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Climate Change and Resource Management in the Columbia River Basin

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Abstract: *Scenarios of global climate change were examined to see what impacts they might have on transboundary water management in the Columbia River basin. Scenario changes in natural streamflow were estimated using a basin hydrology model. These scenarios tended to show earlier seasonal peaks, with possible reductions in total annual flow and lower minimum flows. Impacts and adaptation responses to the natural streamflow scenarios were determined through two exercises: (a) estimations of system reliability using a reservoir model with performance measures and (b) interviews with water managers and other stakeholders in the Canadian portion of the basin. Results from the two exercises were similar, suggesting a tendency towards reduced reliability to meet objectives for power production, fisheries, and agriculture. Reliability to meet flood control objectives would be relatively unchanged in some scenarios but reduced in others. This exercise suggests that despite the high level of development and management in the Columbia, vulnerabilities would still exist, and impacts could still occur in scenarios of natural streamflow changes caused by global climate change. Many of these would be indirect, reflecting the complex relationship between the region and its climate.*

Keywords: *Climate change, climate impacts, water resources, Columbia River basin, transboundary water management.*

Introduction

Global climate change could have significant impacts on natural resource systems. Water resources and the ecosystems and human activities that depend on water availability are particularly likely to be affected by climate changes. Those impacts will depend very much on how humans have already manipulated the hydrologic system and on the extent to which past and current human activities already stress natural components of the system. In the case of large, complex, and heavily modified river systems, such as the Columbia River system in North America, the potential impacts of future climate changes can only be understood in the context of the evolving stresses and conflicts among the multiple uses of the basin's resources.

The Columbia River is the fourth largest river in North America (Snover, 1997), carrying an average of almost 247 billion cubic meters (200 million acre-feet) of water per year (Volkman, 1997). It is also one of the most valuable and heavily developed transboundary water resources in North America. The Columbia system produces more hydroelectricity than any other river system in North America, with average annual generation of 18,500 megawatts (U.S. Dept. of Energy-Bonneville Power Administration et al., 1991). Canada and the United States have historically managed the basin's water resources for a set of imperfectly coordinated uses, including agriculture, hydropower, navigation, recreation, sport and commercial fishing, log transportation, wildlife habitat, and urban, industrial, and aboriginal uses. Climate variability affects the total volume and temporal pattern of runoff in the basin, which, in turn, affects the value generated by these water uses and the extent to which they come into conflict with one another. This suggests that hydrologic changes caused by any long-term climate change will have ecological and socioeconomic impacts that may affect both the management of the system and the nature of conflicts among various resource users.

Institutional factors are likely to play a significant role in determining the extent to which this complex system can adapt efficiently and equitably to future hydrologic changes. Within each country, various institutions take responsibility for particular uses such as irrigation and hydropower production, and some mechanisms are in place for coordinating water allocation across sectors. In addition, there are binational agreements. The Boundary Waters Treaty of 1909, which created the International Joint Commission (IJC), also governs pollution control issues. The Columbia River Treaty, ratified in 1964, provided for the development of substantial storage capacity in the Canadian portion of the basin. Construction of the Canadian storage projects resulted in downstream flood management and hydroelectric benefits, which are shared between the two nations under the terms of this treaty.

There have been conflicts both within each country and between the two nations regarding the use and management of the Columbia's water resources. These conflicts have become more heated and costly as the variety and complexity of the uses and users of the Columbia River have grown. These developments have led to increasing calls for new systems of management that would allow for an integrated or holistic approach to water management within the basin (Day et al., 1997; Volkman, 1997). Current pressures for change may thus set the institutional stage for future efforts to accommodate competing interests in a changing natural resource base. Because policy choices made now could alter the costs of adapting to the effects of climate change, it will be important to consider the possible implications of climate change in weighing current policy options. There is tremendous uncertainty regarding the exact nature of future hydrologic changes in this region, but analyses of the potential impacts of a range of possible changes may be useful in developing strategies to deal with the effects of climate variability and climate change.

This article describes some of the available assessments of the impacts of global climate change on the water resources of the Columbia basin. The question of climate change impacts in the Columbia is not a new one (e.g., Lettenmaier et al., 1992; Marks et al., 1993), but the transboundary nature of this basin requires consideration of impacts on both sides of the border. We therefore offer to draw upon the published literature, recent work of the Climate Impacts Group at the University of Washington, and a set of interviews with various stakeholders in the Canadian portion of the basin to present a preliminary set of findings regarding vulnerabilities and alternatives for adaptive management.

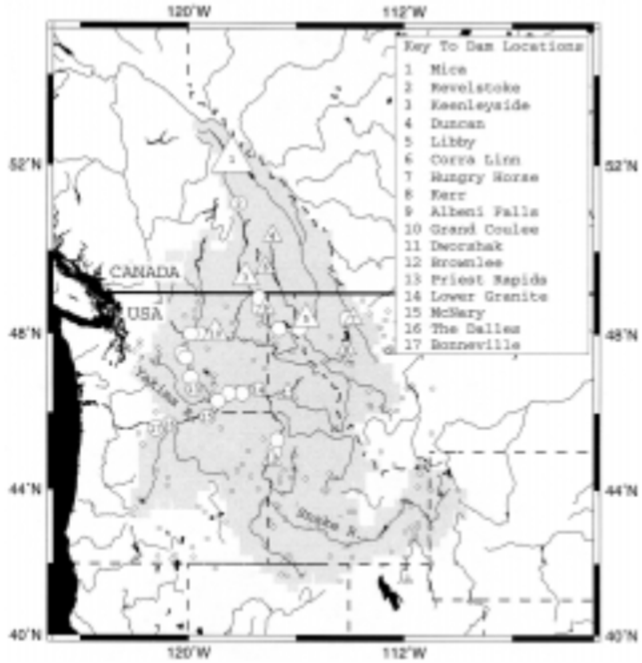

Figure 1a. Columbia River basin, including major dams and reservoirs. **Δ** = storage reservoirs (size is proportional to amount of storage capacity), and **O** = run-of-river facility.

