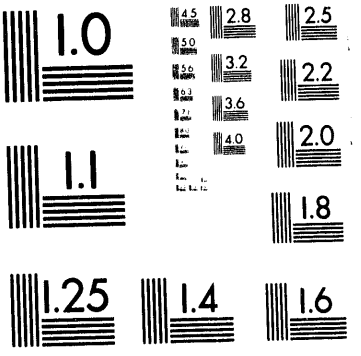
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# Effects of Climate Change on Pacific Northwest Water-Related Resources: Summary of Preliminary Findings

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# Executive Summary

The Pacific Northwest Case Study is a multi-agency analysis of atmospheric/climatic change impacts on the Pacific Northwest (which includes Washington, Oregon, Idaho, and portions of the Columbia River Basin in Western Montana). The purpose of the case study, which began in fiscal year 1991, was to develop and test analytical tools, as well as to develop an assessment of the effects of climate change on climate-sensitive natural resources of the Pacific Northwest and economic sectors dependent on them. The overall study, jointly funded by the U.S. Department of Energy (DOE) and the U.S. Environmental Protection Agency, was a broad-based, reconnaissance-level study to identify potential climate impacts on agriculture, coastal resources, forest resources, and irrigation in the Pacific Northwest. DOE participated in the reconnaissance study, with responsibility for hydroelectric and water supply issues.

While this report briefly discusses a broader array of water issues, attention is mainly focused on three aspects of the water study: 1) the effects of the region's higher temperatures on the demand for electric power (which in turn puts additional demand on hydroelectric resources of the region); 2) the effects of higher temperatures and changes, both in precipitation amounts and seasonality, on river flows and hydroelectric supply; and 3) the effect of higher temperatures and changed precipitation amounts and seasonality on salmonid resources — particularly the rearing conditions in tributaries of the Columbia River Basin. Because the meaning of regional climate forecasts is still quite uncertain, most of the preliminary findings are based on sensitivity analyses and historical analog climate scenarios. The findings are as follows:

- A warmer climate in the Pacific Northwest would reduce average annual electricity consumption because of the importance of electric space heat in the region. The amount of the climate-related decrease depends on the temperature scenario. For example, the general circulation model (GCM) of the Geophysical Fluid Dynamics Laboratory, run for a doubled atmospheric concentration of carbon dioxide, results in a temperature increase for the region that yields a decrease of 4.5% in annual electricity consumption. By contrast, the Goddard Institute for Space Studies scenario results in a decrease of 6.9% in annual electricity consumption. Increases in market penetration of air conditioning in the residential and commercial sectors and increases in irrigated acreage modify, but do not fundamentally change, this result.

- Based on historical analog stream flows, runoff and hydroelectric generation would increase significantly in a warm-wet climate analog case (substituted for warmer-wetter conditions forecasted by the most of the GCMs) and would decrease significantly in a low-flow analog case (used to depict warmer and drier conditions). Shifting of electricity consumption from winter toward summer in the Pacific Northwest, the climate change results in a somewhat better match of power consumed to power generated. However, these results are tempered by the fact that there is no good historical analog for the rain-dominated winter season that the GCMs forecast.

- Climate change scenarios that increase the flows in the Columbia River system are likely to have positive impacts on salmon and steelhead because the salmonids tend to suffer the most during low water years. Survival may be improved at the mainstem dams if additional water is available in the system. While low water (warmer, drier climate) has an ambiguous effect on survival in the main stream of the Columbia River, the effects on survival in the tributaries, especially east of the Cascades, are largely negative.

- There are significant increases in demand for water in the Pacific Northwest, even without climate change. Increases include additional demand for electricity and water to serve an increasing population and industrial development, for irrigated agriculture, and for instream flows to sustain the region's salmon resource. Climate change could exacerbate the difficulties facing water managers in the region to meet all of these conflicting pressures on the resource base.

# Contents


Executive Summary . . . . . iii

1.0 Introduction . . . . . 1.1

2.0 Impacts, Findings, and Conclusions . . . . . 2.1

2.1 Electricity Demand . . . . . 2.1
2.2 Water Supply and Hydroelectric Power . . . . . 2.2
2.3 Salmon and Steelhead Survival . . . . . 2.3

3.0 Current and Future Conditions Without Climate Change . . . . . 3.1

4.0 Sensitivity of the Resource to Current and Future Climate Change . . . . . 4.1

5.0 Electricity Demand . . . . . 5.1

5.1 Methodology . . . . . 5.1
5.2 Electricity Demand Results . . . . . 5.4

6.0 Water Supplies in the Columbia River Basin . . . . . 6.1

6.1 Methodology . . . . . 6.2
6.2 Water Supply Results . . . . . 6.5

7.0 Salmon and Steelhead Survival . . . . . 7.1

7.1 Methodology . . . . . 7.1

7.1.1 Columbia Mainstem, Mouth to Bonneville Dam . . . . . 7.3
7.1.2 Columbia Mainstem, Bonneville Dam to Priest Rapids Dam . . . . . 7.4
7.1.3 Columbia Mainstem, Priest Rapids Dam to Chief Joseph Dam . . . . . 7.4
7.1.4 Snake River, Mouth to Hells Canyon Dam . . . . . 7.5
7.1.5 Critical Habitat Issues . . . . . 7.5

7.2 Salmon Survival Results . . . . . 7.6

8.0 References . . . . . 8.1

Appendix A - Climate Scenarios and Stream Flows . . . . . A.1

Appendix B - Peak Impacts and Other Electricity Demand Issues . . . . . B.1

# Figures

5.1 Impact of Climate Change on Pacific Northwest Temperatures, GFDL Warming Case . . . . . 5.2

5.2 Impact of Climate Change on Pacific Northwest Temperatures, GISS Warming Case . . . . . 5.3

5.3 Effects of Climate Change on Annual Pacific Northwest Electric Energy Consumption in 1990 and 2010 . . . . . 5.9

5.4 Effects of Climate Change in the GFDL Case on Pacific Northwest Electricity Demand in the Year 2010 . . . . . 5.10

5.5 Effects of Climate Change in the GISS Case on Pacific Northwest Electric Energy Demand in the Year 2010 . . . . . 5.10

# Tables


3.1 Potential Increases in Development of Irrigation in the Pacific Northwest in the Absence of Climate Change . . . . . 3.2

3.2 Objectives and Costs of the Current Columbia River Fish and Wildlife Plan . . . . . 3.3

3.3 Total Fresh Water Withdrawals for Off-Stream and Consumptive Use in the Pacific Northwest, 1985 . . . . . 3.4

3.4 Non-Irrigation Use of Surface Water in the Columbia Basin . . . . . 3.6

5.1 Predictors for Electricity Demand . . . . . 5.4

5.2 Average Monthly Temperatures for Seattle . . . . . 5.5

5.3 Monthly Electricity Consumption in 2010 Base Case . . . . . 5.6

5.4 Electricity Consumption in 2010 GFDL Global Warming Case . . . . . 5.7

5.5 Electricity Consumption in 2010 GISS Global Warming Case . . . . . 5.8

5.6 Monthly Electricity Consumption in 2010 Residential Sector . . . . . 5.11

6.1 Description of Subbasins in the Water Supply Model . . . . . 6.2

6.2 Annual Temperature and Precipitation Anomalies for Spokane and Yakima, Washington, and Boise, Idaho, for the GFDL and GISS GCM Scenarios and Historical Analog Water Years . . . . . 6.4

6.3 Columbia River Hydroelectric Power . . . . . 6.6

6.4 Electrical Coverage Ratio: Columbia Hydroelectric Generation Divided by Total System Electric Load . . . . . 6.7

6.5 Base Water Flow at John Day Dam . . . . . 6.8

6.6 Incremental Effect of Irrigation Water Demand on River Flow at Key Points in the Columbia River System . . . . . 6.9

6.7 Incremental Effect of Irrigation Acreage Expansion Plus Climate Change on River Flow at Key Points in the Columbia River System . . . . . 6.10

7.1 Postulated Effects of Climatic Warming on Key Characteristics of Columbia River Subbasins . . . . . 7.2

7.2 Critical Habitat Characteristics for Columbia River Salmonids . . . . . 7.5

7.3 Postulated Effects of Climatic Warming on the Subbasins of the Columbia River Basin and the Resultant Impact on Salmonid Populations . . . . . 7.7

# 1.0 Introduction

The work in this report was performed by Pacific Northwest Laboratory (PNL) and was precipitated by the acknowledged need of the U.S. Department of Energy's (DOE's) Office of Policy, Planning, and Program Evaluation (DOE/PO) to better understand the impacts of potential climate change on natural resources and human economic and social systems at the regional level.[a] Previous studies had either not considered important issues in sufficient depth (e.g., the 1989 U.S. Environmental Protection Agency [EPA's] study of the effects of global climate change on the United States [Smith and Tirpak 1989]) or, while thorough, had been focused on regions that did not address certain critical natural resources and economic sectors that may be affected by anthropogenic climate change (e.g., the Missouri-Iowa-Nebraska-Kansas [MINK] study funded by the DOE Office of Health and Environmental Research [Rosenberg 1993]).

The Pacific Northwest Case Study is a multi-agency analysis of atmospheric/climatic change impacts on the Pacific Northwest. During fiscal year (FY) 1991, about $150K of funding and in-kind support was provided to several other institutions by the U.S. EPA Office of Policy, Planning, and Evaluation to support a broad-based, reconnaissance-level study to identify potential climate impacts on agriculture, coastal resources, forest resources, and irrigation in the Pacific Northwest. DOE/PO participated in the reconnaissance study, with responsibility for hydroelectric and water supply issues.

The purpose of the case study was to develop and test analytical tools, as well as to develop an assessment of the effects of climate change on climate-sensitive natural resources of the Pacific Northwest and economic sectors dependent on them. During FY 1991, the project focused on providing an initial assessment of the Columbia River water resource sensitivity to climate change, studying the impacts of water resource changes on the region's other economic resources, and investigating the effectiveness of various adaptive strategies. The project eventually will aggregate "index" watersheds, with well-understood hydrology and climate, to develop estimates of the effects of changed climate on large-scale river basin runoff; link regional hydrological and climate conditions to Columbia Basin reservoir operation models for the purpose of calculating effects on regional power supply; incorporate the effects of climate change on the demand for water for irrigation in the reservoir models; calculate the effects of climate change on regional weather-dependent electricity demands; link climate and hydrological systems to the survival of salmonids in the Columbia River system; and integrate these analyses to provide an initial assessment of the effects of climate change on the Columbia River system.

This report provides preliminary findings from the water resources portion of the overall case study, with emphasis on electricity demand and supply, water resources supply, and salmon survival. (Appendix A provides additional information regarding climate scenarios and stream flows, and

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(a) Portions of material throughout this report (including text, figures, and tables) have been reprinted from the *Northwest Environmental Journal's* article, Neitzel et al. 1991, with permission from the Institute for Environmental Studies, University of Washington, Seattle, Washington.

Appendix B covers peak impacts and other electricity demands.) Information concerning the effects of climate change on demand for water in irrigated agriculture was supplied by researchers at Goddard Institute for Space Studies (GISS), Oregon State University, and Washington State University. This information was incorporated with data from general circulation models and several historical analog periods, and the information has been used with computer models of Pacific Northwest energy demand, Columbia River reservoir operations, and salmon survival to characterize the impact of potential climate changes in the Pacific Northwest. This reconnaissance-level study was designed to identify the important issues concerning water and climate change in the region. Further research is under way to provide better quantitative assessments.

# 2.0 Impacts, Findings, and Conclusions

## 2.1 Electricity Demand

An analysis was prepared of the potential effect of climate change (mainly the effect of increased temperature) on the region's climate-sensitive demands for electric energy. Estimates for changes in annual electricity consumption and its seasonal distribution are presented. Because there currently is no basis in Pacific Northwest regional power planning for long-range electricity demand forecasting, the analysis is focused on the year 2010, the last year for which an official forecast is available.[a] Temperature effects are associated with doubled levels of atmospheric carbon dioxide ($CO_2$), which is not expected to occur as early as 2010; thus, our analysis possibly overstates the effect of climate warming on electricity consumption.

The electric energy demand analysis concludes that a warmer climate in the Pacific Northwest would reduce average annual electricity consumption. The Bonneville Power Administration's (Bonneville's) medium forecast for the year 2010 assumes that annual electricity consumption will grow from 17,722 average megawatts (MW) in 1991 to 22,076 average MW in the year 2010, an increase of 24.6%. Annual electricity consumption would be lower with warmer temperatures. The amount of the climate-related decrease depends on the scenario. For example, the Geophysical Fluid Dynamics Laboratory (GFDL) scenario for doubled $CO_2$ results in a decrease of 4.5%, while the GISS scenario results in a decrease of 6.9%.[b] A greater temperature increase in the winter and decreased demand for irrigation in the summer account for the lower annual GISS consumption relative to GFDL.

The results are somewhat sensitive to assumptions concerning market penetration of air conditioning and irrigation. Market penetration of residential air conditioners in the Pacific Northwest is currently about half of the national average. If warmer weather results in additional market penetration of residential air conditioning, so the proportion of buildings with air conditioners doubles from what it would have been without global warming, then electricity consumption in the month of July in the GFDL case would grow by an additional 1,160 average MW. Annual consumption, though still reduced relative to a no-warming scenario, would be higher by 350 average MW. The basic electricity demand analysis does not assume any significant increase in the extent of irrigated acreage in the Pacific Northwest, although a hot-dry scenario might actually result in an increase in the demand for

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(a) There is currently no reasonable basis for projecting electricity demand for the middle of the next century in the Pacific Northwest. We interpret the effects on the forecast for the year 2010 as being illustrative of the types of effects that can be expected and the proportions of demand that might be affected by changes in the climate. We are reasonably certain that both the estimates of total demand and the absolute size of the climate effect would be larger as we proceed into the next century. The proportional effect of climate change might not be as large as illustrated, however, if space heating and cooling become less important uses of electricity after 2010.

(b) Information on GFDL and GISS scenarios were provided by A. Iglesias of the Goddard Institute for Space Studies, New York, New York.

irrigation in some areas that are not currently irrigated. In a sensitivity case that allows for a 16.5% expansion in irrigated acreage by the year 2010, the GFDL scenario would increase electricity consumption for irrigation by 120 average MW on an annual average basis (363 MW in July). The combination of increased irrigation and increased air conditioning adds approximately 470 average MW to Pacific Northwest electricity consumption, which is not enough to offset winter savings, but it is almost enough to create a summer peaking electrical system.

## 2.2 Water Supply and Hydroelectric Power

To analyze the effect on the Pacific Northwest hydroelectric power system and irrigation water supplies, a simplified model of the Pacific Northwest hydroelectric power system was used. The model calculates water flow and electrical generation at every hydroelectric project on the Columbia River and its tributaries. Because a hydrologic model based on index basins was not available in time to provide the necessary calculations to link the general circulation model (GCM) scenario temperature and precipitation changes to stream flows in the region, historical analog water years were used instead to construct scenarios of streamflows under a number of different climatological conditions.

The results showed that stream runoff and hydroelectric generation would increase significantly in a warm-wet climate analog case (substituted for warmer, wetter conditions forecasted by the most of the GCMs) and would decrease significantly in a low-flow analog case (used to depict warmer, drier conditions). The results show that shifting electricity consumption from winter to summer in the Pacific Northwest under climate warming actually results in a somewhat better match of power consumed to power generated. This also likely means that there would be less power available in most years to export to the Pacific Southwest.

