also hoping that future research can provide more definitive information on whether precipitation will increase or decrease, and the variability of temperature increases (for example, increases in nighttime temperature could alter SMUD's air conditioning loads).

The **San Francisco Public Utilities Commission (SFPUC)** generates in excess of 400 MW of hydroelectric power through the Hetch Hetchy system. Generation is used first to provide power to the City of San Francisco. Excess power is sold to the Modesto and Turlock Irrigation Districts. The SFPUC is not evaluating climate change effects at this time.[59]

The **East Bay Municipal Utility District (EBMUD)** has reviewed how climate change may affect water delivery into the future. Based on preliminary evaluations, the district believes climate warming will not have a large impact on its ability to deliver water, primarily because of the high elevation of the snowpack that feeds the EBMUD system.[60] Flood control is more of a worry. The utility is currently developing a temperature model that will allow greater analysis of climate change effects.

The **Placer County Water Agency (PCWA)** is utilizing a new "climate change calculator" that was recently developed by the American River Watershed Institute, with funding from the U.S. Environmental Protection Agency. The calculator models precipitation and temperature changes. Otis Wollan, a Director with PCWA, presented information on the calculator at the April 2005 American River Watershed Conference. While PCWA does not currently operate any hydropower facilities, it will begin receiving power from its reservoirs in the upcoming decade (currently, PG&E receives the power).

Metropolitan Water District of Southern California (MWD) has been tracking global climate change research reports and at one point was partnering with the University of California Santa Cruz on alternative modeling of its system to incorporate climate change.[61] The utility operates a dozen or so very small hydropower systems that would not likely be affected by climate change. For systems that would be affected, it currently relies on DWR and USBR evaluations of climate change.

The **Modesto Irrigation District** is following efforts by the Energy Commission and others in the state to keep abreast of the effects of climate change.[62]

Pacific Northwest

In its Fifth Power Plan,[63] the **Northwest Power and Conservation Council (NWPPC)** has evaluated the effects of global climate warming on Northwest hydroelectric facilities. These effects are discussed in Chapter 3, "Review of Climate Change Studies." One of the key actions noted in the plan is to monitor climate change science and policy for developments that could affect resource choices. In addition, the plan makes the following suggestions regarding actions that could be taken to mitigate potential impacts to hydropower reliability:

- Adjust reservoir operating rule curves to assure that reservoirs are full by the end of June.
- Allow reservoirs to draft below the biological opinion limits in summer months.
- Negotiate to use more Canadian water in summer.
- Use increased winter streamflows to refill reservoirs (U.S. and Canadian).
- Explore the development of non-hydro resources to replace winter hydro generation and to satisfy higher summer needs.

However, based on the uncertainty regarding the data and models used to determine effects, the NWPPC has proposed no near-term response actions other than to monitor the research. The Global Climate Change Policy contained in the plan deals with reducing levels of carbon dioxide (CO_2) from generating units.

The **Bonneville Power Administration (BPA)** is a federal agency that markets electrical power from 31 federal hydro projects. These dams are owned and operated by the USBR and the U.S. Army Corps of Engineers. BPA provides about 45 percent of the Pacific Northwest's electric power and it relies on hydropower for 80 percent of its total generation.[64]

As a federal power market agency, BPA is not required to prepare an IRP. It prepares a White Book that includes a regional load/resource balance. The 2003 White Book (updated December 2004) does not include any reference to climate warming effects. BPA's "A Guide to Tools and Principles for a Dry Year Strategy" describes tools that BPA can use when hydro resources are not adequate.[65] The agency uses 1939 (critical water conditions) as a base year for critical flow and planning long-term contracts.