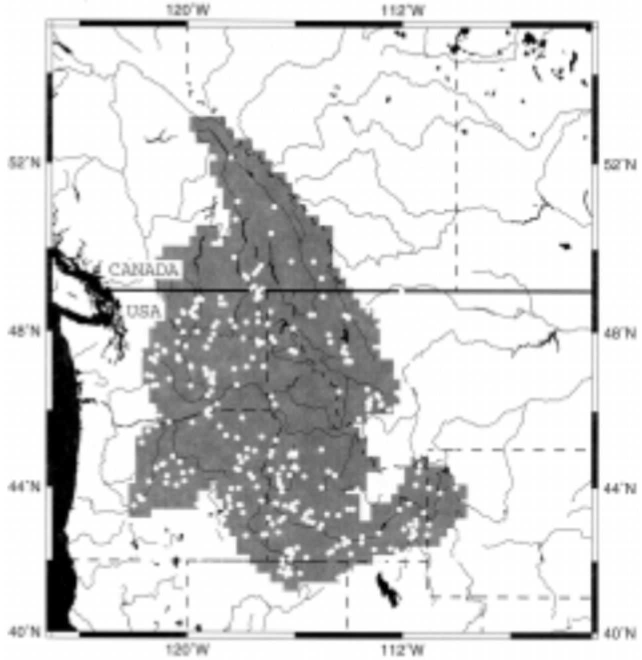

Figure 1b. Colombia River basin and all major structures.

Background

It is necessary to consider the implications of climate change for the Columbia basin in the context of the region's changing relationship with climate. This change is taking place in response to evolving competition for the region's water and related resources. When considering possible futures, climate will not be the only component to change.

Description of the Columbia Basin and its Development

The Columbia River basin covers a total area of 614,000 km^2 (236,000 mi^2) encompassing portions of six U.S. states and one Canadian province (Figures 1a and 1b). Striking geographical and seasonal contrasts mark the current climate of the Columbia basin. In winter, Pacific maritime air masses bring moisture into the basin, while the summer climate is dominated by warm and dry continental air masses (Power, 1985). The mountainous areas along the basin's perimeter receive heavy winter precipitation, while low-elevation areas in the center of the basin are hot and dry in summer and receive little precipitation even in winter. Figure 2 depicts the distribution of average annual precipitation over the basin. The areas of greatest precipitation are located in the Canadian portion of the basin and west of the Cascade Mountains. Flows from the latter area do not contribute significantly to power generation at the major mainstem dams, but there is hydropower generation on the Columbia's major tributaries on the west side of the Cascades, including the Cowlitz, Lewis, and Willamette Rivers.

The Canadian portion of the basin accounts for a major share of the runoff that can be used for hydropower generation at the Columbia River mainstem dams on the U.S. side of the border. In addition, flood flows on the lower river have historically been strongly affected by snowmelt runoff from Canada. "Although only 15 percent of the Columbia River Basin's land mass is in Canada, Canadian snow pack accounts for about 30 percent of the river's total discharge. Excluding tributaries west of the Cascades Mountains in the United States, Canada supplies about 44 percent of the river's discharge" (Volkman, 1997: 188). It was the potential value of controlling those Canadian flows that spurred the negotiation of the Columbia River Treaty.

Under current climate, the Columbia is a snowmelt-dominated system, with natural flow peaking sharply in June. The development and operation of water storage and diversion projects throughout the basin have substantially altered this natural flow regime. Climate change is likely to have further impacts on the seasonal distribution of runoff, with warmer temperatures causing earlier snowmelt and shifting the form of winter precipitation from snow to rain over parts of the basin.

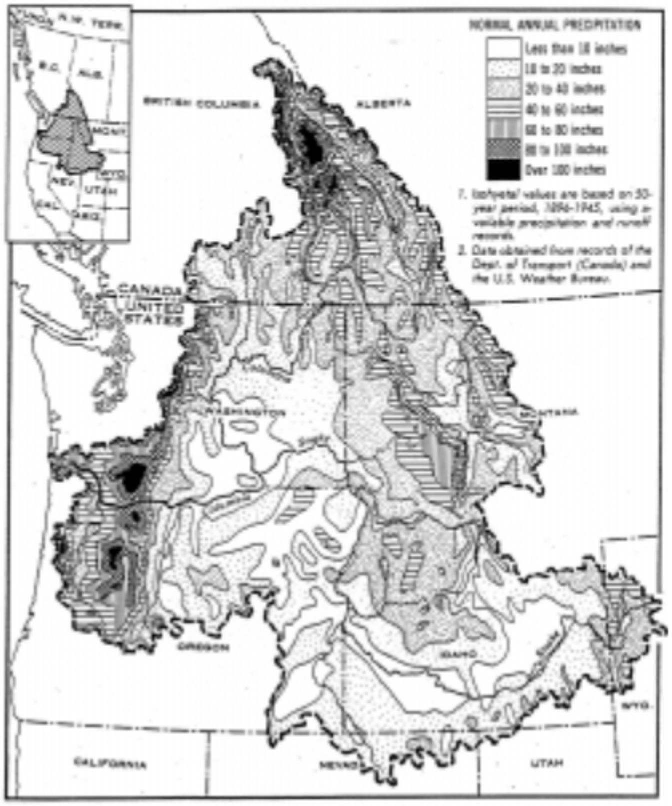

Figure 2. Annual precipitation (U.S. Congress, 1962).

Throughout the 20th century, the construction of large multipurpose dams and storage projects on the Columbia, Snake, and upper Columbia tributaries fundamentally altered the Columbia's hydrology and transformed it into a "working river" (Volkman, 1997). The construction of Bonneville, Rock Island, and Grand Coulee Dams, beginning in the 1930s, marked the beginning of this era of rapid development. Construction of the Canadian storage projects subsequent to the ratification of the Columbia River Treaty completed the transformation. The Columbia is now a highly developed multipurpose river system.

Hydropower production, flood control, navigation, irrigation, and fishery protection are all considered in the operation of the large multipurpose dams. Irrigation is the major consumptive water use in the basin. Almost 2.4 million hectares (6 million acres) are irrigated on the U.S. side of the border. Much of that irrigated agriculture is concentrated along the Snake River and in tributary watersheds such as the Yakima and thus does not depend on flows coming from Canada. The massive Columbia Basin Project, on the Columbia Plateau in the central part of Washington State, however, draws its water from the mainstem of the river. The project currently irrigates about 0.2 million hectares (half a million acres) by pumping water out of Roosevelt Lake above Grand Coulee Dam, which is the first mainstem dam south of the Canadian border (U.S. Dept. of Energy-Bonneville Power Administration et al., 1991). While irrigation use is large in absolute terms, irrigation withdrawals only account for about six percent of the Columbia basin's water (U.S. Dept. of Energy-Bonneville Power Administration et al., 1991).