The analog cases used in this analysis probably understate spring flows and overstate summer and fall flows in comparison with what a more complete hydrologic analysis based on GCM results might show. This is because no recent historical analog year has experienced the degree of increase in winter temperatures expected in the GFDL and GISS cases; consequently, there is no good historical analog for the rain-dominated winter season that the GCMs forecast.

The water supply/hydroelectric analysis assumes that climate change would not result in changes to the reservoir operating rules that are currently in place on the Columbia River system. However, if the reservoir managers were convinced that the climate had changed, they could modify their "rule curves" that specify individual reservoir levels based on the time of year and runoff forecast to better accommodate the changed snowpack. In sensitivity experiments with the model, water withdrawals for irrigation were increased commensurate with the increased water applied to crops (the efficiency of irrigation systems was not improved), while future irrigation systems were allowed to expand. The results showed that, in most cases, the changes in water demand were not large enough to significantly

affect operating rules in the system. The hydroelectric supply penalties associated with increased irrigation appeared to be relatively small. However, water supply for instream needs in the Snake River and some of the smaller, but still major, tributaries of the Columbia River could be adversely affected.

## 2.3 Salmon and Steelhead Survival

Pacific Northwest salmon and steelhead populations have been adversely affected by hydroelectric development, irrigation, land-use changes, and overfishing. Climate change scenarios that increase the flows in the Columbia River system are likely to have positive impacts on salmon and steelhead, because the salmonids tend to suffer the most during low water years. Survival may be improved at the mainstem dams if additional water is available in the system. It is not clear whether a hotter, drier scenario would necessarily reduce salmon survival in the mainstem of the Columbia River, because water managers have some flexibility in scheduling water releases from storage and filling reservoirs.

The same is not true of the tributaries. A qualitative analysis showed that chinook and sockeye salmon, already in trouble throughout most of their range and near extinction in many of the tributaries of the Pacific Northwest, would generally suffer additional harm from a warmer, drier climate. Because of their ability to survive and propagate in intermittent streams and warmer waters, steelhead might obtain some competitive advantage.

# 3.0 Current and Future Conditions Without Climate Change

Pacific Northwest water demand is likely to increase significantly in the absence of climate change. Bonneville, for example, estimates in its medium long-term forecast case that population growth and increased industrialization of the region will result in an increase of 1.2% per year in average annual electricity consumption over the next 20 years, or a 28% increase overall by the year 2010. This increase is 4,500 average MW of consumption, or the equivalent of four and one-half nuclear power plants (Northwest Power Planning Council 1991).[a]

A number of other significant new uses for Pacific Northwest water supplies might also affect water demand. In 1988 the Depletions Task Force of the Columbia River Water Management Group forecasted a considerable potential increase in the extent of irrigated land in the Pacific Northwest by the year 2030 in the absence of climate change, which also would increase the demand for water (Depletions Task Force 1988). While technically feasible, these extensions of the Pacific Northwest irrigation system must be considered speculative because of limitations in federal capital budgets and changes that have taken place in the last ten years in the regulation of both surface and groundwater in the region. However, Table 3.1 shows that substantial increases in irrigation development are at least possible, should they be found economically and environmentally desirable.

In addition, the Northwest Power Planning Council, Bonneville, the U.S. Army Corps of Engineers, and numerous other federal and state agencies are engaged in a program to approximately double the salmon and steelhead runs in the Columbia River Basin. The potential increases are unevenly distributed among the various stocks, as shown in Table 3.2. Increased water flows may be needed in many parts of the river basin to secure these increases.

Finally, economic and population growth anticipated in the Pacific Northwest will result in additional demand for water for residential, commercial, and industrial uses. Currently these demands are a tiny fraction of total water withdrawals, which in turn are generally a small fraction of total water available.[b]

Table 3.3 illustrates the pattern of total water withdrawals in the Pacific Northwest states during the mid-1980s, while Table 3.4 provides an estimate of the consumption of surface water in the Columbia

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(a) In the *1991 Northwest Conservation and Electric Power Plan*, the Northwest Power Planning Council (1991) resource supply curves indicate that this amount of new resources could be met with additional conservation, small hydroelectric power plants, and combined-cycle power plants. Neither additional nuclear power nor large-scale fossil fuel power would be needed.

(b) Irrigation uses approximately 6% of the Columbia Basin flow (see Bonneville Power Administration et al. 1991.) In some locations outside of the Columbia River basin, non-irrigation demand is a significant proportion of flow. For example, the City of Seattle reportedly takes about 70% of the Cedar River's flow, and the City of Tacoma takes about 10% of the Green River's flow.

**Table 3.1.** Potential Increases in Development of Irrigation in the Pacific Northwest in the Absence of Climate Change

| Area | Acres Irrigated[a] 1980 | Acres Irrigated[a] 2030 | Difference | Percent Difference |
|---|---|---|---|---|
| Upper Columbia and Kootenai | 65.6 | 150.1 | 84.5 | 128.8 |
| Clark Fork, Pend Oreille, and Spokane | 514.4 | 696.1 | 81.7 | 15.9 |
| Mid-Columbia | 1,685.2 | 2,402.0 | 716.8 | 42.5 |
| Upper Snake | 2,808.7 | 3,808.0 | 999.3 | 35.6 |
| Central Snake | 1,438.2 | 1,846.0 | 407.8 | 28.4 |
| Lower Snake | 4563.3 | 5,504.0 | 940.7 | 20.6 |
| Lower Columbia and tributaries | 690.3 | 1,214.0 | 523.7 | 75.8 |
| Willamette | 295.1 | 503.0 | 207.9 | 70.4 |
| Total | 12,060.8 | 16,123.2 | 4,062.4 | 33.7 |

(a) Based on 1,000 acres irrigated.

River Basin in these three Pacific Northwest states from both irrigation and non-irrigation uses. It is clear from these tables that irrigation is the dominant use of both surface water and groundwater in the Pacific Northwest states and that this is also true of surface water in the Columbia River Basin. In general, even a substantial increase (say, a doubling in the next 50 years) in the non-irrigation uses would not significantly influence total water demanded in the Columbia River Basin. However, certain smaller, heavily utilized tributaries, such as the Upper Snake and Yakima, may have difficulty supplying additional water without some rearrangement of access to water.[a]

(a) This could also be true for some water supplies west of the Cascade Mountains that depend on surface flows, such as the Cedar River. In these cases, further withdrawals may be problematic.

**Table 3.2.** Objectives and Costs of the Current Columbia River Fish and Wildlife Plan[a]

| Salmon Species/Run | Current Escapement | Run Objective | Difference | Percent Difference | Estimated Strategy Cost: Capital | Estimated Strategy Cost: Operation and Mainten/Year |
|---|---|---|---|---|---|---|
| Upriver spring chinook | 35,159 | 239,176 | 204,017 | 580.3 | $87,931,449 | $5,242,542 |
| Summer chinook | 9,900 | 71,027 | 61,127 | 617.4 | 28,520,076 | 2,037,435 |
| Upriver fall chinook | 89,718 | 167,779 | 78,061 | 87.0 | 33,440,380 | 785,370 |
| Upriver summer chinook | 305,554 | 676,218 | 370,664 | 121.3 | 129,775,435 | 6,303,362 |
| Sockeye | 64,329 | 64,329 | 0 | 0.0 | 20,590,000 | 1,030,400 |
| Upriver coho | 137,600 | 142,983 | 2,173 | 3.9 | 3,151,207 | 394,799 |
| Lower river spring chinook | 146,800 | 168,559 | 21,759 | 14.8 | 23,303,020 | 600,300 |
| Lower river fall chinook | 22,200 | 106,213 | 84,013 | 378.4 | 5,591,000 | 321,210 |
| Winter steelhead | 81,155 | 144,430 | 63,275 | 78.0 | 22,847,692 | 1,256,015 |
| Lower river summer steelhead | 69,409 | 124,035 | 54,626 | 78.7 | 19,914,160 | 1,276,773 |
| Lower river coho early return | 263,200 | 291,704 | 28,504 | 10.8 | 8,819,045 | 512,213 |
| Lower river coho late return | 188,200 | 301,295 | 1,609 | 60.1 | 10,422,545 | 635,963 |
| Total | 1,413,224 | 2,497,748 | 1,084,524 | 76.7 | $394,306,009 | $20,396,381 |

(a) In several cases, major current runs were not modeled. In some of these cases, the current run was substituted for the (non-existent) run objective, under the assumption that the stocks at least would not decline. This explains the zero difference in sockeye stocks even though the investment in mitigation strategy is substantial. Not all runs were included in this table.
(Source: Columbia Basin Fish and Wildlife Authority 1991).

**Table 3.3.** Total Fresh Water Withdrawals for Off-Stream and Consumptive Use in the Pacific Northwest, 1985 (million gal./day)[a]

| | Withdrawals | | | Consumptive Use Total |
|---|---|---|---|---|
| | Surface | Ground | Total | |
| Washington: | | | | |
| Public | 616 | 339 | 955 | NA[b] |
| Self-supplied | | | | |
| Domestic | 0.0 | 98 | 98 | 82 |
| Commercial | 0.3 | 20 | 20.3 | 21 |
| Irrigation | 4,310 | 629 | 4,939 | 4,479.[c] |
| Livestock | 8.8 | 21 | 29.8 | 25 |
| Industrial | 411 | 108 | 519 | 107 |
| Mining | 0.6 | 2.4 | 3.0 | 0.4 |
| Thermal | 427 | 0.7 | 427.7 | 22 |
| Total | 5,780 | 1,220 | 7,000 | 4,736 |
| Irrigation % of Total | 74.6% | 51.6% | 70.6% | 94.6% |
| Oregon: | | | | |
| Public | 332 | 83 | 415 | NA[b] |
| Self-supplied | | | | |
| Domestic | 9.6 | 70 | 79.6 | 89 |
| Commercial | 0.1 | 1.5 | 1.6 | 9.3 |
| Irrigation | 5,240 | 471 | 5,711 | 3,222.[c] |
| Livestock | 21 | 3.8 | 24.8 | 25 |
| Industrial | 263 | 29 | 292 | 22 |
| Mining | 7.2 | 0.3 | 7.5 | 1.6 |
| Thermal | 12 | 0.0 | 12 | 2.8 |
| Total | 5,880 | 660 | 6,540 | 3,371 |
| Irrigation % of Total | 89.1% | 71.4% | 87.3% | 95.6% |

**Table 3.3.** (contd)

| | Withdrawals | | | Consumptive Use Total |
|---|---|---|---|---|
| | Surface | Ground | Total | |
| Idaho: | | | | |
| Public | | | | |
| Self-supplied | | | | |
| Domestic | 13 | 76 | 89 | 5.3 |
| Commercial | 0 | 16 | 16 | 0.0 |
| Irrigation | 17,300 | 3,310 | 20,610 | 11,610.[c] |
| Livestock | 0 | 1,040 | 1,040 | 102 |
| Industrial | 26 | 172 | 198 | 5.4 |
| Mining | 135 | 0 | 135 | 0.0 |
| Thermal | 0 | 0 | 0 | 0.0 |
| Total | 17,500 | 4,800 | 22,300 | 11,722 |
| Irrigation % of Total | 98.9% | 69.0% | 92.4% | 99.0% |
| Grand Total | 29,160 | 6,680 | 35,840 | 19,820 |
| Irrigation % of Total | 92.1% | 66.0% | 87.2% | 97.4% |

(a) Detail may not add to totals because of independent rounding.
(b) Public supplies are not listed separately from self-supplied use in each category.
(c) Conveyance losses plus consumptive use.
(Source: Van der Leeden et al. 1990, pp. 335, 341-342, 344, 362-363, 375-376, 395.)

**Table 3.4.** Non-Irrigation Use of Surface Water in the Columbia Basin (millions of gal./day)[a]

| | Estimated Surface Water | | | |
|---|---|---|---|---|
| | Non-Agricultural Consumption | Agricultural Consumption | Total | Non-Agricultural Consumption As % of Total |
| Washington | 359 | 3,794 | 4,152 | 8.6 |
| Oregon | 78 | 1,519 | 1,597 | 4.9 |
| Idaho | 3 | 3,931 | 3,934 | <0.1 |
| Total | 439 | 9,244 | 9,683 | 4.5% |

(a) Consumption use in agriculture includes use for livestock but excludes conveyance losses.
(Source: Carr et al. 1990, pp. 232-233, 428-429, 518-519.)

# 4.0 Sensitivity of the Resource to Current and Future Climate Change

In the Pacific Northwest, more than 70% of the annual runoff is derived from snowmelt. West of the Continental Divide, precipitation is highly seasonal, with a precipitation maximum in winter corresponding to the arrival of storm fronts from the Pacific Ocean. Summer convective storms, which are an important source of moisture in the summer east of the Continental Divide, occur less frequently farther west of the Divide. This results in a summer minimum in the seasonal distribution of precipitation in the Pacific Northwest. Depending on elevation and latitude, peak runoff in the region occurs from April to July. In years of low snowpack, water shortages are most likely to occur in the summer and fall months because of early cessation of snowmelt and subsequent reduced baseflow.

Because the pattern of seasonal runoff all over the western United States is closely linked to snowmelt, water supplies in any western river basin could be highly sensitive to global warming. Gleick (1987) and Lettenmaier and Scheer (1990) have shown that, for the Sacramento River Basin of California, the warming predicted by global-scale GCMs for a doubling of $CO_2$ and other so-called greenhouse gases would result in a major shift in the seasonal runoff pattern. For the four headwaters catchments investigated by Lettenmaier and Gan (1990), which had mean elevations ranging from 4,100 to 8,200 feet, reductions in maximum seasonal snow accumulation ranged from 50% to 85%. Aside from any changes in precipitation, the hydrologic effects of such warming would be to reduce winter snow accumulations, increase winter runoff, and reduce spring and summer runoff. Simulation studies reported by Lettenmaier and Scheer (1990) showed that such changes in the seasonal pattern of runoff would have a significant impact on the performance of the California State Water Project.

The Pacific Northwest shares the western-type hydrology of California and could be affected in a similar fashion by climate change. Two subbasins in the Pacific Northwest appear to be of particular concern: the upper and middle reaches of the Snake River and the Yakima River, both of which are already heavily used for irrigation. The salmon and steelhead production plan for the Yakima subbasin (Columbia Basin Fish and Wildlife Authority 1990b) states that, although total subbasin runoff is 1.5 times the irrigation demand (3.4 million acre-feet of runoff, 2.3 million acre-feet of demand), only 1.07 million acre-feet is storable, and much of the runoff occurs only during May and June. Natural flow supplies the first part of the irrigation season (April through June), while storage must supply water from July 1 through the end of the season in October. Irrigation demand after July 1 and storage are nearly equal, requiring very careful water management and allocation of releases. There is almost no room in the system as currently configured for additional irrigation demand or for additional instream flows.