The **State of Oregon** has an aggressive program to address greenhouse gas emissions. The Governor's Advisory Group on Global Warming has released the draft document "Oregon Strategy for Greenhouse Gas Reductions."[66] The following observed changes to regional climate were noted: increase in precipitation both east and west of the Cascades; 50 percent decline in April 1 snowpack in the Cascades from 1950 to 2000; 20 to 50 percent reduction in summer stream flows; and 4- to 6-week earlier peak flows. Impacts to hydropower are addressed in terms of economics: the price of summer power could rise substantially while a drop in winter hydropower supplies could reduce cost. The design of the regional reservoir system provides little or no room for growth in supply. The state has the ability to store behind dams only for about 30 percent of the average annual flow. The report advises that the state think through strategies for dealing with lower snowpack and altered regional hydrology over the next 100 years. To address this significant concern, Oregon is in the process of setting up a task force to address adaptation.[67]

The Institute for Natural Resources at Oregon State University recently hosted a symposium on climate change to solicit guidance from climate and resource scientists. This symposium resulted in the "Draft Scientific Consensus Statement on the Likely Impacts of Climate Change on the Pacific Northwest," included in the Oregon Strategy document as Appendix D. Although precipitation changes are noted as being very uncertain as compared to other changes (sea level changes, snowpack, and so forth), the statement notes that enhanced wintertime and diminished summertime hydropower production could challenge the current approach to hydropower production in the Columbia River.

The **State of Washington's** 2003 Biennial Energy Report/Energy Strategy Update Guiding Principle #13 (of 13) is to "Promote energy policies that maintain or improve environmental quality." Emissions of greenhouse gases and the resulting climate change impacts are specifically noted. Although most emphasis is placed on emissions reductions, the text does note that in the Pacific Northwest, changes in precipitation patterns due to global warming may affect the seasonal availability of hydropower. The *2005 Biennial Energy Report* includes a section on greenhouse gas emissions, but information is limited to the source of emissions and strategies to reduce them.

The state relies on information developed by the University of Washington Climate Impacts Group and NWPPC to assess climate change.[68] The state does not intend to conduct near-term assessments of hydropower impacts from global climate change, although it recognizes that a small change in snowpack levels could have a 30 to 40 percent decrease in snowpack with serious impacts to hydropower generation.

A leading researcher at the University of Washington, Dr. Philip Mote, indicated that several discussions have taken place with utilities in the state regarding global climate change. His reaction is that the utilities in the state are starting to pay attention, are interested and concerned, but for the most part are not taking discrete actions at this time.[69]

PacifiCorp operates as Pacific Power in Oregon, Washington, Wyoming, and California. Its hydroelectric portfolio consists of 54 plants with a net plant capability of 1,164 MW; these plants account for almost 15 percent of PacifiCorp's total generating capacity.[70] Its 2004 Integrated Resource Plan (IRP) contains information on climate change mostly from the stand point of lowering greenhouse gas emissions. However, the IRP also states "PacifiCorp will track [such] developments to see how it can inform our assessment of regulatory risk and even operational impacts, though currently such impacts are too uncertain to incorporate into planning." In discussions with staff,[71] PacifiCorp has observed greater climate variability in the recent past, but attribution to global climate change is uncertain.

About 90 per cent of **BC Hydro's** electricity is generated by water powering turbines. Hydrologists at the utility are working with researchers at the University of Victoria to determine how climate change may affect BC Hydro. Projected changes could alter the shape of BC Hydro's existing load, reducing winter peak load and increasing summer peak load. A decrease in precipitation could reduce hydropower generation.[72]

The **Bureau of Reclamation, Pacific Northwest Division**, has no formal process for incorporating global climate change. In general, the agency does not do system-wide modeling but rather relies on modeling performed by Bonneville and the NWPPC. However, the USBR has just completed a flood control study for the Hungry Horse reservoir and is now conducting an internal, follow-on study to determine how global warming flows, supplied by the University of Washington, would affect study results.[73]

The Colorado River Basin

One of six areas of research and development for the USBR relates to global climate change, in particular "support of programs for the development of strategies to respond to predicted effects of climate change on the availability of water supplies and the demand for water."[74] However, any climate change efforts with respect to research and development have not filtered down to operations and planning staff. The Boulder Canyon Operations Office of the U.S. Bureau of Reclamation supports the Lower Colorado region's water and hydropower management efforts in the Lower Colorado Region. Hydroelectric powerplants on the Colorado River and their installed capacity include: Hoover Dam, 2,078 MW; Davis, 255 MW; Parker, 120 MW; and Glen Canyon, 1,296 MW. The manager of Hoover Dam indicated that they have not looked into climate change recently.[75] The 2005 Colorado River Annual Operating Plan is, as it name indicates, a short-term planning document. No long-term plans are in place that would address climate change.[76]