Figure 1a displays the major dams in the Columbia basin, but these are only the largest projects out of more than 200 hydroelectric projects in the basin (U.S. Dept. of Energy-Bonneville Power Administration et al., 1991). Figure 1b displays these smaller facilities. In addition, there are numerous irrigation impoundments at which no hydroelectricity is produced. Storage projects now provide the capacity to store approximately 30 percent of the average yearly runoff.

The effects of these dams on the Columbia's hydrograph are displayed in Figure 3. As more storage was added to the system, it was used primarily for flood control and hydropower generation. This allowed system operators to reduce the size of the annual peak in the lower Columbia and to increase the discharge of the river at other seasons, when it would be more valuable for power production. The addition of major Canadian storage projects during the 1960s–80s played a significant role in

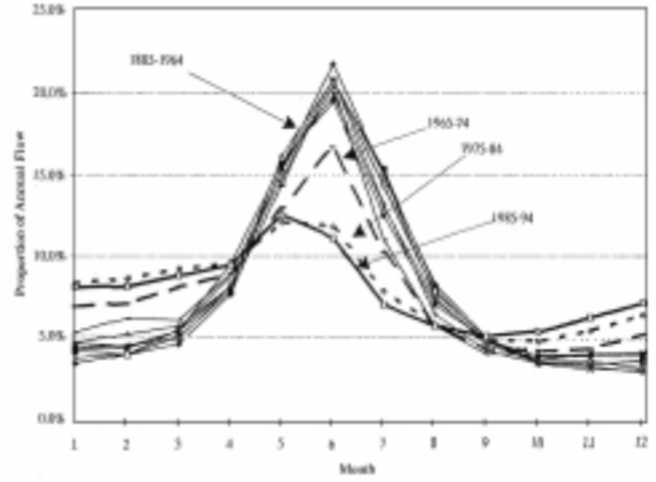

Figure 3. Changing the shape of the hydrograph. Source: Volkman, 1997. The cluster of 10-year blocks during the 1885–1964 period exhibited only minor variations in annual distribution at The Dalles. The addition of Duncan in 1967, Keenleyside in 1968, and Mica in 1973 reduced the spring peak and increased winter flows.

"flattening out" the Columbia's hydrograph (Figures 3 and 4). Use of that storage to alter the timing of flows increased the "firm," or reliable, power loads that could be generated at the downstream dams. That, and the flood control benefits, were the major sources of the value for those projects (Krutilla, 1967). In essence, these projects are an attempt to force the basin's hydrologic cycle to adapt to human needs.

The relationship between seasonal electric power demands, the natural annual hydrologic cycle, and operation of the system's hydropower generating system is currently evolving as increased transmission capacity and regulatory changes transform the electric power market. Formerly a regional market, where supplies of cheap hydropower fueled power-hungry industries such as aluminum and aircraft production, regional electric power producers now participate in a continental-scale market. Since continental electricity demand peaks in both midwinter and midsummer, these are the periods when water releases from the basin's hydroelectric facilities are most likely to occur. However, this bimodal cycle differs from the single peak that prevails in the natural cycle of runoff during the spring snowmelt period. Flood control and irrigation requirements also influence the timing and amount of releases and create water quality problems unique to dam and reservoir operations. These varied pressures alter hydrologic conditions for the basin's fishery resources. At the same time, water-related conflicts have developed among other stakeholders as demands for the resource continue to increase.

Current Resource Use Conflicts

In recent years, the nature of water use conflicts in the Columbia basin has changed appreciably. Environmental, aesthetic, cultural, and recreational values that were given little attention during the period of dam development have become the central focus of policy debates. Awareness of the adverse environmental effects of the massive transformation of the Columbia system has grown, and the region's larger and increasingly urban population is expressing greater concern for environmental preservation than was evident a few decades ago. Current natural resource management issues and tensions among competing water users in the basin provide a context for understanding the potential implications of climate change.

Table 1 provides an overview of these issues. More complete discussions can be obtained from Volkman, 1997; Day et al., 1997; Pulwarty and Redmond, 1997; Bankes, 1996; Ellis, 1996; Miller, 1996, 2000; and Sustainable Fisheries Foundation, 1998.

Interjurisdictional Aspects

In addition to intersectoral conflicts, Table 1 includes reference to conflicts between jurisdictions. Several sets of actors with varying mandates influence operational decisions on different scales. This complex web of decision making on the part of governments and private interests affects the relationship between the basin and its climate.

The Columbia is an international basin, so the IJC has the mandate to regulate levels and flows primarily for flood control and navigation. Kootenay Lake and Osoyoos Lake operations are regulated through Boards of Control. The International Columbia River Board of Control monitors the Grand Coulee Dam, constructed 20 years before the 1964 Columbia River Treaty.

Reservoirs and hydroelectric generating facilities constructed within the Columbia River Treaty framework (Mica, Duncan, Keenleyside, and Libby Dams) are managed through operating plans jointly developed by the respective national entitites: BC Hydro on the Canadian

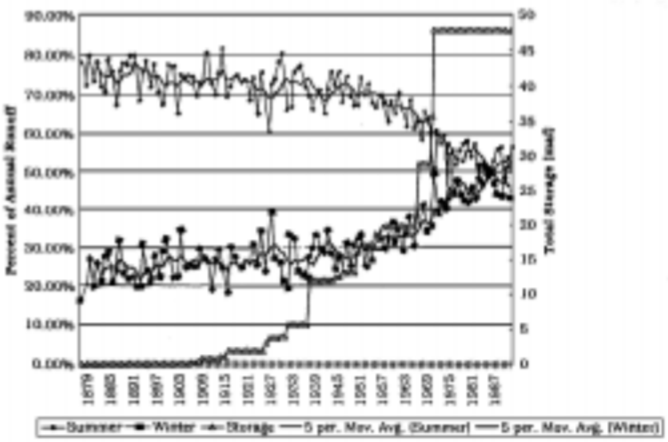

Figure 4. Change in Columbia River hydrograph at The Dalles, 1879–1992. Source: Volkman, 1997. The effect of storage projects on seasonal flow was modest until the 1960s. One maf (million acre-feet) = 1,233.5 million cubic meters.