To assess the robustness of Pacific Northwest reservoir operation to shifts in seasonal runoff, Lettenmaier et al. (1990) developed simulations of monthly runoff for the American River in Washington, using the National Weather Service River Forecast System. The American River is a tributary of the Yakima River that drains the eastern slopes of the Cascade Mountains. The American River is presently unregulated; however, the performance of hypothetical reservoirs was tested with

capacity of 0.25 and 0.50 times mean annual flow for changes in precipitation and temperature consistent with the predictions of the GISS and GFDL GCMs. The reservoirs were operated for minimum instream flow release (a surrogate for fisheries protection and enhancement), agricultural water supply (summer demand peak), and hydroelectric power generation. Most of the reservoir storage in the Pacific Northwest (the Columbia River Basin in particular) is within the year; therefore, the range of reservoir sizes tested is regionally representative. The total reservoir storage in the Columbia River system is 0.30 mean annual flow.

A multiple purpose reservoir system was simulated and operated for water supply and hydropower, with minimum releases required for fisheries enhancement. The results showed that water supply reliability would be significantly degraded by a shift in the seasonal runoff pattern that would accompany a general warming, but that the hydroelectric revenues might increase due to larger releases during the winter peak demand season. Previous studies have shown that warmer climates may increase flood hazard on mountainous catchments currently having snow-dominated hydrology. Although the effect of climatic warming on flood operations was not considered here, it will be the subject of future study.

An additional adverse impact of global warming is the reduction in reliability of runoff forecasts resulting from decreased snowpack. The actual storage of the reservoir system is augmented by storage of water in the snowpack. Reservoir operating policies will have to adopt a more conservative release policy to account for the loss of snowpack storage.

# 5.0 Electricity Demand

## 5.1 Methodology

PNL has conducted several studies of hourly and peak electrical consumption for Bonneville. Computerized energy end-use demand models that were developed for Bonneville. These models use hourly end-use load data acquired by Bonneville's End-Use Load and Consumer Assessment Program (ELCAP). ELCAP data provide metered electricity consumption by end use for several hundred residential and commercial buildings in the Pacific Northwest. Monthly and daily electricity consumption is modeled as a function of weather so different weather scenarios may be simulated.

For global warming, the scenarios include a base case and two increased temperature cases. Weather-sensitive end uses include space heat, air conditioning, refrigeration, residential water heat, and irrigation. In the following analysis, results from the GFDL and GISS GCMs were used to specify average temperatures and heating and cooling degree days under equilibrium climate from a doubling of atmospheric $CO_2$ (as if that equilibrium climate were present in the years 1990 and 2010). Because there currently is no basis in Pacific Northwest regional power planning for long-range electricity demand forecasting (e.g., the year 2030 or 2050), the analysis is focused on the year 2010, the last year for which an official forecast was available. Temperature effects are associated with doubled levels of atmospheric $CO_2$, which are not expected to occur as early as 2010, thus possibly overstating the effect of climate warming on electricity consumption. Figures 5.1 and 5.2 show the $2XCO_2$ monthly average change in Pacific Northwest temperatures for two major GCMs: GFDL (Figure 5.1) and GISS (Figure 5.2). Temperature changes associated with the difference between current and doubled $CO_2$ climate were added to current actual average monthly temperatures; heating and cooling degree days then were calculated for use in computing changes in weather-sensitive loads. The weather-sensitive loads and the weather variables used to predict them are shown in Table 5.1.

The steps in the analysis were as follows:

- Bonneville's medium forecast of annual electricity consumption by end use was used as a base-case benchmark for the years 1990 through 2010.

- Monthly and daily electricity consumption data by end use were obtained from Bonneville's ELCAP data set for the residential and commercial sectors. ELCAP data collection began in 1985 for most sites. Electricity consumption data from July 1988 and February 1989 provided observations for very warm and very cold days, respectively.

- Historical temperature data were collected for three cities representing three geographic areas: Seattle for western Washington and western Oregon; Spokane for eastern Washington and eastern Oregon; and Boise for Idaho and western Montana. Daily high and low temperatures were used from October 1985 through March 1991, which is approximately the same time period covered by the ELCAP data set.

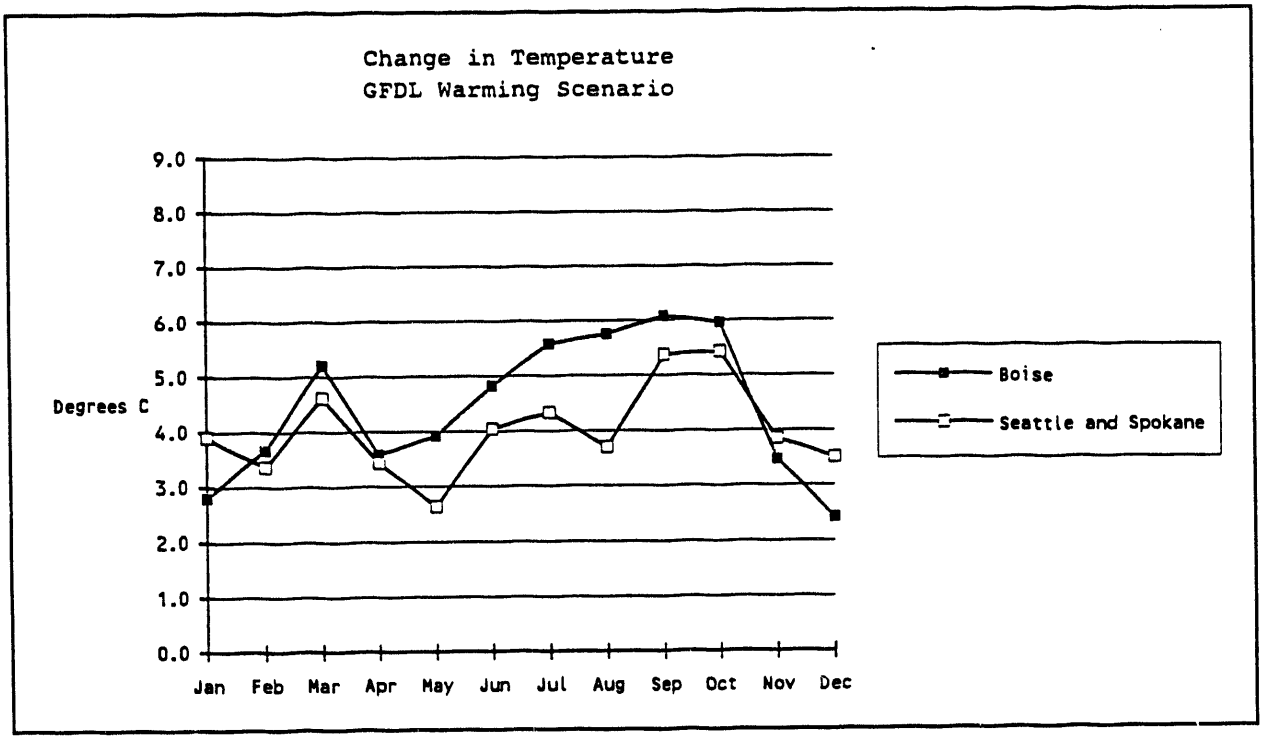


**Figure 5.1.** Impact of Climate Change on Pacific Northwest Temperatures, GFDL Warming Case

- Historical weather-sensitive electricity consumption was modeled for most end uses as a linear function of historical heating degree days, cooling degree days, or average temperature.[a] The large amount of data in the residential sector allowed residential space heat to be modeled as a non-linear function of heating degree days. Electricity consumption for residential hot water depends on the temperature of water flowing from outside the home into the water heating tank and was modeled as a constant plus a component that varies directly with outdoor temperature. Electricity consumption for irrigation was assumed proportional to the relative volume of water applied to crops in each scenario. Applied water increases by 22% in the GFDL scenario and decreases by 7% in the GISS scenario relative to baseline conditions.[b]

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(a) Experiments with engineering-based building energy end-use models, such as DOE2, indicate that humidity, wind speed, and solar insolation are important factors in energy use for heating and air conditioning (Scott et al. 1993). Data were not available in this case to adjust the simpler heating and cooling degree-day relationships, which did an accurate job predicting 1990 historical energy use.

(b) Data from R. M. Adams and N. K. Whittlesey, *The Effects of Climate Change on Water Demand: A Case Study of Irrigated Agriculture in the Pacific Northwest* (Draft), Oregon State University, Corvallis, Oregon, August 1991.

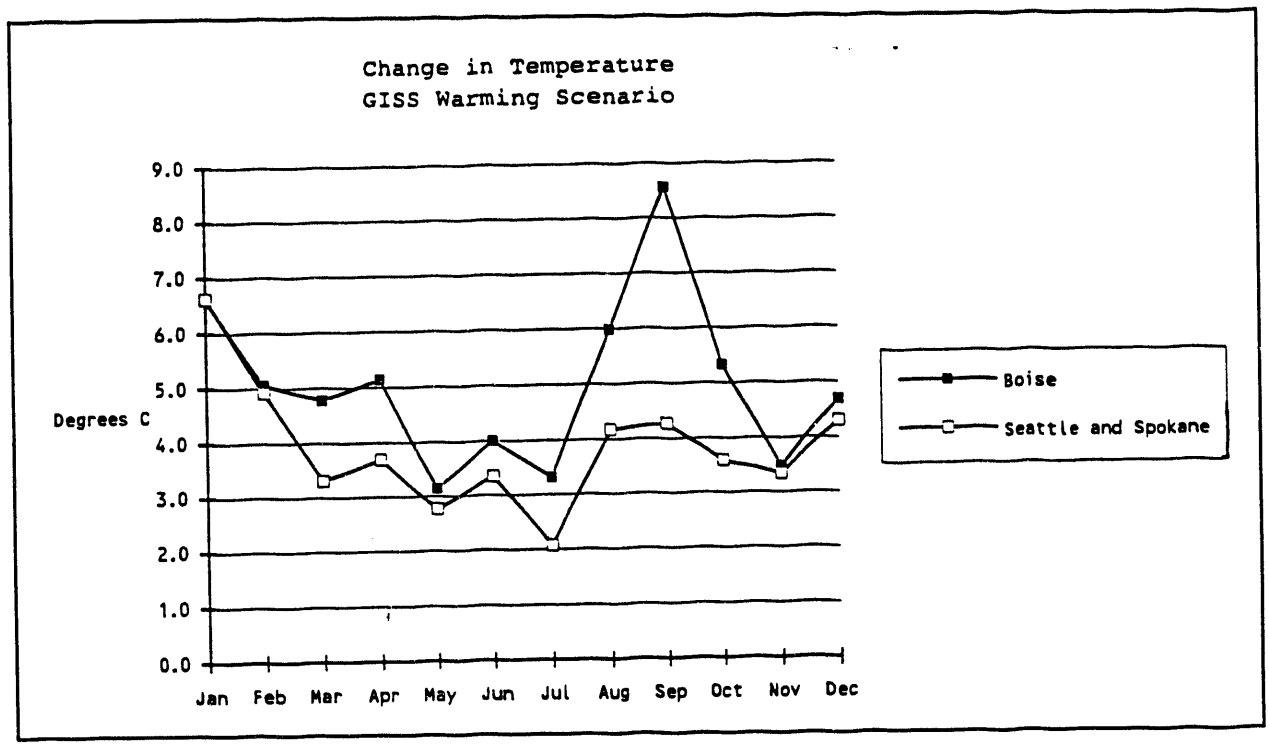


**Figure 5.2.** Impact of Climate Change on Pacific Northwest Temperatures, GISS Warming Case

- A global warming scenario was chosen and new average monthly temperatures were calculated. New measures of cooling degree days and heating degree days were constructed using daily high and low temperatures from October 1985 through March 1991. Weather-sensitive electricity consumption was then simulated by geographic area with the new weather assumptions. Table 5.2 shows average monthly temperatures used for Seattle. GFDL and GISS case values were obtained by adding the difference between average monthly temperatures for $1XCO_2$ and $2XCO_2$ equilibrium runs of each model to the monthly average historical Seattle temperatures, which are reported in the first column of Table 5.2. Similar data were derived for Spokane and Boise. Historical averages in Table 5.2 are based on data from October 1985 through March 1991.

- Daily electricity consumption on very warm and very cold days was simulated using daily cooling and heating degrees. February 3, 1989, was chosen as the winter peak day and July 20, 1988, as the summer peak day. Hourly peaks on those days were calculated using daily coincident load factors (the ratio of daily average energy to hourly consumption at the time of system peak). Winter peaks occur between 8:00 and 9:00 in the morning, while summer peaks occur in late afternoon.

**Table 5.1.** Predictors for Electricity Demand

| Load | Variable and Balance (Base) Temperature[a] |
|---|---|
| Residential Sector | |
| Space heat | Heating degree days (65°F) |
| Air conditioning | Cooling degree days (65°F) |
| Water heat | Average monthly temperature |
| Refrigeration | Cooling degree days (65°F) |
| Commercial Sector | |
| Space heat | Heating degree days (55°F) |
| Air conditioning | Cooling degree days (55°F) |
| Refrigeration | Average monthly temperature |
| Agricultural Sector | |
| Irrigation | Volume of applied water (no balance temperature) |

(a) For buildings, the balance temperature is the outdoor temperature at which neither heating nor cooling is assumed to occur. For refrigeration, it is the temperature at which the end use begins to respond significantly to temperature changes in the ELCAP data.

## 5.2 Electricity Demand Results

Tables 5.3, 5.4, and 5.5 provide estimates of monthly electricity consumption for each of five sectors. Only the residential, commercial, and irrigation sectors are assumed to be weather-dependent. Base-case estimates in Table 5.3 assume that weather in the year 2010 will match averages from October 1985 through March 1991. Table 5.4 contains the GFDL scenario, and Table 5.5 contains the GISS scenario.

In the global warming scenario, electricity consumption is reduced during winter month, but increases in the summer. Appliance stocks (or equipment saturation rates) were taken from Bonneville's long-term forecast. All values in Tables 5.3, 5.4, and 5.5 are in units of average megawatts, which are the common units of annual energy consumption used in Pacific Northwest power planning.

**Table 5.2.** Average Monthly Temperatures for Seattle (°F and °C)

| | Historical | | GFDL | | GISS | |
|---|---|---|---|---|---|---|
| | °F | °C | °F | °C | °F | °C |
| Jan | 41.4 | 5.2 | 48.4 | 9.1 | 53.3 | 11.8 |
| Feb | 42.8 | 6.0 | 48.9 | 9.4 | 51.7 | 10.9 |
| Mar | 46.5 | 8.0 | 54.7 | 12.6 | 52.4 | 11.3 |
| Apr | 51.2 | 10.6 | 57.3 | 14.1 | 57.8 | 14.3 |
| May | 55.6 | 13.1 | 60.4 | 15.8 | 60.6 | 15.9 |
| Jun | 61.6 | 16.4 | 68.8 | 20.5 | 67.6 | 19.8 |
| Jul | 64.7 | 18.2 | 72.5 | 22.5 | 68.5 | 20.3 |
| Aug | 66.5 | 19.2 | 73.1 | 22.8 | 74.0 | 23.3 |
| Sep | 61.9 | 16.6 | 71.6 | 22.0 | 69.6 | 20.9 |
| Oct | 53.5 | 12.0 | 63.3 | 17.4 | 60.0 | 15.5 |
| Nov | 44.7 | 7.1 | 51.6 | 10.9 | 50.7 | 10.4 |
| Dec | 39.6 | 4.2 | 45.9 | 7.7 | 47.3 | 8.5 |

Although summer electricity consumption increases in both the GFDL case and the GISS case, Figure 5.3 shows a net decrease in annual electricity consumption of about 4.5% overall in the GFDL case and 6.9% in the GISS case compared with baseline values. The drop in winter electricity consumption is greater than the summer increase (see Figures 5.4 and 5.5). The effect of climate change in the GFDL case is to reduce year 2010 combined annual commercial and residential electricity consumption by 8.5% relative to the base case, while in the base GISS case the decrease is 11.2%. While a transient scenario was not run to simulate the time-phased change in the demand for energy (from that in today's climate to that of a future doubled $CO_2$ climate), it appears that climate change could have a significant effect on delaying the need for new electricity-generating resources in the next century.