However, planning for climate change and reservoir management is being undertaken by the National Oceanic and Atmospheric Administration's (NOAA) Climate Diagnostics Center (CDC). Its scientists are working with USBR reservoir managers in Arizona to develop ways to use climate information in management of the Colorado River and its large reservoirs. In November 2004, CDC co-sponsored a one-day Colorado River Basin Outlook briefing in Salt Lake City, Utah for water managers, decision makers, and planning groups in the region to provide an assessment of current and projected climate conditions and water availability impacting the lower and upper Colorado River Basins.[77]

The Western Water Assessment[78] was created in 1999 and is a joint effort between the CDC and the Cooperative Institute for Research in Environmental Sciences at the University of Colorado. Its mission is to identify and characterize regional vulnerabilities to climate variability and change and to develop information, products and processes to assist water-resource decision-makers through out the Intermountain West.[79] A current project is to work with Upper Colorado reservoir managers to improve the relevance, use, and value of climate information.

Andrea Ray, a senior research scientist with the CDC, is working closely with water managers in the Colorado River Basin. She believes that resource managers in the Basin are definitely aware of predicted climate change predictions; however, because models results are so variable, they consider them too uncertain to act upon.[80] Dr. Ray also suggested that the impacts of warming may also be less significant because of the very high elevations of the mountains. She noted that climate change should be considered whenever operations and other plans (such as Endangered Species Recovery Plans) are being drafted in order to build in future flexibility.

CHAPTER 7 CLIMATE CHANGE EFFECTS ON COASTAL POWER PLANT OPERATIONS

In addition to the change in precipitation and snowpack expected as a result of global climate change, California may also experience a rising sea level and more intense storm periods. These conditions could affect power plants located along the coast. The following section discusses the potential rise in sea level in California and the potential for increased storm intensity and frequency. Two representative coastal power plants are reviewed to determine the potential for operational impacts from global climate change. However, coastal climate change effects appear to only impact the Diablo Canyon Power Plant.

Both the expansion of the upper layers of the ocean as they warm and the melting of ice sheets and glaciers contribute to sea level rise. A new study by climate modelers at the National Center for Atmospheric Research (NCAR) indicates that global sea levels could rise about 4 inches from greenhouse gases already in the atmosphere.[81] This increase would reflect the warming and expansion of ocean waters and does not include sea level increases from melting ice sheets and glaciers. The latter could double the sea level rise caused by the thermal expansion alone.

Sea level rise is already occurring in California, although to a lesser extent than the eastern United States.[82] The coast south of La Jolla has experienced a rise of 8 inches over the last century, while the coast from Los Angeles to San Francisco has had a rise of 0 to 6 inches. The coast north of San Francisco has seen a reduction in sea level of 2 to 6 inches for the same period. The San Francisco Bay Area and the coast south of Santa Barbara are considered particularly vulnerable. Sea level rise impacts on the Oxnard Plain of Ventura County could increase significantly by 2040 with storm surges as the major determinant of impacts.[83]

Salt water intrusion, inundation of coastal wetlands, beach erosion and damage to property could all result from sea level rise. A study by Gleick and Maurer published in 1990 and recently released in electronic form, determined that the cost of protecting existing development in California from a one meter rise (3.3 feet) in sea level would exceed $940 million, with an additional $100 million per year to maintain protective structures.[84] This study also stated that a sea-level rise of only 5.9 inches would change the frequency of the 1-in-100 year storm to a 1-in-10 year storm at the entrance to San Francisco Bay.