Table 1. Resource Management Issues in the Columbia River Basin

Sectors	*Conflict or Instrument*	*Source*[1]
Hydroelectricity versus fish	Mortality of juvenile salmon during passage through hydropower turbines Damage to spawning beds and destruction of eggs due to flow changes Injury or death to fish due to high gas pressures in water downstream from dams Flow rates during fish migration and spawning affected by dams	Pulwarty and Redmond (1997), Volkman (1997), Sustainable Fisheries Foundation (1998)
Agriculture versus urbanization	Competition for water between expanding urban centers and irrigators	
Fish versus fish	Side effects of remedical actions to support certain species (e.g., whitefish, salmon, and trout have different requirements for timing of enhanced flows)	Sustainable Fisheries Foundation (1998)
Hydroelectricity versus flood control	Flood risk affected by residential encroachment onto low elevation sites IJC flow orders pre-date fisheries issues and shoreline encroachment	Bankes (1996)
Agriculture versus fish	Irrigation withdrawals affecting fish habitat (e.g., Snake River and Yakima River salmon) Water banks established to facilitate sharing of water	Ellis (1996), MacDonell et al. (1994), Miller (2000), Volkman (1997)
Interjurisdictional aspects	National legislation applied with binational side effects due to interaction of hydroelectricity and fish management responsiblities	Day et al. (1997), O'Neil (1997)

1. Also includes information obtained from interviews. See "Structured Interviews."

side and Bonneville Power Administration (BPA) and the Corps of Engineers on the U.S. side. The treaty empowers the Permanent Engineering Board (PEB) to assist in the settlement of any technical disputes relating to flow control or the operating plans (Wandschneider, 1984; Day et al., 1997). The treaty signatories can refer disputes to the IJC, but they have not yet done so.

There are numerous producers of hydropower in the basin who interact with one another either through explicit formal agreements or through competition in the regional electricity market. In Canada, Mica, Keenleyside, and Duncan Dams are operated by BC Hydro in cooperation with BPA. West Kootenay Power (WKP) operates four run-of-river hydroelectric facilities on the Kootenay River in BC. WKP also operates the Brilliant Dam near Castlegar as part of an agreement to purchase its power entitlement from the Columbia Power Corporation (CPC). CPC was recently established by the Province of British Columbia and the Columbia Basin Trust — a regional not-for-profit corporation (Government of British Columbia, 1995; Columbia Basin Trust, 1997, 1998). Other facilities are operated by Cominco Ltd., a mining and smelting operation.

In the U.S. portion of the basin, there are more than 250 storage and run-of-river projects, with ownership split among federal agencies, investor-owned utilities, consumer-owned utilities, and independent operators. The U.S. Army Corps of Engineers operates some of the sites, including Libby Reservoir (Lake Koocanusa), which it operates partly for downstream power benefits in the U.S. and Canada.

The coordination of British Columbia's electricity production and transmission and the growing interconnections between utilities are reflected in the activities of the British Columbia Power Exchange Corporation (Powerex), a subsidiary of BC Hydro. On the U.S. side, BPA operates the transmission lines and markets power directly and through other utilities. It is by far the largest actor in the region's electricity market, and its actions have a significant influence on those of Powerex and other utilities.

Fish conservation and rehabilitation concerns are also expressed at different scales. In Canada, the main responsibility belongs to the federal Department of Fisheries and Oceans (DFO) and the BC Ministry of Environment, Lands, and Parks (MELP). The U.S. Fish and Wildlife Service (USFWS), National Marine Fisheries Service (NMFS), and agencies in each state fill these roles in the U.S.

The Northwest Power Planning Council also continues to play a role in coordinating salmon restoration with power system operation, but that role has diminished in recent years. When the U.S. Congress passed the Northwest Power Act in 1980, it created the Northwest Power Planning Council. The Council was to plan the region's energy future while implementing a program to offset the effects of the dams on salmon and other fish and wildlife populations. Under the Northwest Power Act, the BPA uses hydropower revenues from federal projects to cover the costs of the fish and wildlife program. The Council adopted its first fish and wildlife program in 1982.

> The 1987 version of the program, which was the most fully developed program before the Endangered Species Act listings, aimed to double the salmon runs through a series of measures affecting all stages of the salmon life cycle: mechanical screens and bypass channels at the dams, flow augmentation, habitat restoration projects and other initiatives. (Volkman, 1997: 68).

Recent endangered species listings have largely overshadowed the Council's fish and wildlife program. In 1991, the NMFS listed Snake River sockeye salmon as endangered, and the following summer, classified Snake River spring/summer and fall chinook as threatened. In 1994, NMFS reclassified these chinook as endangered. In 1993, in accordance with the provisions of the Endangered Species Act, NMFS issued a biological opinion identifying minimum flows in the Snake and Columbia Rivers that would be necessary for the successful downstream migration of juvenile salmon. Unfortunately, in 1994, flows fell below those minimum targets: "Columbia River flows for the spring migration were more than ten percent below target flow levels, while Snake River flows for the summer migrations were short by more than 25 percent" (Ellis, 1996: 300). Mild drought conditions prevailed that year, with reconstructed Columbia River flow at The Dalles (adjusted for diversions) slightly below the long-term mean (Pulwarty and Redmond, 1997). The shortfalls occurred despite the fact that during the summer of 1994, water rentals from the Upper Snake River Rental Pool provided for the release of more than 431 million cubic meters (350,000 acre-feet) to augment the flow of the Lower Snake River for hydropower generation and anadromous fish passage (Miller, 2000).

Current efforts to preserve the remaining salmon stocks have focused on providing sufficient supplemental flows to return the flow regime to a more natural pattern. The agencies responsible for the operation of 14 U.S. federal dams now plan to operate those facilities in a manner consistent with two more Biological Opinions by: (a) NMFS for Snake River salmon and (b) USFWS for the Kootenai River white sturgeon (U.S. Dept. of Energy-Bonneville Power Administration et al., 1995). These opinions call for a set of strategies to enhance fish survival. In the case of the Snake River salmon, these include barge transportation of some smolts and provision of sufficient spill at Snake and lower Columbia River dams to move most naturally migrating smolts past the dams without passing through the turbines. The NMFS and USFWS biological opinions "are now regarded as setting the basic rules for system operations for salmon" (Volkman, 1997: A.1–A.2).