The global warming simulations reported in Tables 5.4 and 5.5 hold the stock of air conditioners fixed at market penetration rates provided in Bonneville's forecast, but the simulations allow for existing air conditioners to be used more during warmer weather. With the increased temperatures shown in Table 5.2, it is very likely that many more homes will install air conditioning.

Only 32% of homes in the Pacific Northwest currently have some type of air conditioning, either room or central. This compares to a national average of about 64%. If the market penetration rate of air conditioners reaches the national average, then residential air conditioning loads would roughly

**Table 5.3.** Monthly Electricity Consumption in 2010 Base Case (average MW)[a]

| Month | RES | COM | IRR | IND | OTH | Total |
|---|---|---|---|---|---|---|
| Jan | 10,423 | 7,591 | 4 | 8,082 | 218 | 26,318 |
| Feb | 9,707 | 6,991 | 9 | 8,082 | 218 | 25,006 |
| Mar | 8,501 | 5,886 | 14 | 8,082 | 218 | 22,701 |
| Apr | 7,058 | 4,835 | 140 | 8,082 | 218 | 20,333 |
| May | 6,083 | 4,351 | 556 | 8,082 | 218 | 19,289 |
| Jun | 5,664 | 4,497 | 1,229 | 8,082 | 218 | 19,690 |
| Jul | 5,601 | 4,771 | 1,804 | 8,082 | 218 | 20,476 |
| Aug | 5,573 | 4,919 | 1,503 | 8,082 | 218 | 20,295 |
| Sep | 5,623 | 4,467 | 950 | 8,082 | 218 | 19,341 |
| Oct | 6,588 | 4,549 | 408 | 8,082 | 218 | 19,845 |
| Nov | 9,198 | 6,438 | 460 | 8,082 | 218 | 24,396 |
| Dec | 10,916 | 8,084 | 63 | 8,082 | 218 | 27,363 |
| Annual | 7,568 | 5,610 | 599 | 8,082 | 218 | 22,076 |

(a) RES = residential sector
COM = commercial sector
IRR = irrigation sector
IND = industrial sector
OTH = other.

double.[a] The last column in Table 5.6 shows the impact of doubling electricity consumption for residential air conditioning in the GFDL scenario (note the large increase in electricity consumption during July).

If warmer weather results in additional market penetration of residential air conditioning so the Pacific Northwest air conditioning market penetration is double what it would have been without global warming, then electricity consumption in the month of July in the GFDL case would be higher by

(a) We have no studies that suggest this degree of market penetration would actually occur. Thus, this doubling scenario should be considered as a sensitivity test only.

**Table 5.4.** Electricity Consumption in 2010 GFDL Global Warming Case (average MW)

| Month | RES | COM | IRR | IND | OTH | Total |
|---|---|---|---|---|---|---|
| Jan | 8,659 | 6,135 | 5 | 8,082 | 218 | 23,009 |
| Feb | 8,086 | 5,774 | 10 | 8,082 | 218 | 22,170 |
| Mar | 6,357 | 4,461 | 17 | 8,082 | 218 | 19,135 |
| Apr | 5,927 | 4,316 | 171 | 8,082 | 218 | 18,714 |
| May | 5,729 | 4,359 | 678 | 8,082 | 218 | 19,066 |
| Jun | 5,823 | 5,277 | 1,499 | 8,082 | 218 | 20,898 |
| Jul | 6,192 | 5,668 | 2,201 | 8,082 | 218 | 22,360 |
| Aug | 6,199 | 5,708 | 1,833 | 8,082 | 218 | 22,041 |
| Sep | 5,857 | 5,414 | 1,159 | 8,082 | 218 | 20,731 |
| Oct | 5,514 | 4,533 | 497 | 8,082 | 218 | 18,845 |
| Nov | 7,374 | 5,193 | 561 | 8,082 | 218 | 21,428 |
| Dec | 9,378 | 6,780 | 76 | 8,082 | 218 | 24,535 |
| Annual | 6,753 | 5,300 | 730 | 8,082 | 218 | 21,083 |

1,160 average MW and annual consumption would be higher by about 350 average MW (see Table 5.6). The decrease in annual energy consumption in the GFDL case is then reduced from 4.5% to 2.9%.

Changes in irrigation pumping loads are assumed to be proportional to changes in the amount of water applied to crops. This change in water use was supplied by R. Adams of Oregon State University and N. Whittlesey of Washington State University from output of computer models of irrigated farms in the Pacific Northwest,[a] which was in turn based on changes in crop water demand calculated by C. Rosenzweig and A. Iglesias at the GISS.[b] In the GFDL case, Adams and Whittlesey calculated that irrigation water applications would increase by 21%, while in the GISS case, it was calculated that water applications would decrease by 6%. In neither case was the impact large

(a) R. M. Adams and N. K. Whittlesey, *The Effects of Climate Change on Water Demand: A Case Study of Irrigated Agriculture in the Pacific Northwest* (Draft), Oregon State University, Corvallis, Oregon, August 1991.

(b) C. Rosenzweig and A. Iglesias, *Estimated Crop Yield and Water Use Impacts of Climate Change in the Pacific Northwest* (Draft), Goddard Institute for Space Studies, New York, New York, August 1991.

**Table 5.5.** Electricity Consumption in 2010 (GISS) Global Warming Case (average MW)

| Month | RES | COM | IRR | IND | OTH | Total |
|---|---|---|---|---|---|---|
| Jan | 7,282 | 5,227 | 3 | 8,082 | 218 | 20,813 |
| Feb | 7,346 | 5,346 | 8 | 8,082 | 218 | 20,999 |
| Mar | 6,891 | 4,711 | 13 | 8,082 | 218 | 19,914 |
| Apr | 5,879 | 4,312 | 130 | 8,082 | 218 | 18,621 |
| May | 5,715 | 4,347 | 517 | 8,082 | 218 | 18,879 |
| Jun | 5,748 | 5,139 | 1,143 | 8,082 | 218 | 20,330 |
| Jul | 5,808 | 5,224 | 1,678 | 8,082 | 218 | 21,010 |
| Aug | 6,295 | 5,799 | 1,397 | 8,082 | 218 | 21,792 |
| Sep | 5,813 | 5,304 | 884 | 8,082 | 218 | 20,301 |
| Oct | 5,708 | 4,345 | 379 | 8,082 | 218 | 18,733 |
| Nov | 7,588 | 5,307 | 428 | 8,082 | 218 | 21,623 |
| Dec | 8,883 | 6,399 | 58 | 8,082 | 218 | 23,640 |
| Annual | 6,577 | 5,121 | 557 | 8,082 | 218 | 20,555 |

enough to change the qualitative waterr supply results. However, the combination of new air conditioning loads and additional irrigation demand would come close to changing the Pacific Northwest into a summer peaking system, in terms of average monthly electricity consumption. More energy would be consumed in a hot summer month than in a mild winter month. Hourly peak loads, however, would still be greater in the winter than in the summer. Appendix B provides a summary of the peak impacts of global warming.

The possible future extension of irrigated acreage in the Pacific Northwest was not part of the Adams and Whittlesey analysis. If the climate becomes warmer and drier in the Pacific Northwest, then irrigated agriculture may become more economically attractive to farmers than dryland agriculture in some cases, leading to additional electric energy consumption. However, offsetting this tendency

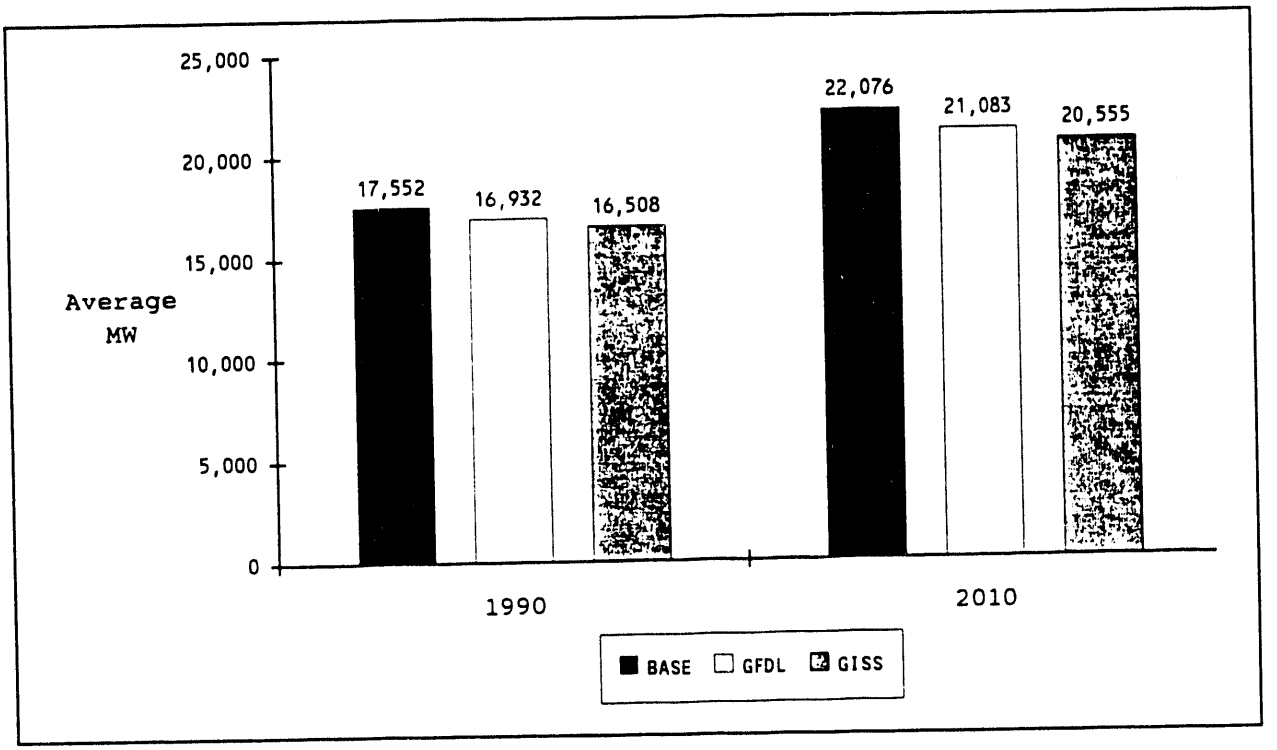


**Figure 5.3**. Effects of Climate Change on Annual Pacific Northwest Electric Energy Consumption in 1990 and 2010

could be a future increasing scarcity of water supplies in the region (leading to more efficient use of water) and a continuing penetration of low-pressure sprinkler irrigation systems in substitution for high-pressure systems.[a]

Irrigation loads presently comprise about 3.7% of the annual electrical load of the Pacific Northwest power system. In Bonneville's medium forecast, the load is projected to decline by approximately 6.4% over the next 20 years. Combined with the faster growth in other sectors, this implies a decline of irrigation's share from 3.7% to 2.7% (approximately 8.7% in the peak month of July). Without significant expansion of irrigated acreage in the GFDL case, the irrigation share shrinks to 3.5% (9.8% in July). If acreage expanded by the full 33.7% discussed by the Columbia River Water Management Group for the year 2030 (Depletions Task Force 1988), the difference in electricity

(a) This assumes that the extra water demanded and the electricity to pump the water are both proportional to the potential increase in acreage. It is probable that the new acreage would be less conveniently located for irrigation and, therefore, may require relatively more energy per acre-foot. On the other hand, the added cost might cause the water used per acre and the number of acres irrigated to be lower than forecasted. For purposes of our sensitivity calculations we have assumed that these effects would offset; however, it is questionable given foreseeable institutional conditions that anything approaching a one-third increase in total irrigated acreage in the Columbia Basin will ever come to pass.

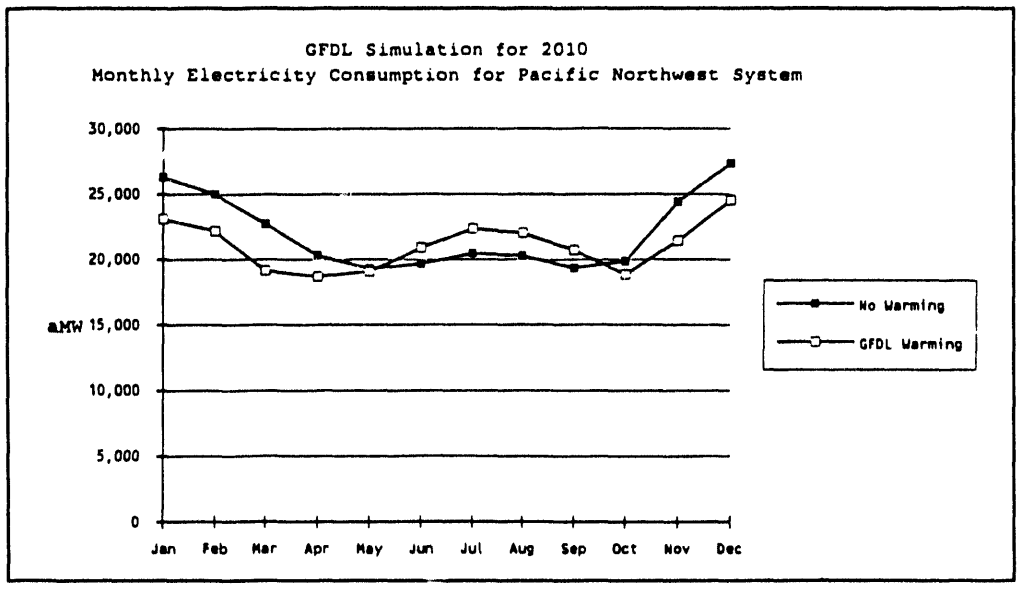


**Figure 5.4.** Effects of Climate Change in the GFDL Case on Pacific Northwest Electricity Demand in the Year 2010 (by month)

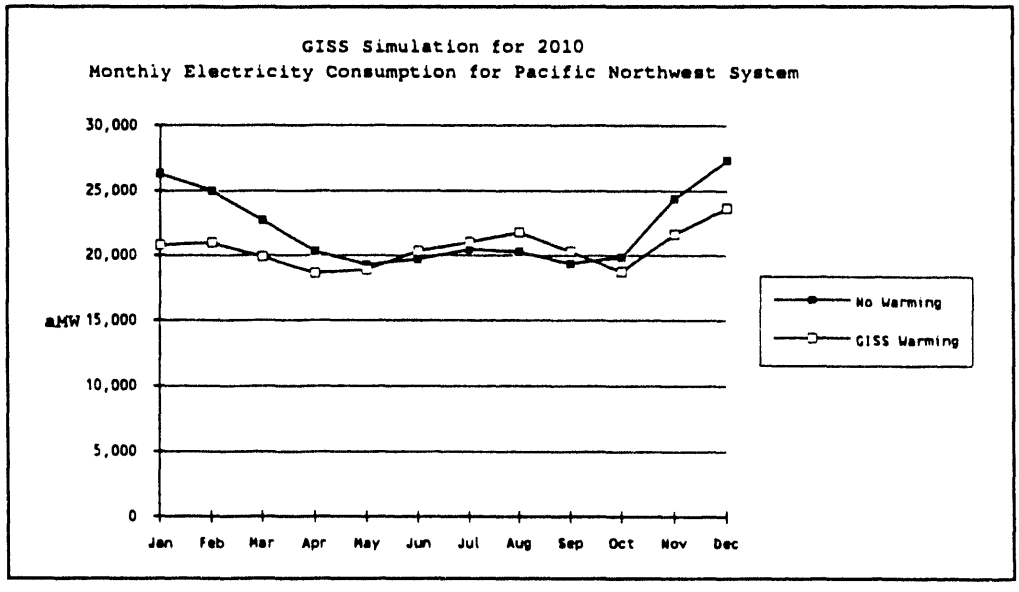


**Figure 5.5.** Effects of Climate Change in the GISS Case on Pacific Northwest Electric Energy Demand in the Year 2010 (by month)