More recent studies by the Energy Commission indicated that the undiscounted cost (the amount of funds needed in the future) to protect vulnerable areas over the next 100 years would be approximately $700 million for a 20-inch (50 centimeters) sea level rise and $4.7 billion for a 39-inch (1 m) rise.[85]

Although modeling results are less refined for storm variability, increased storm intensity is consistently forecast, whether or not frequency increases. California has already shown its vulnerability to intense storm activity; February storms during the 1998 El

Niño[86] event brought three times the normal amount of rainfall and caused significant damage to the state.[87] The 1982/1983 El Niño brought high rainfall and coastal wave surge, resulting in extensive flooding, landslides, coastal erosion, and damage to coastal structures.[88]

Bromirski et al. reviewed hourly tide gauge records at San Francisco to determine whether the level of “storminess” exhibited by the 1982-83 and 1997-98 El Niño events is greater or less than other strong El Niños over the past century and whether storminess has increased along the West Coast.[89] The results indicated that the two reference El Niño events were not exceptional as compared to earlier periods in the century. However, there has been an increasing trend in extreme (high) sea level residuals over the last 50 years.

Potential Impacts to Coastal Power Plants

Climate change could potentially impact coastal power plants through either sea level rise, which could inundate low-lying facilities, or through increased storm frequency or intensity, which could affect off-shore water intake and discharge pipes. Intakes and outfalls in shallower water would likely be affected more by storm surge and debris than those located further offshore in deeper waters. The vulnerability of a facility would depend on its elevation, the neighboring area, and the extent to which it faces heavy wave action.

California has 24 power plants located along the coastline. A number of power plants are also located on interior bays. No studies reviewed to-date assess whether sea level rise, coupled with more intense and frequent storm events, could affect California’s coastal power plants. However, storms have impacted several power plants in the recent past. In January of 2001, the governors of California, Oregon, and Washington met to consider how to deliver energy during an energy crisis made worse by three days of powerful storms.[90] During the storms, the Diablo Canyon nuclear power plant was forced to reduce its output by 80 percent. Other power plants were affected, although not identified.

The Diablo Canyon Power Plant (DCPP) is located on a coastal terrace well above sea level; however, cooling water is pumped from an intake pipe located in a rocky intertidal zone that takes the full brunt of northern swells from Pacific storms.

The facility has had to curtail power during storm events on average twice per storm season.[91] Both generating units are cut back to 20 percent power as a preventative measure to avoid tripping the units if intake flow is impeded by debris buildup on the intake screens. The units can be down anywhere from 18 to 24 hours to several days. The more frequent the storms, or the greater the intensity, the more likely that the facility would have to cut power from debris generated from the storms. If El Niño conditions were to become more frequent, the facility would likely see an increase in number and duration of curtailments. DCPP currently has an oceanographer on staff that is responsible for storm impact predictions.

The Ormond Beach and Mandalay Bay Generating Stations were also reviewed, given their location on the Oxnard Plain. Cooling water intake locations differ for the two plants: the Ormond Beach facility takes water through an intake pipe located 2,500 feet offshore, and the Mandalay Bay facility takes water through a canal. For the latter, the canal is susceptible to shoaling and debris and trash accumulation during storm events[92]. However, no plant shutdowns have occurred at either facility due to storms. Climate change has not been raised as an issue for these coastal power plants.[93]