The Columbia River Treaty addresses the use of Canadian storage facilities only for hydropower generation and flood control. The treaty's negotiators did not envision any substantial use of that stored water for fishery preservation or other environmental purposes. Now that parties on the U.S. side are struggling to provide sufficient flows to preserve the Columbia's remnant wild salmon runs, they may wish to alter the pattern of releases from the Canadian storage reservoirs, particularly in low-flow years. However, under the terms of the treaty, Canada would have to be compensated if such changes reduced Canadian power generation (Day et al., 1997).

> There is no formal way to incorporate the needs of salmon or other environmental considerations into river management other than through economic trades . . . Adjustments can be made in system operations to accommodate such concerns, but the treaty's hydropower generation and flood control purposes require compensation for these changes. Thus, in the low-flow year of 1977 when fish interests sought water for salmon flows, Canadians were willing to help out at six US dollars per acre-foot (or around 0.05 US dollars per cubic meter). United States interests declined the offer at that price, and tried to make do. The fact that the Treaty makes river operations for fish and wildlife a cost rather than a value is a subject that has yet to be addressed in negotiations between the two countries. (Volkman, 1997: 30)

The interaction of power and fish management responsibilities creates a situation in which federal legislation can be applied with binational side effects. Recent concerns about ecosystem health in the lower Columbia led to a legal challenge by the Sierra Legal Defense Fund to the U.S. government, under the Endangered Species Act, to shift water management practices to a "fish first" approach. The challenge is based on the 1994 USFWS declaration of the Kootenay (Kootenai in the U.S.) white sturgeon as an endangered species in the U.S. This unilateral action led to changes in releases from Libby during sturgeon spawning season in 1995 and 1996. The British Columbia government asked for 5.6 million Canadian dollars in compensation for lost power, but the U.S. government rejected this (O'Neil, 1997). In two other cases, DFO has had to request flow changes at Keenleyside to protect rainbow trout and mountain whitefish. In all three cases, federal legislation in either Canada or the U.S. was used. The side effect was that changes in flow resulted in changes in flood control and power benefits, which were not contemplated in the international agreement covering the treaty facilities (Day et al., 1997).

The involvement of aboriginal and environmental interests in fisheries and water resources concerns (Canadian and U.S. Columbia River Inter-Tribal Fisheries Commissions, BC Wildlife Federation, Grand Forks Watershed Alliance, Pacific Rivers Council, Environmental Defense Fund, and others) has added to the complexity of regional decision making. These interests look for public participation arenas and have become involved in various committees such as the Columbia Operations Fisheries Advisory Committee (COFAC) and the Columbia Basin Trust Advisory Committee. There was also the May 1997 challenge by the BC Wildlife Federation, Sierra Legal Defense Fund, and the BC Aboriginal Fisheries Commission to the North American Commission for Environmental Cooperation (NACEC), established by the North American Free Trade Agreement (NAFTA). Part of the claim was that BC Hydro was not operating according to Canada's environmental standards, and that DFO was not enforcing Canada's Fisheries Act by protecting fish habitat from hydropower operations.

In summary, there are many actors operating at local, regional, provincial/state, federal, and international scales. Some nongovernment actors work across scales in order to promote their agendas. As issues have evolved, interjurisdictional bodies have been established that bring these various actors together. The evolution of these mechanisms may already be affecting the relationship between the basin and its regional climate.

Potential Sensitivities to Climate Change

As radiatively active trace gases continue to accumulate in the atmosphere, global warming may result. Current model projections suggest substantial warming in western North America over the course of the next century (IPCC, 1996). This has been recognized by the International Joint Commission (IJC) as a potential force of change that could alter drought and flood frequencies, hydroelectric power production, water demand, fish habitats, water quality, and navigation in transboundary watersheds (IJC, 1997).

How might the water-dependent resources and economic activities in the Columbia basin be affected by such a climate change? Two kinds of impacts are anticipated: (a) direct impacts on hydrology, vegetation, crop potential (e.g., growing season length), aquatic ecosystems, energy demand for heating and cooling, hydropower production, and flood risk and (b) indirect impacts through the various conflicts outlined above. These may influence institutional arrangements and create the potential for new conflicts.

A first step in assessing these impacts is to describe the range of possible changes in the hydrologic regime of the Columbia basin. "Climate Change Scenarios and Hydrologic Impacts" discusses several assessments of climate change impacts on the Columbia basin's water resources. While these suggest a wide range of possible results, they point to some general conclusions, including the high likelihood of a shift in the timing of seasonal peak flows, possible reductions in summer flows in at least some parts of the basin, and increases in water temperatures.

Our discussion of possible impacts will focus primarily on the implications of a climate change scenario reflecting these characteristics, as described below. Interviews conducted as part of this project made use of this scenario to guide the respondents' thinking about climate change impacts. It is important to emphasize, however, that any particular scenario represents only one possible picture of the future. The implications of a wide range of scenarios should be explored to develop a more complete picture of the possible impacts of a changing climate.

Climate Change Scenarios and Hydrologic Impacts

Global climate models (GCMs) have been the primary tool used to analyze the potential impacts of increased greenhouse gases (and more recently, the effects of aerosols) on global climate (IPCC, 1996). A GCM is a mathematical representation of the behavior of the atmosphere in which a horizontal and vertical grid structure is used to track the movement of air parcels and the exchange of energy and moisture between parcels. To be useful for the analysis of climate change, the atmospheric model must be coupled to models of other components of the climate system, such as the oceans and sea ice. A fairly elaborate climate model may include several vertical layers in the atmosphere and the oceans, as well as a dynamic sea ice model.

Despite improvements in the ability of these climate models to simulate large-scale climate processes, there continue to be inaccuracies in the representation of current regional climates due, in part, to the coarse spatial resolution on which these models must operate. Computational costs increase rapidly as the horizontal resolution of a model is increased. At present, it is prohibitively costly to run coupled climate models at a resolution that would be sufficiently fine to accurately depict the effects of mountains and other complex surface features on regional climates.