**Table 5.6**. Monthly Electricity Consumption in 2010 Residential Sector (average MW)

| | | Global Warming (GFDL) | |
|---|---|---|---|
| Month | Base Case | Fixed Appliance Stock | Double Stock of Air Conditioners |
| Jan | 10,423 | 8,659 | 8,659 |
| Feb | 9,707 | 8,086 | 8,086 |
| Mar | 8,501 | 6,357 | 6,359 |
| Apr | 7,058 | 5,927 | 5,971 |
| May | 6,083 | 5,729 | 5,894 |
| Jun | 5,664 | 5,823 | 6,564 |
| Jul | 5,601 | 6,192 | 7,355 |
| Aug | 5,573 | 6,199 | 7,334 |
| Sep | 5,623 | 5,857 | 6,636 |
| Oct | 6,588 | 5,514 | 5,649 |
| Nov | 9,198 | 7,374 | 7,374 |
| Dec | 10,916 | 9,378 | 9,378 |

consumption would be about 240 average MW on an annual basis. Even with an ambitious and successful acreage expansion program, however, only about half of the acreage goal for the year 2030 would likely be achieved by 2010. This would increase electricity consumption in the year 2010 by about 120 average MW, moving irrigation's share from 3.5% to approximately 4.0%. The increase in July would be significant (about 365 average MW) and would increase irrigation's share from 9.8% to 11.2%.

This analysis primarily dealt with annual and seasonal energy demand. Peak power demand is also affected by climate change, probably by more in percentage terms than is energy demand. Appendix B covers some of the additional energy demand issues and further discusses peak demand.

# 6.0 Water Supplies in the Columbia River Basin

The distribution of precipitation in the Pacific Northwest is dominated by orographic influences. The climate of the rain forest of the Olympic Peninsula and the semi-arid sage steppe of the Lower Columbia Basin can both be attributed to orographic influences. Clouds moving eastward from the Pacific Ocean release moisture as they successively encounter the Coastal, Cascade, and Rocky Mountain ranges. Precipitation amounts decrease significantly east of the Cascade Mountains. Precipitation, particularly in the form of snow, again begins to increase as it moves up the western slope of the Rocky Mountains. Precipitation in most of the lower elevations of the Columbia River Basin is not adequate to supply the local water demand. Most of the water demand in these regions requires diversions from the Columbia River and its tributaries.

A complete system of reservoirs has been developed to help ensure the reliability of water supply for domestic, agriculture, fishery, and hydropower demands. Compacts between the variety of reservoir owners/operators have been established to reduce conflicts between upstream and downstream reservoir operations.

The total usable reservoir storage in the Columbia River system is approximately 41 million acre-feet. The 41 million acre-feet of storage amounts to about 30% of the Columbia River's average annual flow. In comparison, storage has been developed on the Colorado River and upper Missouri River equal to about 3.9 and 3.1 times their average annual flows, respectively. The relatively low storage of the Columbia River system means the firm energy load carrying capability (the ability of the hydroelectric system to satisfy demand under lowest runoff conditions) is significantly less than the long-term average capability.

Natural recharge of the groundwater reservoirs occurs very slowly in the drier regions of the Pacific Northwest — probably less than one inch per year.[a] Groundwater pumping in excess of natural recharge has resulted in a decrease in water table elevation in and limitations to additional water withdrawals in several localities,[b] as well as possible problems with land subsidence and reduced water quality.

There are 106 hydroelectric power plants in the Columbia River Basin above the Willamette River confluence with a total generating capacity of 35,724 MW. Of these reservoirs, 54 have a combined generation capacity of 936 MW. Of the remaining 52 reservoirs, 19 are operated for seasonal power storage with a combined water storage capacity of 41 million acre-feet.

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(a) U.S. Geological Survey 1984, pp. 355 and 433.
(b) Ibid., pp. 196, 358, 436.

## 6.1 Methodology

For analysis purposes, the hundreds of stretches of river comprising the complete Columbia River Basin system above the Willamette River were aggregated into 14 water and hydroelectric supply nodes. The plant data (i.e., relationship between hydropower generation, flow, and storage) for each of the nodes were generated by aggregating data from the individual plants and reservoirs. Table 6.1 defines each of the 14 nodes and their respective number of hydropower plants, percent of basin-wide hydropower production, number of storage reservoirs, and percent of basin-wide energy storage.

**Table 6.1.** Description of Subbasins in the Water Supply Model[a]

| Subbasin | | No. of Plants | Percent Generation | No. of Reservoirs | Percent of Stored Energy |
|---|---|---|---|---|---|
| No. | Description | | | | |
| 1 | Bonneville - McNary | 4 | 19.4 | 1 | 0.2 |
| 2 | Round Butte - Pelton Reregulation | 3 | 0.8 | 1 | 0.3 |
| 3 | Ice Harbor - Lower Granite | 4 | 6.7 | 0 | 0.0 |
| 4 | Dworshak | 1 | 1.4 | 1 | 4.5 |
| 5 | Brownlee - Hells Canyon | 3 | 4.3 | 1 | 1.1 |
| 6 | Priest Rapids - Coulee and Arrow | 8 | 33.8 | 2 | 23.2 |
| 7 | Chelan | 1 | 0.3 | 1 | 1.1 |
| 8 | Spokane River | 6 | 0.7 | 2 | 0.8 |
| 9 | Waneta - Thompson Falls | 10 | 8.3 | 4 | 4.8 |
| 10 | Kerr | 1 | 8.3 | 1 | 4.9 |
| 11 | Hungry Horse | 1 | 0.7 | 1 | 14.8 |
| 12 | Kootenay River and Duncan | 7 | 3.9 | 2 | 3.9 |
| 13 | Libby | 1 | 1.1 | 1 | 14.9 |
| 14 | Revelstoke and Mica | 2 | 18.0 | 1 | 25.5 |
| | Totals | 52 | 100.2 | 19 | 100.0 |

(a) While not reflected in the 14 nodes of the operating system above Bonneville Dam, the electrical generation of projects in the Willamette River, Lewis River, and Cowlitz River is included in the electrical production of the hydroelectric system.

The dams on the Columbia River and its tributaries are operated in a multi-layered planning system for purposes of flood control, navigation, instream flow for fish, irrigation, and hydroelectric power. The levels of individual reservoirs are set according to time-dependent "rule curves" that specify the rate at which reservoirs may be drawn down or refilled. There is, for example, a flood control rule curve that provides for adequate flood control storage space in the system. The power system planners also work with a worst-case sequence of low-flow water years called the "critical period," which is a 42-month sequence of flows that would produce the least amount of assured power production. The system works with flows leading to fixed reservoir draw-down rates from August through December, variable draw-down rates (depending on snowpack) from January through March, and reservoir refill from April through July. One of four different critical rule curves is used, depending on how full the reservoirs are on July 31 and how low the stream flows are throughout the year. During variable draw down and refill, the planners are guided by a variable energy content curve, which will assure a 95% chance that reservoir levels will reach 100% by July 31 without also risking severe flooding.[a]

Aggregating the complete reservoir network to 14 reservoir nodes maintains the overall structure of the complete Columbia Basin reservoir system, while bringing it down to a tractable size for regional impact assessments. This network model was designed to be driven by precipitation and runoff for a collection of "index" watersheds. The index watersheds are a representative sample of watersheds within the basin that can be aggregated to represent the entire basin. Conducting detailed hydrologic simulations of the entire region for which the assessment is being performed is both infeasible and unnecessary. The response of the entire basin can be reasonably assessed by aggregating the effect of a set of properly selected index basins. The criteria for selecting these index basins will depend on the hydrologic variability of the study region and the type of impact being considered. The project is developing a methodology for selecting and aggregating index basins in a hydrologically heterogeneous region for a variety of impact assessments.

One of the major problems in conducting regional climate effects studies is specification of climate scenarios that are consistent with large-scale climate simulations, similar to those produced by GCMs, providing information at the appropriate spatial scale for effects modeling. For instance, most natural processes respond to climatic inputs at spatial scales much less than the typical GCM grid spacing of several hundred kilometers. This is especially true of soil moisture, runoff production, and the dynamics of natural and cultivated vegetation (e.g., forestry and agriculture), as well as other sectors in which topography and/or geologic features play a critical role.

At a later stage in this ongoing study, the water supply analysis will be driven by runoff directly calculated from GCM output at four index watersheds in the power system model (see Appendix A). However, for this preliminary report we used a much simpler analysis. The analysis was based on analog water years, chosen by a two-step filtering process from the historical record, to simulate the effects of a shift in the Columbia River hydrograph under unusually warm conditions, as well as to simulate changes in the level of precipitation. In step 1, annual regional runoff estimated by GCMs was used as the basis for choosing five years with annual Columbia Basin runoff similar to that which

(a) For further details, see Bonneville Power Administration et al. 1991.

would be expected under GCM-simulated climate. Of the five, a year was chosen in step 2 that had its peak annual runoff closest to that expected under the desired climate change scenario. The baseline climate water year, chosen to be as typical as possible, was 1949 through 1950. A warm-wet analog was loosely based on the GFDL and GFDLs cases (increased temperatures and runoff). A sensitivity analog case assuming increased temperatures and reduced runoff (warm and dry conditions, rather than warm and wet) was also chosen. The water year chosen for a warm-wet analog was 1964 through 1965, while the warm-dry analog was 1965 through 1966. A more extreme hot-dry analog scenario similar to the Hypsithermal period of 6,000 to 8,000 years ago was chosen by picking the five lowest flow years on record and then choosing one that had its peak flow shifted the most toward the winter. The water year 1929 through 1930 was used to demonstrate the effect on power supply and flows for this low-flow case.

Table 6.2 shows the annual average temperature and precipitation anomalies for the GFDL and GISS $2XCO_2$ cases used by Rosenzweig and Iglesias for three Pacific Northwest locations, compared with the temperature and precipitation anomalies in the historical analog years used in the water supply

**Table 6.2.** Annual Temperature and Precipitation Anomalies for Spokane and Yakima, Washington, and Boise, Idaho, for the GFDL and GISS GCM Scenarios and Historical Analog Water Years (differences from long-term annual average temperature and annual average precipitation)

| | Location | | | | | |
|---|---|---|---|---|---|---|
| | Spokane | | Yakima | | Boise | |
| Case | Average Temp. (°C) | Annual Precip. (%) | Average Temp. (°C) | Annual Precip. (%) | Average Temp. (°C) | Annual Precip. (%) |
| GCM $2XCO_2$ cases | | | | | | |
| GFDL | +4.0 | + 6.8 | +4.0 | + 6.8 | +4.4 | + 7.9 |
| GISS | +3.9 | +23.6 | +5.0 | +23.4 | +5.0 | +23.4 |
| Historical analog cases | | | | | | |
| Warm-wet (1964 through 1965) | -1.4 | +25.0 | -0.5 | -9.9 | +0.6 | +0.9 |
| Warm-dry (1965 through 1966) | +0.1 | -22.2 | -0.4 | -12.1 | +1.4 | -31.8 |
| Low-flow (1929 through 1930) | +1.2 | -38.0 | +1.3 | -46.5 | +0.6 | -32.6 |
| Hypsithermal (6,000 to 8,000 years before present) | +1 to 2 | -38 | +1 to 2 | -33 | +1 to 2 | -38 |

analysis. Because climatological data were not available in many locations in the Pacific Northwest from 1929 through 1930, the date of our earliest historical analog year, nearby weather stations at Ellensburg, Washington, and Caldwell, Idaho, were used to provide historical anomaly data for Yakima and Boise, respectively.

In Table 6.2, the GCM scenarios appear warmer at all three locations than the historical analog scenarios, while the historical analogs appear drier but not quite as warm. In actuality, the effects of both types of scenarios on annual surface water runoff (and, hence, streamflow) may be much more similar than is apparent from focusing on temperature and precipitation alone. This is because the higher temperatures in GCM cases induce higher evapotranspiration, making relatively less water actually available for runoff. No adjustment was made for higher evapotranspiration. Thus, although precipitation increases slightly in the GFDL case, for example, the amount of water actually available for stream flow may decline slightly. It is likely that the historical analog cases include a greater reduction in total water supply when compared with GCM cases; however, it not clear which is more accurate.

Detailed simulations eventually will be performed on each of the selected index basins for the selected climate scenarios. Simulations will require some adaptation of state-of-the-art process models of snow, surface and subsurface flow, and evapotranspiration. The simulations will be validated using historical meteorological records and historical stream flow data.

## 6.2 Water Supply Results

Preliminary results have been produced for flow by month at each node in the system model, total hydroelectric power, and related statistics. The warm-wet analog was based on the GFDL and GISS cases, warm-dry analog climates were based on the GFDL case (with reduced precipitation), and a low-flow analog was based on the Hypsithermal case. It should be pointed out that the current system operation's rule curves, used to operate the system's reservoirs, take into account the protection of salmon and steelhead smolts as they migrate through the Columbia and Snake River mainstem reservoirs through the water budget (a block of 4.64 million acre-feet of water that can be released, if necessary, to maintain flows at target levels from upstream storage on the Columbia and Snake Rivers. This results in the hydroelectric generation figures shown in Table 6.3. The water flows in the warm-wet and warm-dry GCM scenarios are both comfortably above the flows experienced during critical water years used as a basis for Pacific Northwest power planning. However, the flows under the Hypsithermal historical analog are similar to what is expected during a critically low-water year.

The drier scenarios result in less hydroelectricity being generated than under current average conditions. However, a certain amount of shifting of generation capability does take place. For example, in both the low-flow year of 1929 through 1930 and the warm-dry scenario, about as much power is generated in the late summer, fall, and winter as under current average conditions, while less power is

**Table 6.3**. Columbia River Hydroelectric Power (average MW)

| Time Period Ending | Current Average | Warm-Dry | Warm-Wet | Low-Flow |
|---|---|---|---|---|
| Jul 31 | 10,120 | 10,199 | 22,194 | 10,514 |
| Aug 15 | 9,800 | 9,827 | 15,889 | 9,769 |
| Aug 31 | 9,637 | 9,676 | 13,396 | 9,607 |
| Sep 30 | 9,772 | 10,670 | 12,007 | 9,750 |
| Oct 31 | 10,042 | 10,961 | 13,644 | 10,127 |
| Nov 30 | 11,598 | 12,590 | 17,318 | 11,814 |
| Dec 31 | 12,954 | 13,935 | 22,312 | 13,054 |
| Jan 31 | 18,013 | 13,800 | 23,500 | 13,302 |
| Feb 28 | 15,879 | 12,775 | 22,486 | 12,009 |
| Mar 31 | 15,565 | 12,783 | 21,784 | 12,085 |
| Apr 15 | 15,533 | 12,069 | 20,779 | 11,144 |
| Apr 30 | 19,641 | 13,786 | 22,949 | 13,125 |
| May 31 | 21,474 | 17,114 | 22,769 | 16,197 |
| Jun 30 | 19,351 | 11,214 | 17,868 | 10,656 |
| Annual | 14,241 | 12,243 | 19,207 | 11,654 |
| Percent of average | 100.0% | 86.0% | 134.9% | 81.8% |

generated in the spring. The difference between the current climate and the warm-wet scenario is most noticeable in the November through April period, with warm-wet scenario providing considerably more power. However, this scenario actually generates less hydroelectric power during June than under the current climate. Generation of power is not the entire story, however, because the changed flow regime under a warmer climate moves the higher flows in the system toward the months when they are needed for space heat (see Table 6.4).