APPENDIX A

Table A-1 California Hydropower Capacity and Usable Reservoir Storage

Elevation Range	Capacity (MW)		Usable Reservoir Storage (acre-feet)*
	Nameplate	Dependable	
ALL AMERICAN CANAL			
Sea level – 1,000 feet	35.8	35.82	N/A
Below Sea Level	0.4	0.4	N/A
AMERICAN RIVER			
6,000 – 6,999 feet	82	82	66,200
4,000 – 4,999 feet	103.2	100.2	432,320
3,000 – 3,999 feet	253.8	253.8	204,638
2,000 – 2,999 feet	177	178	35,238
1,000 – 1,999 feet	330.348	330.3	10,713
Sea level – 999 feet	212.22	212.2	1,042,750
BATTLE CREEK			
2,000 – 2,999 feet	9.5	9.9	1,535
1,000 – 2,000 feet	14.4	15	1,581
Sea level – 1,000 feet	12.15	5	10.6
BISHOP CREEK			
8,000 – 8,999 feet	12.951	11	N/A
7,000 – 7,999 feet	7.32	7.5	78
6,000 – 6,999 feet	7.84	7.9	N/A
5,000 – 5,999 feet	19.205	18.9	493
4,000 – 4,999 feet	6.132	5.8	N/A
BUTTE CREEK			
3,000 feet	18.45	18.5	144
2,000 – 2,999 feet	1.8	1.5	6,205
1,000 – 1,999 feet	2	2	143
Sea level – 999 feet	7.4	7.3	6,547
CALIFORNIA AQUEDUCT			
3,000 – 3,999 feet	32.775	30	N/A
1,000 – 1,999 feet	1,706.73	1,880.9	495,171
Sea level – 999 feet	424	421	2,027,800
COLORADO RIVER			
5,000 – 5,999 feet	33	33	N/A
Sea level – 999 feet	120	108	619,000
CONFLUENCE OF WARM SPRINGS AND DRY CREEKS			
Sea level – 999 feet	2.79	3	212,000
COW CREEK			
2,000 – 2,999 feet	3	0.9	4
Sea level – 999 feet	1.44	1.8	0.8
COLORADO RIVER AQUEDUCT (CRA)			
1,000 – 1,999 feet	16.8	17.1	N/A
Sea level – 999 feet	10.9	11	N/A

Elevation Range	Capacity (MW)		Usable Reservoir Storage (acre-feet)*
	Nameplate	Dependable	
COLORADO RIVER AQUEDUCT (CRA) / STATE WATER PROJECT (SWP)			
1,000 – 1,999 feet	13.2	13.2	800,000
DELTA-MENDOTA CANAL			
Sea level – 999 feet	25.2	25.2	56,000
EEL AND EAST FORK RUSSIAN RIVERS			
1,000 – 1,999 feet	9.46	9.2	102
ESCONDIDO CREEK			
1,000 – 1,999 feet	1.5	1.5	4,500
FALL AND SPRING CREEKS			
2,000 – 2,999 feet	2.2	2	N/A
FEATHER RIVER			
4,000 – 4,999 feet	229.29	214.8	1,125,705
3,000 – 3,999 feet	227.25	232.6	138,441
2,000 – 2,999 feet	250.54	237	11,057
1,000 – 1,999 feet	171.83	149	1,748
Sea level – 999 feet	782.366	771.25	2,715,927
GRAEAGLE CREEK			
4,000 – 4,999 feet	0.45	0.5	N/A
KAWEAH RIVER			
1,000 – 1,999 feet	8.85	1.2	143,000
KERN RIVER			
2,000 – 2,999 feet	66.455	61.6	247
1,000 – 1,999 feet	9	11	N/A
Sea level – 999 feet	9.54	11.5	20
KINGS RIVER			
7,000 – 7,999 feet	1,053	1,212	123,300
3,000 – 3,999 feet	135	138	118,254
2,000 – 2,999 feet	79.6	86	782
1,000 – 1,999 feet	97.2	104	N/A
Sea level – 999 feet	165	165	1,000,000
KLAMATH RIVER			
2,000 – 2,999 feet	112	129.8	17,620
LYTLE CREEK			
1,000 – 1,999 feet	3.45	2.7	N/A
MERCED RIVER			
Sea level – 999 feet	106.54	86.6	854,794
MILL CREEK			
7,000 – 7,999 feet	3	3	3,820
3,000 – 3,999 feet	0.8	0.9	N/A
2,000 – 2,999 feet	3	2.7	N/A
MOKELUMNE RIVER			
3,000 – 3,999 feet*	94.28	92	174,225
2,000 – 2,999 feet	13.6	13	1,007
Sea level – 999 feet	136.78	139.3	616,316
OWENS RIVER			
6,000 – 6,999 feet	75	74	183,465
4,000 – 4,999 feet	44.5	44.5	N/A
3,000 – 3,999 feet	7.1	7.8	45,000