Inherent uncertainties in modeling the effects of global warming at the regional scale are compounded, in this case, by the influence of the region's complex topography on the Columbia basin's climatic regime. As indicated in Figure 2, precipitation is heavily concentrated in a few high-elevation areas, while much of the basin's land area lies in an intermountain rain shadow. At present, the flow of the Columbia is dominated by snowmelt from those high-elevation areas, with melt from glaciers contributing to late summer flows. The natural flow of the mainstem (measured at The Dalles, near Portland) peaks sharply in June, while the natural peak flow of the Snake River occurs in May. All warming scenarios indicate that winter precipitation, particularly at lower elevations, will be more likely to fall as rain rather than as snow and that the annual snowpack will tend to melt earlier. This results in an earlier peak in the annual hydrograph.

MPI Scenario

The scenario used in the interviews was based on a transient run of the Max Planck Institute (MPI) GCM. Lettenmaier et al. (1996) used this global scale data set to construct a regional scenario, which was applied by the Pacific Northwest Regional Climate Change Assessment Project (University of Washington Climate Impacts Group) to examine the near-term consequences of global warming for the Columbia basin (Miles, 1996; Snover, 1997). The term *transient* refers to the fact that the model was run assuming that global concentrations of CO_2 and other radiatively active trace gases would increase gradually over time, following an emissions scenario developed for the Intergovernmental Panel on Climate Change (IPCC) known as IPCC IS92a (Lettenmaier et al., 1996).

Estimates of climate changes are based on differences between the modeled current climate and "quasi-equilibrium" states for particular decades in the future. Estimated temperature and precipitation differences from the GCM run were interpolated to a finer-resolution scale to drive a 1 degree latitude-longitude grid hydrologic runoff model (Hamlet et al., 1997; Lettenmaier et al., 1996). The model uses temperature and precipitation data to calculate simulated natural streamflow at 71 sites within the Columbia River basin (Hamlet et al., 1997).

Under the MPI scenario, the region would experience warmer, wetter winters and warmer, drier summers. By the year 2020, the scenario suggests that average annual temperatures would be approximately 1°C warmer than at present, with average annual precipitation over the Columbia decreasing by approximately 10 percent (Figure 5). Further warming is projected by the year 2050, with temperatures 2.5°C warmer than the current climate. The simulated climate of 2050 shows somewhat greater warming in January and February than in other months (Hamlet et al., 1997). Preliminary analysis of the hydrologic impacts suggests that total average annual runoff at The Dalles would decline by 14.7 percent for 2020 and by 16.0 percent for 2050 (Hamlet et al., 1997). The projected impacts on the Columbia's hydrograph at The Dalles are displayed in Figure 6.

Other GCM-Based Scenarios

Figures 5 and 6 also show the implications of two other GCM-based scenarios for Columbia basin streamflows and system operation (Lettenmaier et al., 1996; Hamlet et al., 1997; Hamlet et al., 1998). The team used transient model runs from the Geophysical Fluid Dynamics Laboratory (GFDL) and United Kingdom Meteorological Office-Hadley Center (UKMO) and a steady-state doubled CO_2 run of the GFDL (not shown).

The differences and similarities among the transient simulations can be seen by comparing their results for 2050. All three models predict similar changes in average annual temperatures, with the GFDL showing the greatest warming at 3.39 °C and the MPI the least at 2.57 °C. An even larger temperature increase (3.91 °C) is predicted by the GFDL 2 x CO_2 simulation (not shown). The UKMO scenario for 2050 and the GFDL 2 x CO_2 simulation show the largest temperature increases in midsummer, about 5.5 °C. The MPI and GFDL temperature changes are more uniform through the year. All three transient simulations show increasing precipitation from November through March and large decreases in precipitation for spring and summer (May through September). In contrast, the GFDL 2 x CO_2 scenario contains increased precipitation in all months except June and July. The runoff calculations from these various scenarios display similar shifts to an earlier seasonal peak, but there are rather large differences in total annual runoff. For 2050, the GFDL scenario showed little change in total annual runoff compared with the current climate, while the UKMO scenario showed a slight decrease, and the MPI showed a fairly large decrease (about 16 percent). For the GFDL 2 x CO_2 scenario, the increased precipitation resulted in large increases in runoff, especially in the fall and spring, with a 22 percent increase in total runoff (Lettenmaier et al., 1996). More recent simulations are similar, with the various models predicting somewhat different changes in the annual hydrograph, but all pointing to lower late summer flows (Hamlet et al., 1998).

All of these scenarios rely on a rather simple method of interpolating the temperature and precipitation changes from the output of a coarse-resolution GCM to the local scale. A problem with this technique is that it does a poor job of capturing the effects of complex topography. For example, because the coarse-resolution models do not adequately resolve the Cascade Mountains, their rain-shadowing effects are not represented. The method of applying differences from the GCM current and perturbed simulations only partially corrects for this problem, because any moisture increases tend to be carried too far inland (Giorgi et al., 1998; Mearns et al., 1999).

Nested climate modeling is a promising approach to resolving the inaccuracies arising from coarse GCM resolution. This technique uses the output of a large-scale GCM to provide the meteorological boundary conditions needed to drive a high-resolution climate model over a limited geographic area. In other words, a coarse-resolution GCM simulates the large-scale climate features, while the effects of topography and other surface features are captured by the nested regional model (Giorgi and Mearns, 1991). One such model is NCAR's regional climate model (RegCM2) (Giorgi et al., 1993a,b). Results from runs of that model are available for the U.S. portion of the Columbia basin (Giorgi et al., 1998; Mearns et al., 1998). The high spatial resolution at which the regional climate