In examining month-to-month differences, it appears that in the warm-wet scenario, the Pacific Northwest hydropower system generally would come closer to generating the total needs of the Pacific Northwest's electrical demand sectors at most times of the year than under current conditions. Only June appears to be an exception and may be artifact of the years used as analogs for warm-wet and average conditions. In the warm-dry scenario, water (and hydropower) would be generally more avail

**Table 6.4.** Electrical Coverage Ratio: Columbia Hydroelectric Generation Divided by Total System Electric Load (average MW)

| Period Ending | Current Average | Warm-Dry (GFDL) | Warm-Wet (GFDL) | Low-Flow |
|---|---|---|---|---|
| Jul 31 | 0.494 | 0.456 | 0.993 | 0.470 |
| Aug 15 | 0.483 | 0.446 | 0.721 | 0.443 |
| Aug 31 | 0.475 | 0.439 | 0.608 | 0.436 |
| Sep 30 | 0.505 | 0.515 | 0.579 | 0.470 |
| Oct 31 | 0.506 | 0.582 | 0.724 | 0.537 |
| Nov 30 | 0.475 | 0.588 | 0.808 | 0.551 |
| Dec 31 | 0.473 | 0.568 | 0.909 | 0.532 |
| Jan 31 | 0.684 | 0.600 | 1.021 | 0.578 |
| Feb 28 | 0.635 | 0.576 | 1.014 | 0.542 |
| Mar 31 | 0.686 | 0.668 | 1.138 | 0.632 |
| Apr 15 | 0.764 | 0.645 | 1.110 | 0.595 |
| Apr 30 | 0.966 | 0.737 | 1.226 | 0.701 |
| May 31 | 1.113 | 0.898 | 1.194 | 0.850 |
| Jun 30 | 0.983 | 0.537 | 0.855 | 0.510 |
| Annual | 0.645 | 0.581 | 0.911 | 0.553 |

able in the winter but generally less available in the spring than under current conditions. In the low-flow (1929 through 1930 flow) scenario, water is less available in general, but appears to better match the timing of late fall and early winter demands; thus, average demand coverage is nearly as good as under current conditions. The difference is that there would likely be less secondary power available for sale to California in the spring, while slightly less power may have to be generated by the region's thermal plants or imported at other times. Water supplies are variable even when power generated is not variable. This is because the hydroelectric power system is operated conservatively, based on the

**Table 6.5.** Base Water Flow at John Day Dam (cubic feet/second)

| Period Ending | Current Average | Warm-Dry | Warm-Wet | Low-Flow |
|---|---|---|---|---|
| Jul 31 | 193,700 | 164,000 | 337,600 | 168,900 |
| Aug 15 | 117,700 | 111,900 | 183,700 | 117,800 |
| Aug 31 | 88,670 | 86,920 | 145,700 | 90,550 |
| Sep 30 | 76,820 | 88,830 | 101,200 | 66,200 |
| Oct 31 | 70,020 | 88,620 | 105,600 | 54,420 |
| Nov 30 | 83,320 | 77,060 | 137,300 | 46,690 |
| Dec 31 | 87,600 | 74,710 | 202,200 | 56,380 |
| Jan 31 | 86,780 | 71,030 | 190,200 | 37,200 |
| Feb 28 | 75,880 | 70,880 | 135,000 | 80,320 |
| Mar 31 | 125,400 | 99,750 | 165,600 | 72,430 |
| Apr 15 | 152,300 | 159,400 | 281,600 | 145,300 |
| Apr 30 | 336,000 | 175,500 | 451,300 | 230,500 |
| May 31 | 427,000 | 257,200 | 420,400 | 242,600 |
| Jun 20 | 478,100 | 266,600 | 315,100 | 288,200 |
| Annual | 171,378 | 128,029 | 226,607 | 121,249 |
| Percent of average year | 100.0% | 74.7% | 132.2% | 70.7% |

critical water period.[a] Table 6.5 illustrates the base flows at John Day Dam, which broadly represents the flows from the Columbia Basin as a whole. Base flows for other selected locations are shown at the end of Appendix A. Base flows are the natural flows net of irrigation withdrawals.[b] Base flows are not the same as actual flows (which can be a fraction of base flow or several times base

(a) As briefly discussed earlier, the critical water period is a historical period of 42 months, from 1928 through 1932, that shows the worst-case, multiple-year sequence of flows on record. This period's flows are used to determine how low-water levels can be allowed in each reservoir in the system under adverse flow conditions, given requirements for electric power, irrigation, navigation, flood control, and flows for fish. Because a 42-month period is used, all reservoirs do not have to refill completely in every year. However, the degree of protection of reservoir levels (restriction of flow) increases if the reservoir is not full on July 31, at the beginning of the water year (Bonneville Power Administration et al. 1991).

(b) Withdrawals for 1980 were used to compute base flows.

flow) because water is being released from upstream storage in the system during some parts of the year, increasing actual flow above base flow. Also, upstream reservoirs may be being filled at other times of the year, reducing actual flow. However, base flows more accurately reflect the effects of climate on the system's water supply than do actual outflows at the dams.

If there is no extension of the Pacific Northwest irrigated acreage, then climate warming would require changes in applied water in the existing irrigation system ranging from a decrease of 6% (GISS) to an increase of 21% (GFDL). The effects of irrigation on the water available for hydroelectric power are scenario-dependent but generally trivial for the system as a whole. For example, GISS crop water demand results in reduced depletion (slight improvement of flow) in the reservoirs on the Columbia River. However, on an annual average basis, the improvement is equivalent to only 508 cubic feet/second, measured at the mouth of the Columbia River, because of the ability of the water managers to manipulate the power system and robustness of the rule curves that they use. At the other extreme, GFDL increases depletions by a net 6,351 cubic feet/second averaged across the year, which is still a relatively small number in comparison with total flow. Summer outflow at the various reservoirs on the system is increased slightly in the GISS cases and reduced in the GFDL cases, resulting in a gain of 121 MW years (0.01 average MW) in the GISS case, a loss of 463.2 MW years (0.05 average MW) in the GFDL cases.

There is some irrigation-induced change in flow in the various subbasins that may turn out to be significant. Table 6.6 contrasts average base flow at selected projects in July with the change in water supply due to upstream depletions associated with existing irrigated acreage and flow gain or loss due to changes in precipitation in the GISS and GFDL cases.[a] The change is because of changes in water applied for irrigation, which depletes flow. Table 6.6 shows that the effect of climate-induced changes in irrigation of existing acreage, while not significant for the Columbia River as a whole, appears to be significant in the case of the Snake River subbasin above Brownlee Dam. For example, the relatively warm and dry GFDL case increases water demand per acre by about 22% and reduces water available flow above Brownlee by almost 17% under low-flow conditions.

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(a) While the warm-wet analog case and the low-flow analog case are not equivalent to the GISS and GFDL cases for reasons discussed earlier, combining them, as shown here, provides the reader with a sense of the combined effects of more (less) surface water being available, less (more) irrigation water being required per acre, and more acres under irrigation. The actual results will vary in a complex relationship to technology, institutions, and climate. After the hydrologic model is available, the comparison can be made directly.

**Table 6.6**. Incremental Effect of Irrigation Water Demand on River Flow at Key Points in the Columbia River System (cubic feet/second)

| Reservoirs | Warm-Wet Base Flow | Low-Flow Base Flow | Effect of Irrigation on Flows (Existing Acreage) Warm-Wet[a] | Low-Flow[b] |
|---|---|---|---|---|
| Bonneville | 337,100 | 176,900 | 508 | -6,351 |
| Ice Harbor | 54,750 | 30,260 | 467 | -5,029 |
| Dworshak | 5,793 | 2,629 | 305 | -630 |
| Brownlee | 10,080 | 9,051 | 791 | -1,516 |
| Priest Rapids | 267,600 | 137,700 | 63 | -930 |
| Spokane | 5,629 | 2,533 | 13 | -72 |

(a) Includes changes in GISS-related water use on today's irrigated acreage.
(b) Includes changes in GFDL-related water use on today's irrigated acreage.

Table 6.7 shows that the additional water use associated with the hypothetical increase of acreage (projected by the Depletions Task Force [1988] of the Columbia River Water Management Group for the year 2030) would, in most cases, offset the water savings associated with a warm-wet climate (GISS case) and would exacerbate the additional water demand associated with a warm-dry climate (GFDL case). For example, if the full hypothetical expansion of irrigation occurred as projected upstream from Brownlee and the climate were both warmer and drier, then July flow at Brownlee would be reduced by some 2,500 cubic feet/second (28%) from its already low value.

**Table 6.7.** Incremental Effect of Irrigation Acreage Expansion Plus Climate Change on River Flow at Key Points in the Columbia River System (cubic feet/second)

| | | | Effect of Expanded Acreage Alone | | Effect of Expanded Acreage Plus Climate Change | |
|---|---|---|---|---|---|---|
| Reservoirs | Warm-Wet Base Flow | Low-Flow Base Flow | Warm-Wet | Low-Flow | Warm-Wet | Low-Flow |
| Bonneville | 337,100 | 176,900 | -8,764 | -6,015 | -8,256 | -12,366 |
| Ice Harbor | 54,750 | 30,260 | -1,971 | -1,452 | -1,504 | -6,481 |
| Dworshak | 5,793 | 2,629 | 0 | 0 | +305 | -630 |
| Brownlee | 10,080 | 9,051 | -870 | -1,022 | -79 | -2,538 |
| Priest Rapids | 267,600 | 137,700 | -5,887 | -3,993 | -5,824 | -4,923 |
| Spokane | 5,629 | 2,533 | -17 | -10 | -4 | -82 |

Some problems worth mentioning are caused on some tributaries used heavily for irrigation although they do not generate significant hydropower. An example is the Yakima River, which does not appear in Tables 6.6 and 6.7. In the Yakima River subbasin, additional irrigation depletion amounts to approximately 390 cubic feet/second in the GFDL case. The river's late summer critical flow is considered to be about 560 cubic feet/second in the lower reaches, a figure that is not met in most years due to irrigation demand; thus, it is not at all clear that the additional water demand requirements could be met. Several of the Yakima's tributaries are virtually dry in their lower reaches by irrigation under current conditions. In most years in the late summer and early fall, the Yakima mainstem's flow in the lower reaches mainly consists of irrigation return flow, with high water temperature, inadequate volume, and low water quality all current or potential problems. According to the salmon and steelhead production plan for the Yakima River subbasin (Columbia Basin Fish and Wildlife Authority 1990), some degree of water rationing to irrigators is theoretically necessary in 9 out of 52 years, even under the current climate.

# 7.0 Salmon and Steelhead Survival

One of the more taxing problems associated with climate change in the Pacific Northwest is the potential effects on the region's salmon and steelhead resources, many of which are in great danger under current climate conditions. Our analysis focuses on the stream environment in the tributaries, in part because the main stream can be manipulated to protect salmon during their migration periods.

A preliminary qualitative analysis was performed on the effects of climate change on the salmon and steelhead resources of the Columbia Basin. This preliminary analysis focused on the historical analog climate from the Hypsithermal period (6,000 to 8,000 years ago). Analysis will be performed at a later date using GCM results, which are expected to be more favorable to salmon than the more extreme Hypsithermal case. The future results also will be quantitative, while the results in this preliminary report are qualitative (Chatters et al. 1991).[a]

## 7.1 Methodology

The qualitative analysis concentrated on four variables relating to the reproductive cycle of salmon and steelhead, likely to affect their survival, especially in the tributary environment. Subbasins within the Columbia River Basin were assigned values for these four variables. In Table 7.1, each variable was given a "+" rating if the Hypsithermal climate was likely to affect the variable in such a way as to improve survival, a "0" sign if the change was neutral in its effect on survival, and "-" if the effect on survival was deleterious. Descriptions follow for each effect.

The hydrograph is the annual distribution of water flows, which, in general, peaks each year in late fall or winter and early spring in drainages west of the Cascade crest and in late spring in the easterly drainages. A positive value in Table 6.1 means that there is an increase in the length of the period of peak flows during the period when smolts (juvenile salmon undergoing physiological changes to allow them to survive in salt water) are migrating out to sea. A negative value indicates either a constriction in this period of peak flow (freshet) or an earlier occurrence of peak flows, which would be mistimed for optimal smolt migration.

Sedimentation refers to the texture of the stream bed, which in drier regions will become progressively finer with reduced vegetation cover and reduced stream flows, but which may vary with flow in more heavily vegetated regions where sediment is obtained largely from stream banks. Values of

(a) A quantitative analysis has been performed for one stock (spring chinook in the Yakima River subbasin).

**Table 7.1.** Postulated Effects of Climatic Warming on Key Characteristics of Columbia River Subbasins

| Subbasin | Hydrograph | Sediment | Temperature | Flow |
|---|---|---|---|---|
| Columbia mainstem, mouth to Bonneville Dam | | | | |
| Grays River | 0 | 0 | 0 | + |
| Elochoman River | 0 | 0 | 0 | + |
| Willamette River | 0 | 0 | - | 0 |
| Sandy River | 0 | + | 0 | + |
| Kalama River | 0 | 0 | - | - |
| Washougal River | 0 | 0 | - | - |
| Lewis River | 0 | 0 | - | - |
| Cowlitz River | 0 | 0 | - | - |
| Columbia mainstem, Bonnevile Dam to Priest Rapids Dam | | | | |
| Hood River | 0 | + | 0 | + |
| Wind River | 0 | + | 0 | + |
| White Salmon River | 0 | 0 | 0 | 0 |
| Klickitat River | - | - | - | - |
| Fifteenmile Creek | - | - | - | - |
| Deschutes River | - | - | - | - |
| John Day River | - | - | - | - |
| Umatilla River | - | - | - | - |
| Walla Walla River | - | - | - | - |
| Yakima River | - | - | - | - |
| Columbia River mainstem, Priest Rapids Dam to Chief Joseph Dam | | | | |
| Wenatchee River | - | 0 | 0 | 0 |
| Entiat River | - | 0 | 0 | 0 |
| Methow River | - | 0 | - | 0 |
| Okanogan River | - | - | - | - |
| Snake River, mouth to Hells Canyon Dam | | | | |
| Tucannon River | - | - | - | - |
| Clearwater River | - | 0 | 0 | - |
| Grande Ronde River | - | - | - | - |
| Salmon River | - | - | 0 | - |
| Imnaha River | - | - | - | - |

(Source: Neitzel et al. 1991, p. 282.)