Elevation Range	Capacity (MW)		Usable Reservoir Storage (acre-feet)*
	Nameplate	Dependable	
2,000 – 2,999 feet	111.375	122.5	N/A
1,000 – 1,999 feet	16.6	16.4	N/A
Sea level – 999 feet	2.6	2.6	N/A
PUTAH CREEK			
Sea level – 999 feet	11.5	7.1	1,600,000
SACRAMENTO RIVER			
3,000 – 3,999 feet	79.3	65	1,172
2,000 – 2,999 feet	193.69	174	16,115
1,000 – 1,999 feet	503	525	37,146
Sea level – 999 feet	746	742	3,970,600
SAN ANTONIO CREEK			
3,000 – 3,999 feet	0.6	0.9	N/A
1,000 – 1,999 feet	0.8	1	N/A
SAN JOAQUIN RIVER			
7,000 – 7,999 feet*	210.6	217.5	1,547
3,000 – 3,999 feet	110.99	99.4	159,103
2,000 – 2,999 feet	272.3	259.3	117,482
1,000 – 1,999 feet	287.25	294.1	26,185
Sea level – 999 feet	207.88	223.3	391,084
SANTA ANA RIVER			
3,000 – 3,999 feet	3.2	0.2	N/A
2,000 – 2,999 feet	3.1	0.2	N/A
SOUTH COAST RIVER			
4,000 – 4,999 feet	2.438	2.2	N/A
1,000 – 1,999 feet	23.9	23.9	N/A
Sea level – 999 feet	43.1	42.4	N/A
STANISLAUS RIVER			
4,000 – 4,999 feet	16.2	16.2	9,832
3,000 – 3,999 feet	64	65	78,372
1,000 – 1,999 feet	339.9	339	189,318
Sea level – 999 feet	320.17	320	2,501,006
STONY CREEK			
Sea level – 999 feet	11.6	11.7	N/A
TRINITY RIVER			
2,000 – 2,999 feet	140.4	130.35	1,999,154
1,000 – 1,999 feet	154.4	154	N/A
Sea level – 999 feet	180	182	213,554
TRUCKEE RIVER			
5,000 – 5,999 feet	6.8	6.45	226,500
TULE RIVER			
Sea level – 999 feet	7	8.9	N/A
TUOLOMNE RIVER			
4,000 – 4,999 feet	92.4	88.9	**360,400**
3,000 – 3,999 feet	113.5	94.3	378,666
2,000 – 2,999 feet	166.6	168	302,224
Sea level – 999 feet	189.35	220.88	1,802,000
YUBA AND BEAR RIVERS			
5,000 – 5,999 feet*	20.95	15.7	216,746
3,000 – 3,999 feet	110.8	103.6	1,960

Elevation Range	Capacity (MW)		Usable Reservoir Storage (acre-feet)*
	Nameplate	Dependable	
2,000 – 2,999 feet	55	46.9	45,860
1,000 – 1,999 feet	346.87	369.9	960,000
Sea level – 1,000 feet	85.2	33.2	211,103

Note: N/A indicates that data is not available or not applicable;

Table A-2 California Average Annual Energy Production by Watershed

Watershed/Project Name	Average Annual Energy Production (GWh)
American River	2,770.7
Bear River	757.2
Butte Creek	160.6
Chemehuevis	620
Feather River	5,532.9
Kern River	354.6
Kings River	1,482.51
Klamath River	521.6
L.A.–San Gabriel River	135
Marysville	37.16
Merced River	35.9
Middle Sierra	1,541.6
Mojave	13.0
Mono	92.4
Owens	510.8
Pit River	3,393.9
Russian River	65.5
San Joaquin River	4,075.7
Santa Ana River	57.1
Santa Clara-Calleguas	386.0
Shasta Bally	1,085.97
Shasta Dam	2,368.6
Stanislaus River	1,938.5
Trinity River	458
Tuolumne River	1,842.4
Upper Calaveras	10.1
Valley Putah-Cache	52.0
Valley-American	650.0
Whitmore	254.6
Yuba River	1,602.3
West Fork Carson River	604.0
WATER PROJECTS	
Delta-Mendota Canal	325.3
Mojave Siphon (aqueduct)	13.0
William E. Warne (aqueduct)	288.0
Castaic 1-7 (aqueduct)	1,273.0
Devil Canyon (aqueduct)	586.6

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