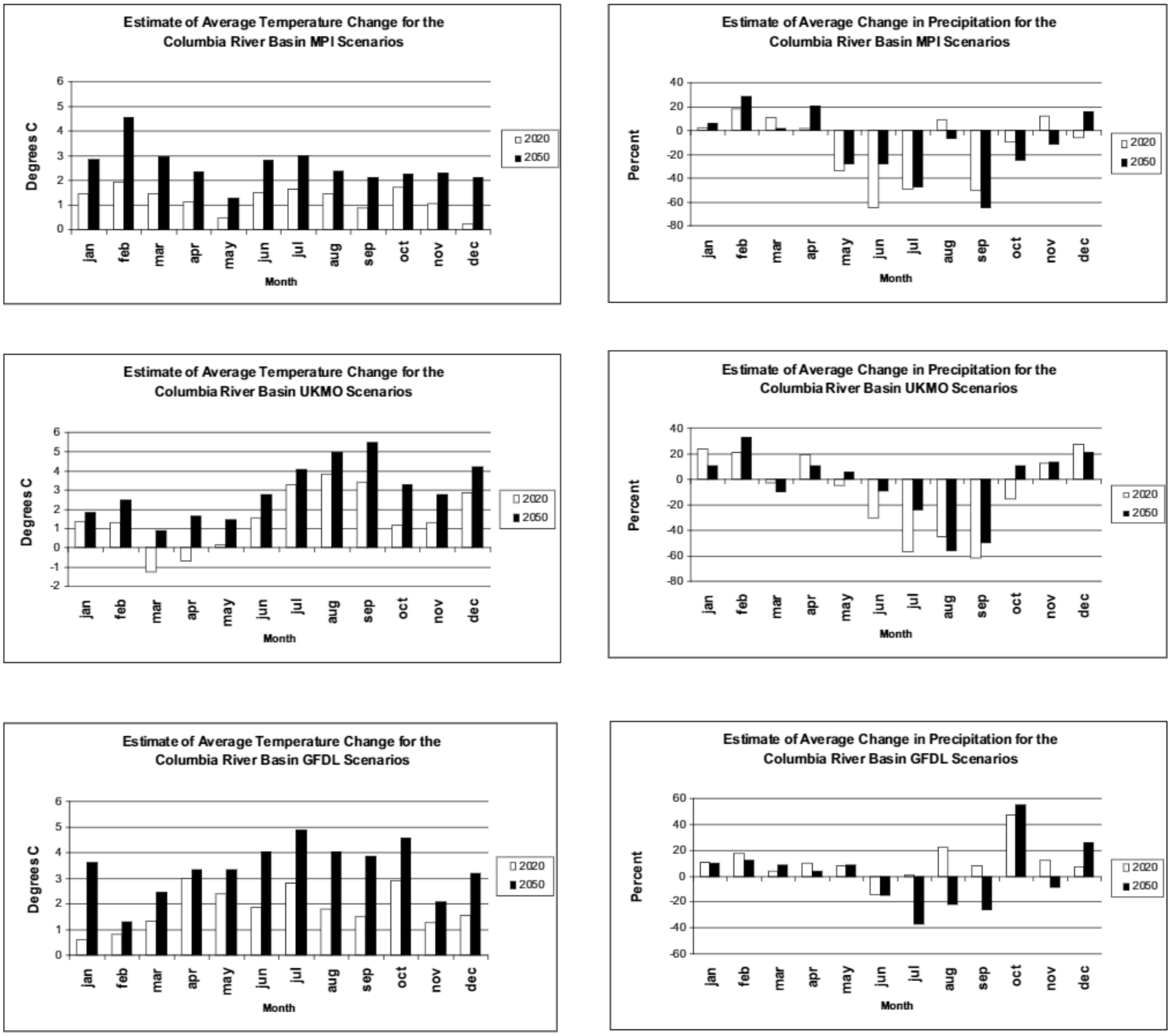

Figure 5. Temperature and precipitation changes in the Columbia basin in the MPI (top), GFDL (middle), and UKMO (bottom) scenarios. Source: Hamlet et al., 1998. One thousand cfs (cubic feet per second) = 283 cubic meters per second.

model was run (50 km) enables detailed responses by the model to the complex topography of the northwest. The predicted changes in seasonal temperatures, precipitation, and runoff are broadly consistent with the other scenarios examined, suggesting increased winter runoff and possible reductions in summer runoff over portions of the basin. However, because the Canadian portion of the basin is not adequately covered, these results cannot be used to estimate changes in the flow of the entire Columbia system.

Other meso-scale climate models have been developed that can be used to drive regional hydrology models of the entire Columbia basin (e.g., Leung et al., 1999). However, these climate simulations contain biases both inherited from the GCM boundary conditions used to drive the meso-scale model and from the meso-scale model itself. In order to achieve reasonable hydrologic simulations using these simulations as driving data, some sort of bias correction is required. Questions about reproduction of existing patterns of natural variability that are important in assessing the ability to meet water resources objectives under changed climate have not been fully addressed at this time.

Summary of Climate Change Scenarios and Hydrologic Changes

These alternative scenarios suggest a range of possible changes for the Columbia basin, but they all project