"+," "0," and "-" indicate a decrease, no change, and increase in fine sediment, respectively. The apparent inversion of values is because of the fact that fine-textured sediments negatively affect egg-to-smolt survival.

Temperature refers to water temperature, both in terms of annual means and seasonal variations. A temperature increase signifies a negative change in survival. An increase in temperature could increase the incidence of disease and fungal attacks in adult salmon and retard spawning to the point that the juvenile salmon are unprepared for marine life when the freshet comes to transport them to the sea.

Flow refers to increases or decreases in the annual volume of flow for the rivers of interest and their major tributaries. An increase has a positive effect on survival, and a decrease tends to reduce survival. Flows affect the out-migration of smolts, timing of adult returns, the extent of smolt habitat, and, to some extent, the survival of eggs and fry. Flows are assumed to decrease on all streams under Hypsithermal conditions.

East of the Cascade Mountains where catastrophic winter floods are less common, the reduction in annual flow would generally have a negative effect by reducing the overall extent of fish habitat and slowing the out-migration of smolts. West of the Cascade Mountains, particularly in the case of steep gradient mountain streams, winter flooding is frequent. In this case, reduced annual flows would mean greater stream-bed stability, greater survival of eggs and fry, and greater ease of adult returns in the fall and winter.

Effects on the Columbia River Basin's subbasins of a climate change to a warmer, drier Hypsithermal-like climate will vary with geography. The geographical groupings used here follow the groupings used in the *Columbia Basin System Planning Production Plan* for salmon and steelhead (Columbia Basin Fish and Wildlife Authority 1990a). The details of these effects are explained below.

### 7.1.1 Columbia Mainstem, Mouth to Bonneville Dam

Subbasins in this segment can be divided into four groups. Coast range streams, such as the Grays and the Elochoman, are all affected either positively or neutrally. Higher temperatures here are mitigated by the proximity of the ocean, and flows are expected to be lower because of a reduction in available moisture. Vegetation is sufficiently dense in that it prevents significant amounts of sediment from running off into streams. The Cowlitz, Lewis, and Willamette Rivers all flow from the west flank of the Cascade Mountains, where elevated temperatures are expected to reduce runoff (and available water) and increase water temperatures. However, the Willamette River, which draws water from the coast and Cascade ranges and flows slowly for great distances through the lowlands, is likely to experience a slight elevation in temperature. All other effects of climate change should be averaged by differences among the source streams. The Sandy River drains the west slope of Mount Hood and should experience some reduction in sedimentation as the basin becomes vegetated at higher elevations. Flows should also decline because of lower moisture availability. Negative effects on the hydrograph and temperature should be prevented by the elevation and aspect of the Sandy River's source.

### 7.1.2 Columbia Mainstem, Bonneville Dam to Priest Rapids Dam

This set of streams can be divided into those that drain the Columbia Gorge area and those that arise entirely east of the Cascades. Columbia Gorge streams would experience either no change or positive changes in flows and sedimentation and largely unchanged temperature and hydrograph characteristics. These streams are either relatively low-elevation, high-gradient streams draining protected basins that receive extensive winter precipitation, or they are streams flowing from snow-capped Mount Adams. Increases in precipitation are likely to be translated into increased vegetation density and cleaner stream beds on this verge of the open forest, along with increased stream flows. Because precipitation is largely winter rain on low areas and snow at high elevations under both Hypsithermal and current climate, the hydrograph under climate change is likely to remain similar to that of today.

With Hypsithermal climate, streams arising east of the Cascades would be negatively affected in all cases. The hydrology of the eastern Washington and Oregon streams is dominated by high-elevation snow accumulation in the winter and snowmelt in the spring and early summer. Snow water storage is important because the difference in the amount of precipitation that occurs in the mountains compared with the areas near the mouths of these streams and the effect on the timing of annual runoff. For example, the average annual precipitation in the upper Yakima River Basin is 355 mm to 760 mm compared with 190 mm near the mouth of the Yakima River. Annual runoff of accumulated precipitation flows out of the basin when the snow melts, not during the winter when the precipitation falls.

Increasing average winter temperatures would reduce the amount of precipitation falling as snow. Winter rains would flow out of the basin during the winter. Additionally, rains would melt accumulated snow earlier in the year. For fish that have evolved to rely on spring snowmelt to assist them in their out migration to the ocean, a winter runoff and a lack of or decreased spring freshet will reduce their probability of survival.

### 7.1.3 Columbia Mainstem, Priest Rapids Dam to Chief Joseph Dam

The streams in this region all drain the east flank of the Cascade range. Impacts of warmer, drier Hypsithermal climate on variables important to salmonid production would vary with the length, elevation, and gradient of the stream. Short, steeper gradient streams draining higher elevations are expected to receive less severe impacts than longer, lower-elevation and lower-gradient streams.

This is true for the both the physical characteristics of the streams and the fish that may be using them. Given the types of climate changes we have described, the water in the lower-gradient stream will be moving more slowly, which allows the river more opportunity to be warmed. Sediments will also settle out over a longer stretch of the stream.

Both of these characteristics are likely to adversely affect fish. In addition to the these changes, there are likely to be more adverse impacts in the longer, lower-gradient streams because the lower

parts of streams are used by more fish. High, steep gradients usually prevent most fish from spawning or rearing in those parts of a river basin. The lower part of a basin is often used as a rearing and spawning area for some species or races.

### 7.1.4 Snake River, Mouth to Hells Canyon Dam

Three of the streams in this subbasin drain the Blue or Wallowa Mountains and two drain the Rocky Mountains. Climate change is expected to negatively impact salmon survival in the Blue and Wallowa group more severely because the drainage basins in these mountains are steppe-covered and/ or farmed over large areas. Impacts will be less in the Rocky Mountain streams because of the more extensive, more densely forested character of these basins (the Salmon River is an exception). It is expected to be harder hit because its basin is less densely forested. It would be subject to stream-bed erosion and stream-bed aggradation (sediment buildup) more than the more northerly basins.

### 7.1.5 Critical Habitat Issues

Each salmonid species and subspecies has a different life cycle that has adapted the fish to the environmental conditions in the stream or river of origin. Depending on these differences in life cycle, different variables are critical to the survival of the species or subspecies. Table 7.2 shows some of the critical habitat characteristics for each of the species in the Columbia River system.

**Table 7.2**. Critical Habitat Characteristics for Columbia River Salmonids

| Species/Subspecies | Critical Habitat Characteristics |
|---|---|
| Spring chinook | Freshet timing, smolt habitat |
| Summer chinook | Freshet timing |
| Fall chinook | Winter flow and temperature |
| Coho | Freshet timing; smolt habitat |
| Sockeye | Summer flow and temperature; spring flows; flows in spawning streams |
| Steelhead | Summer flows; juveniles can inhabit pools in intermittent streams. |

(Source: Neitzel et al. 1991, p. 286.)

## 7.2 Salmon Survival Results

As a result of these different controlling variables and the different effects on rearing habitat in the various subbasins, different effects are expected on different species. Table 7.3 shows these effects, not all of which are negative. Table 7.3 includes both hatchery stocks and naturally spawning populations using the streams listed. Many of the effects of climate change influence the survival of both hatchery and naturally spawning stocks in the stream environment. The effects of climate change on rearing and migrating juveniles and returning spawners, for example, are virtually the same for both types of stocks.

Table 7.3 shows that the effects of a Hypsithermal climate on spring and summer chinook are negative in most streams in which they now appear, largely because of the unfavorable effects of climate change on both the timing and size of the spring freshet. Any climate change that moves the freshet into the late winter would likely have the same effect, regardless of precipitation levels for the year as a whole. The effects on fall chinook and coho are dependent on water flows and temperatures, as well as freshet timing. The effects for these species are mixed, with effects ranging from largely positive in west side rivers to largely negative in the more easterly streams. Sockeye salmon differ from other salmon because they require a lake environment for part of their life cycle. Spawning normally occurs in streams that are tributaries of a lake. The sockeye fry migrate to the lake after emergence, remaining there for 1 or 2 years before migrating to the ocean. The warm summer water temperatures in the lakes and the lower spring flows of a Hypsithermal climate regime would lead mostly to negative effects on sockeye stocks that are, for the most part, severely depressed. Because steelhead tolerate warmer water and intermittent stream environments, they are likely to be either largely unaffected or even helped by a warmer climate.

**Table 7.3.** Postulated Effects of Climatic Warming on the Subbasins of the Columbia River Basin and the Resultant Impact on Salmonid Populations

| | Fish Species or Run[a] | | | | | |
|---|---|---|---|---|---|---|
| | Chinook Salmon | | | | | |
| Subbasin | Spring | Summer | Fall | Coho | Sockeye | Steelhead |
| Columbia mainstem, mouth to Bonneville Dam | | | | | | |
| Willamette River[b] | 3 | NA | 3 | 3 | NA | 3 |
| Sandy River | 4 | NA | 4 | 4 | NA | 4 |
| Grays River[c] | NA | NA | 4 | 4 | NA | 4 |
| Elochoman River[c] | NA | NA | 4 | 4 | NA | 4 |
| Kalama River | 3 | NA | 4 | 4 | NA | 4 |
| Washougal River | 3 | NA | 3 | 3 | NA | 3 |
| Lewis River | 3 | NA | 3 | 3 | NA | 3 |
| Cowlitz River[d] | 3 | NA | 3 | 3 | NA | 3 |
| Columbia mainstem, Bonneville Dam to Priest Rapids Dam | | | | | | |
| Hood River | 4 | NA | 4 | 4 | NA | 4 |
| Fifteenmile Creek | NA | NA | NA | NA | NA | 2 |
| Deschutes River | 2 | NA | 3 | NA | 2 | 4 |
| John Day River | 2 | NA | 3 | NA | 2 | 4 |
| Umatilla River[c] | 2 | NA | 2 | 1 | NA | 3 |
| Walla Walla River | 2 | NA | NA | NA | NA | 2 |
| Wind River | 4 | NA | 4 | 4 | NA | 4 |
| White Salmon River | 3 | NA | 3 | 3 | NA | 4 |
| Klickitat River | 2 | NA | 3 | 2 | NA | 4 |
| Lower Columbia River | 2 | NA | 3 | 4 | NA | 4 |
| Columbia River mainstem, Priest Rapids Dam to Chief Joseph Dam | | | | | | |
| Yakima River | 2 | 1 | 2 | 2 | 2 | 4 |
| Wenatchee River | 3 | 3 | NA | NA | 3 | NA |
| Entiat River | 3 | NA | 3 | NA | NA | 3 |
| Methow River | 3 | 3 | NA | NA | NA | 3 |
| Okanogan River | 2 | 2 | NA | NA | 1 | 3 |
| Snake River, mouth to Hells Canyon Dam | | | | | | |
| Tucannon River | 1 | NA | 1 | NA | NA | 3 |
| Clearwater River | 2 | 2 | 2 | 2 | NA | 4 |
| Grand Ronde River | 2 | 2 | 2 | 2 | NA | 4 |
| Salmon River | 2 | 2 | NA | NA | 1 | 3 |
| Imnaha River | 2 | 2 | 2 | NA | NA | 3 |
| Snake River | 2 | NA | 2 | NA | NA | NA |

(a) Effects on salmonid populations are indicated by the following:
1 = severe, adverse environmental change resulting in possible extinction of salmon stock
2 = adverse environmental change resulting in possible reduction of salmonid production
3 = no impact to the environment and no change salmonid production
4 = environmental improvement resulting in possible increase of salmonid production
5 = environmental conditions maximized for salmonid production
(b) Includes impacts to the Clackamas River salmonid populations.
(c) Did not evaluate chum salmon.
(d) Includes impacts to the Toutle River salmonid populations.
(Source: Neitzel et al. 1991, p. 288.)

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# Appendix A

# Climate Scenarios and Stream Flows

# Appendix A

## Climate Scenarios and Stream Flows

One of the major problems in conducting regional climate effects studies is specification of climate scenarios that are consistent with large-scale climate simulations, such as are produced by general circulation models (GCMs), but which provide information at the appropriate spatial scale for effects modeling. For instance, most natural processes respond to climatic inputs at spatial scales much less than the typical GCM grid spacing of several hundred kilometers. This is especially true of soil moisture, runoff production, and the dynamics of natural and cultivated vegetation (e.g., forestry and agriculture), as well as other sectors in which topography and/or geologic features play a critical role.

In any case, GCM information must be transferred downward to the scale where it can be used with existing sector models (e.g., water resources, agricultural, forestry), which generally make use of point or station weather records of precipitation and temperature. There are three general approaches which have been, or might be, applicable: 1) direct application of GCM output, 2) combined GCM and historical record approach, and 3) weather classification approach. The first technique, the direct application of GCM results, is accomplished by directly relating the output from the GCM grid that lies over the area containing the stations of interest. This is usually accomplished by regression or similar techniques. A linear relationship is developed between upper atmospheric variables and those at the surface of the station. Then GCM output can be substituted into the relationship to get the station variables under climate change conditions. This method, which is related to the approach used to "customize" numerical weather prediction results to the local level, works fairly well for temperature. However, given the general unreliability of GCM precipitation predictions, this technique has not performed well for the estimation of regional precipitation. Also, because of the inherent space-time variability of precipitation, this approach is usually limited to the monthly time scale only. Hydrological processes, in particular, respond to the storm time scale (typically, hours to days), so this limitation can be critical.

The second approach, combining GCM output and historical records, amounts to simply adjusting historical point climatological records, such as gauge precipitation and temperature, to be consistent with changes (e.g., the difference between a carbon dioxide [$CO_2$] doubling and a present climate simulation) for the GCM grid cell of interest. This was the approach used in the U.S. Environmental Protection Agency (EPA) Reports to Congress (Smith and Tirpak 1989; Lettenmaier and Gan 1990) and in more recent work (Lettenmaier et al. 1990; Mimikou et al. 1991). For example, if a GCM predicts an increase of temperature by 2°C for doubled $CO_2$ concentrations for the grid node closest to the region of interest, the temperature at the station is then increased by 2°C uniformly throughout

the historic record. The disadvantage of this method is that it completely decouples the effects analysis from the climate simulation. Further, it implicitly assumes that the stochastic structure of weather — for instance, precipitation, and temperature (such as the pattern of storm arrivals, the length of heat waves, and so on) — will be unaffected by climate change. In addition, the derived reliability of precipitation simulations is questionable because of the inherent problems of GCM precipitation simulations. Finally, precipitation cannot be considered uniform over a GCM grid cell, which imposes a spatial scale discrepancy on the resultant point simulations. GCM modelers caution against the use of GCM results in this manner (Grotch 1988). They argue that the "meaningful scale" of GCM simulations must include several (e.g., 4 to 10) GCM grid cells, which implies a region with a spatial scale on the order of a thousand, or thousands, of kilometers.

The third approach, the use of weather classification schemes, is potentially the most robust of the three. The method uses one of several classification schemes (e.g., cluster analysis, empirical orthogonal functions) to group certain days together into different classes based on large-area atmospheric variables that may include surface pressure, geopotential height at several pressure levels, and temperature and wind at various altitudes. Several investigators recently have pursued approaches that attempt to use large scale atmospheric information as the basis for determining daily "weather type" and small-scale regional precipitation (see, for instance, Bardossy and Platte 1991); McCabe et al. 1989; Wilson et al. 1992).

Large-scale atmospheric records with the same spatial resolution as the GCM can be obtained. These large-scale atmospheric variables are used as input for the clustering technique chosen. The classification technique will separate the days into different weather patterns that should correspond to different temperature and precipitation conditions at the stations. This allows for better simulation of the station variables by providing information through the weather class for the given day. Using these weather classes, existing statistical models of station temperature and precipitation values can be used with their parameters estimated separately for each weather class, providing a more physically based method of estimating climate change effects. It also incorporates the regional weather pattern as opposed to that at a single grid cell. We are currently developing algorithms that could be used to apply the third approach for regional climate assessments.

The source of historical data is the National Meteorological Center archival data set for the northern hemisphere; GCM results from the GFDL R30 model exist for present climate and $CO_2$ doubling for a 5-year period. The process of obtaining 100-year daily simulations of present and $CO_2$-doubling climates from the Max Planck Center is currently underway. These climate simulations will be used in conjunction with classification schemes and a daily stochastic precipitation simulation model for three stations in western Washington.

Because the weather classification system and related hydrologic results were not ready in time for this preliminary report, historical analog stream flows were used to illustrate the effect of wetter and drier stream flow conditions in the Pacific Northwest. Because these are historical analogs, they contain a wealth of detail concerning stream flow records. Because of the size of the Columbia River

Basin, it is not unusual to find that not all of the areas are uniformly warm or cold or even wet or dry. The main text of this report shows the flow of the Columbia River at John Day Dam as a way of characterizing the overall flow of the Columbia River Basin. The following Tables A.1, A.2, and A.3 show flow by month and annual average flow at other selected points in the system: Grand Coulee Dam, to characterize the upper Columbia and Canadian flows; Hells Canyon Dam, to characterize the upper and middle Snake River; and the Spokane River at Little Falls, to characterize flows (runoff) out of northern Idaho. Flows on individual tributaries vary more from case to case than does overall basin flow measured at John Day Dam.

**Table A.1.** Columbia River Base Flow at Grand Coulee Dam (cubic feet/second)

| Period Ending | Current Average | Warm-Dry | Warm-Wet | Low-Flow |
|---|---|---|---|---|
| Jul 31 | 149,500 | 130,800 | 261,300 | 123,600 |
| Aug 15 | 88,970 | 83,610 | 136,300 | 96,910 |
| Aug 31 | 65,820 | 63,270 | 112,100 | 71,380 |
| Sep 30 | 52,600 | 62,960 | 68,360 | 46,970 |
| Oct 31 | 43,140 | 55,130 | 67,950 | 30,790 |
| Nov 30 | 52,530 | 35,530 | 82,280 | 22,450 |
| Dec 31 | 40,880 | 32,840 | 114,100 | 25,030 |
| Jan 31 | 43,740 | 30,430 | 98,980 | 14,580 |
| Feb 28 | 32,460 | 28,940 | 68,410 | 29,140 |
| Mar 31 | 56,360 | 48,720 | 83,390 | 28,190 |
| Apr 15 | 74,160 | 93,500 | 172,000 | 81,170 |
| Apr 30 | 205,200 | 106,100 | 316,100 | 155,000 |
| May 31 | 273,100 | 172,700 | 324,100 | 164,100 |
| Jun 30 | 329,500 | 175,000 | 253,000 | 221,600 |
| Annual | 107,711 | 79,966 | 154,169 | 79,351 |
| Percent of average year | 100.0% | 74.2% | 143.1% | 73.7% |

**Table A.2.** River Base Flow at Hells Canyon Dam (cubic feet/second)

| Period Ending | Current Average | Warm-Dry | Warm-Wet | Low-Flow |
|---|---|---|---|---|
| Jul 31 | 8,313 | 8,768 | 9,336 | 9,167 |
| Aug 15 | 7,760 | 8,338 | 9,194 | 8,488 |
| Aug 31 | 7,752 | 8,329 | 9,168 | 8,484 |
| Sep 30 | 9,453 | 10,970 | 10,500 | 9,636 |
| Oct 31 | 12,470 | 12,760 | 12,110 | 11,750 |
| Nov 30 | 12,590 | 13,990 | 12,760 | 12,600 |
| Dec 31 | 16,940 | 14,870 | 12,890 | 14,750 |
| Jan 31 | 14,600 | 15,280 | 15,060 | 12,930 |
| Feb 28 | 15,540 | 16,980 | 12,660 | 15,730 |
| Mar 31 | 20,560 | 18,220 | 13,760 | 15,900 |
| Apr 15 | 28,830 | 17,220 | 12,600 | 12,310 |
| Apr 30 | 30,200 | 17,240 | 12,690 | 12,250 |
| May 31 | 32,510 | 15,280 | 9,209 | 11,340 |
| Jun 30 | 25,930 | 16,080 | 8,803 | 10,170 |
| Annual | 17,389 | 13,880 | 11,481 | 11,822 |
| Percent of average year | 100.0% | 79.8% | 66.0% | 68.0% |

**Table A.3.** River Base Flow at Little Falls (cubic feet/second)

| Period Ending | Current Average | Warm-Dry | Warm-Wet | Low-Flow |
|---|---|---|---|---|
| Jul 31 | 2,961 | 2,132 | 4,831 | 2,533 |
| Aug 15 | 2,017 | 1,731 | 2,500 | 1,852 |
| Aug 31 | 1,829 | 1,592 | 2,012 | 1,586 |
| Sep 30 | 1,832 | 1,953 | 2,154 | 1,835 |
| Oct 31 | 1,896 | 2,197 | 3,467 | 1,871 |
| Nov 30 | 3,828 | 2,925 | 7,407 | 1,782 |
| Dec 31 | 6,643 | 5,918 | 33,030 | 2,587 |
| Jan 31 | 9,276 | 6,440 | 24,070 | 1,600 |
| Feb 28 | 5,990 | 5,638 | 13,090 | 5,294 |
| Mar 31 | 14,730 | 7.037 | 18,010 | 5,347 |
| Apr 15 | 14,300 | 7,429 | 25,900 | 13,420 |
| Apr 30 | 36,240 | 6,120 | 18,390 | 12,320 |
| May 31 | 17,830 | 8,497 | 9,645 | 8,410 |
| Jun 30 | 7,870 | 5,376 | 4,048 | 5,142 |
| Annual | 9,089 | 4,642 | 12,040 | 4,684 |
| Percent of average year | 100.0% | 51.1% | 132.5% | 51.5% |

# Appendix B

# Peak Impacts and Other Electricity Demand Issues

# Appendix B

# Peak Impacts and Other Electricity Demand Issues

## B.1 Peak Impacts

Electricity consumption in the Pacific Northwest peaks during cold weather because of the large amount of electric space heat and relatively small amount of residential air conditioning in the region. The Pacific Northwest electricity generating and transmission system has been considered energy constrained (and not capacity constrained) because of the large storage and generating capacity of hydroelectric dams. Two recent cold snaps, however, have strained the capacity of transmission lines to bring power to the Puget Sound area, increasing regional interest in peak loads.

This appendix describes potential impacts of global warming on peak loads, both summer and winter, in the Pacific Northwest. Of particular interest are the changes in average monthly electricity consumption and hourly peaks. Required transmission capacity depends primarily on hourly peak loads in the winter. Power sales to markets outside the Pacific Northwest are affected by changes in summer electricity consumption.

Electricity consumption at the regional level is usually measured in units of average megawatts (MW), or average power over some time period. It is often called average energy, which actually has units of megawatt-hours per hour. The Bonneville Power Administration (Bonneville) and the Northwest Power Planning Council provide a joint forecast of annual electricity consumption by end use in average MW, providing a benchmark for the analysis in this document.

A progression of energy measures is constructed by using progressively shorter time periods. This is especially useful for weather sensitive end-uses such as space heat and air conditioning:

1. average annual energy

2. average energy during peak month

3. average energy during peak day

4. average energy during peak hour.

Hourly end-use load data from Bonneville's End-Use Load and Consumer Assessment Program (ELCAP) provided essential information to first break annual electricity consumption into its monthly distribution, and then into peak days and peak hours. For example, space heating is concentrated in the winter months, and average January consumption is greater than the annual average. Space heat consumption is modeled at the monthly and daily levels by using monthly heating degree days and daily heating degrees, respectively. Daily coincident load factors, based on hourly metered data, convert average daily consumption to electricity consumed during the hour of system peak.

Daily high and low temperatures can vary greatly within a month, especially for months with very cold or hot weather. The Pacific Northwest experienced unusually cold weather during February 1989 and December 1990, with system load peaking on February 3, 1989, and December 21, 1990. February 3, 1989, was chosen as the peak winter day for this analysis because the ELCAP sample has decreased in size from 1989 to 1990.

Table B.1 shows the progression from average annual energy to winter and summer peaks for the residential and commercial sectors. Winter peaks are driven primarily by electric space heat in both sectors, while summer peaks depend mostly on air conditioning. Global warming will lower winter peaks and increase summer peaks.

One way to check peak load simulations is to compare them with historical peaks at the system level. This was done using a Geophysical Fluid Dynamics Laboratory (GFDL) simulation for 1990 and actual 1990 Pacific Northwest system peaks, which is shown in Table B.2. The winter hourly peak was in December, while the summer peak was in July.

**Table B.1.** Winter and Summer Peak Electricity Consumption GFDL Simulation for 2010 (average MW)

| | Residential | | Commercial | |
|---|---|---|---|---|
| | Base | GFDL | Base | GFDL |
| Annual average | 7,568 | 6,753 | 5,610 | 5,300 |
| December average | 10,916 | 9,378 | 8,084 | 6,780 |
| Winter peak day | 16,631 | 14,916 | 13,603 | 12,128 |
| Winter peak hour | 22,345 | 20,005 | 16,336 | 14,500 |
| July average | 5,601 | 6,192 | 4,771 | 5,668 |
| Summer peak day | 6,597 | 7,552 | 6,186 | 7,083 |
| Summer peak hour | 9,743 | 11,228 | 10,400 | 12,213 |

**Table B.2**. Comparison to Historical System Peaks (average MW)

| | 1990 System Historical | 1990 Base System Simulation | 1990 GFDL System Simulation |
|---|---|---|---|
| 1990 average | 19,945 | 17,552 | 16,932 |
| December average | 24,336 | 21,026 | 19,006 |
| Winter peak hour | 34,108 | 34,792 | 31,830 |
| July average | 19,144 | 16,864 | 18,379 |
| Summer peak hour | 23,269 | 24,196 | 27,045 |

Note that while simulated hourly peaks match up well with historical data, the 1990 Base simulation begins from a lower baseline (in annual average MW) than does the historical data. This is because 1990 electricity sales were not included in Bonneville's forecast.

The GFDL system simulation in Table B.2 shows that average electricity consumption in July becomes close to average winter electricity consumption. Summer and winter hourly peaks, however, are still far apart.

Estimates of hourly peaks by end use depend critically on the ratio of electricity consumption at the hour of system peak to an average over 24 hours. Some of these ratios are shown in Table B.3.

Commercial heating, ventilation, and air conditioning (HVAC) in January is the sum of heating and ventilation, while commercial HVAC in July is the sum of cooling and ventilation. The main point of Table B.3 is that peak impacts are greater than average daily energy impacts. Air conditioning loads are concentrated in the late afternoon, resulting in a relatively high ratio of peak to average energy.

**Table B.3**. Peak to Average Ratios on Typical Weekdays

| End-Use | January Weekday | July Weekday |
|---|---|---|
| Residential | | |
| Space heat | 1.27 | -- |
| Air conditioning | -- | 1.74 |
| Commercial | | |
| Office HVAC | 1.34 | 2.14 |
| Retail HVAC | 1.15 | 1.78 |

## B.2 Other Issues

**Humidity** - Summers in the Pacific Northwest are generally dry with low humidity. The weather response functions estimated for this study are based on historical data that contain significant temperature variation in the summer but not much variation in summer humidity. The estimated response of summer electricity consumption to hot weather should be viewed as a temperature response with humidity held constant. If humidity were to increase along with global warming, then air conditioning loads would increase more than with constant humidity.

**Residential HVAC** - Bonneville's ELCAP data set provides hourly metered electricity consumption by end use for over two hundred single-family homes in the Pacific Northwest. This wealth of data allowed for a breakdown of homes into old and new and by location east or west of the Cascade Mountains. Residential space heat was modeled as a non-linear function of heating degree days, with 65°F as the base temperature, to allow for differences in balance temperatures between homes. The response curve of space heat consumption to heating degree days becomes linear during very cold weather, when average outdoor temperature is below the balance temperature of all homes.

**Weather diversity** - Three weather stations were chosen for this analysis: Seattle, Spokane, and Boise. As a cold snap or heat wave moves through the region, extreme high and low temperatures for each site may occur on different days. For example, February 3, 1989, is the day of system peak load in 1989. The coldest day in Spokane was February 2, while the coldest day in Boise was February 5. Winter peaks were simulated in this analysis using weather data from February 3 for all weather stations.

**Commercial HVAC** - The three components of HVAC are heating, ventilating, and air conditioning. Commercial HVAC is usually metered as one combined end use, and its three components can be separated analytically using hourly weather data. Pacific Northwest Laboratory analysts have applied such a decomposition to office and retail building types. In this study, however, the decomposition in Bonneville's long-term commercial forecast was used. Because they cannot be measured directly, commercial heating and cooling loads may not be as accurate as other end uses.

**Commercial building sample** - Commercial buildings vary greatly in type and size. The sample used for this analysis consists of approximately 15 office buildings, 15 retail buildings, and several grocery stores. Grocery stores provided commercial refrigeration data. Many building types, such as schools and hospitals, are not well represented.

**Weekday/weekend breakdown** - Weekday and weekend electricity consumption are similar in the residential sector but not always in the commercial sector. Commercial air conditioning can be much lower on weekends than on weekdays. Estimates of hourly air conditioning peaks in the commercial sector would change if the weekend/weekday difference was explicitly modeled.

**System-level data** - Because of the uncertainty of commercial heating and cooling loads, hourly system data were used to check hourly peaks in the base case simulation. Small errors in predictions of annual energy consumption will lead to large errors in predictions of hourly peaks for space heat and air conditioning.

Building closures and local power outages, which may be caused by extremely cold weather, help to keep winter peak loads lower than they would be otherwise. The December 1990 cold snap brought an ice storm that cut off power to some parts of the Puget Sound area.

**Weather variation** - Summer and winter weather can vary widely from one year to the next. The Pacific Northwest has experienced extremely cold weather, thought to occur at most once every ten years, in two of the last four heating seasons.

Daily high and low temperatures from October 1985 through March 1991 were used in this analysis. December was the coldest month in this time period. (January would be the coldest month if a longer time series had been used).

**Conservation programs** - A number of conservation programs are either planned or are in place for the Pacific Northwest. Fuel switching programs that replace electricity with natural gas are also being considered. Weatherization and fuel switching programs will reduce electricity consumption for residential space heat. Programs affecting water heaters, such as low-flow shower heads, will decrease electricity consumption more in the winter than in the summer. The net effect of residential conservation will be to reduce winter peaks more than summer peaks.

One of the largest commercial sector programs is lighting retrofits. This will help to reduce summer air conditioning loads but will increase winter heating requirements for buildings with electric space heat. Conservation in the commercial sector will decrease summer loads more than winter loads, which is the opposite of the residential sector.

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