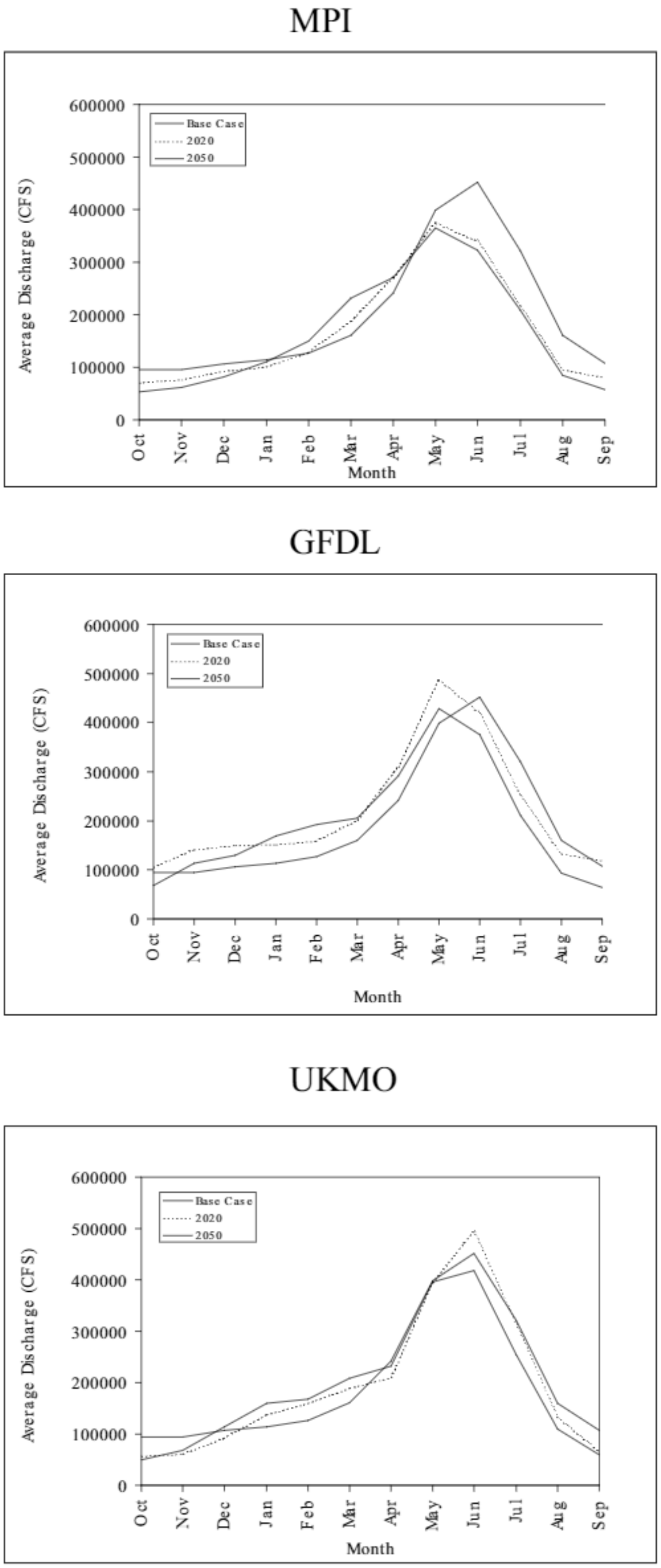

Figure 6. Projected impacts of climate change scenarios on natural streamflow at The Dalles (near Portland); MPI (top), GFDL (middle), and UKMO (bottom). Source: Hamlet et al., 1998.

significant warming and increased winter precipitation. The scenarios differ in the magnitude of these increases, and in some cases, precipitation during summer is projected to decrease (Snover, 1997; Hamlet et al., 1998). All of the scenarios suggest similar changes in the seasonal pattern of streamflows. An earlier peak in the annual hydrograph is highly likely. This is similar to results obtained in water balance studies (Taylor and Taylor, 1997; Coulson, 1997). Several scenarios suggest higher winter flows and possible reductions in summer flows in some parts of the basin.

Another important consideration is the effective lengthening of the time from peak streamflow in spring to return of "normal" fall streamflow. The MPI scenario, for example, shows a lengthening of this period by approximately three months on average. Since irrigation and urban water demand are concentrated in this period (and may increase due to increased population, higher temperatures, and longer growing seasons), existing storage capacity must provide for increased demand over a longer season. In some cases, the existing infrastructure may be insufficient to meet future demand under these adverse conditions much of the time.

Changes in basin hydrology will also be influenced by the projected retreat of mountain glaciers in southeast BC. The glacier melt period would be extended by at least one month, and the late summer snowline would rise by up to 300 meters. This would mean that less than 30 percent of the glacier areas would be covered by snow during late summer, thereby enhancing ice melt. Smaller glaciers less than 100 meters thick could disappear in 20 years. During the retreat phase, increased melt would augment river flow helping to maintain water availability during the high-demand summer months, but that would be temporary. Once the glacial mass diminishes to the point where there is no longer a significant amount of ice to melt annually, the contribution of these areas to the July-to-October natural flow on the Columbia could fall by 20 to 90 percent (Brugman et al., 1997).

There have been relatively few studies of the impacts of global warming on groundwater levels, but these are likely to be important. In the Columbia basin, the groundwater system is closely connected to surface water flows, although the interactions are not well documented or understood in many locations. One study, of the Ellensberg basin in Washington State, found a 25 percent median annual reduction in groundwater recharge under a global warming scenario. This area is in the upper part of the Yakima River basin. Declines in groundwater levels could reduce discharge to surface streams and/or increase seepage losses from surface streams to the groundwater system (Callaway and Currie, 1985).

Impacts

Any changes in the flow regime of the Columbia system may affect several water-dependent sectors. While each of the following sections focuses on a particular sector, it must be understood that there are interactions and in some cases significant competition between these uses of the basins' water resources. These are highlighted in the discussion.

Some of the analyses discussed below are reported in terms of changes in *reliability*. This is defined as the observed or simulated probability of successfully meeting an objective (e.g., a flow target). For our results, if the objective was met in 63 months of a 100-month simulation, the reliability would be reported as 63 percent. Note that no attempt is made to identify an appropriate timescale for any particular objective.

Energy Production and Demand

The hydropower output of the Columbia system is sensitive to the total volume of flow as well as to its seasonal shape. In addition, the value of that generation depends on the reliability with which it can be delivered and the extent to which the timing of generation matches the timing of power demand. Climate change can be expected to affect all of these elements.

Warmer summers are expected to lead to increased demand for air conditioning and pumping services for irrigation. Warmer winters would reduce heating demand. There is a possibility that this would make electric heat pumps more attractive than gas heating and potentially increase electrical demand from a certain sector of the BC market (Ross and Wellisch, 1997). On the U.S. side, overall residential demands would decline, but commercial demands would increase (Snover, 1997).

Hydrologic changes would lead to changes in reservoir management plans and operations. Reduced water supplies would lead to both decreased potential hydropower production and increased competition for available water from other uses, especially during the low-flow period. If the annual supply increases but the seasonal cycle changes, the impacts on the hydropower sector would depend on seasonal differentials in prices and also on management actions required for flood control and accommodation of other user demands. In a survey of BC energy experts, however, most replied that the risks would be smaller than risks associated with climate change-related policies or regulations, such as new taxes on carbon-based fuels (Ross and Wellisch, 1997). On the U.S. side, the University of Washington study assessed changes in reliability of hydroelectric production within a climate change scenario. Results showed that reliability of producing firm energy requirements would decrease in the MPI scenario from the current 96 percent to 82 percent by 2050, a 14 percent reduction. Decreases of 5 to10 percent would still occur in the relatively wetter UKMO and GFDL scenarios (Figure 7).

Fishery Impacts

Warm water species of freshwater fish such as walleye, bass, and northern pike may benefit from a warmer climate and warmer surface water temperatures. Of greater concern is the potential for exotic species to displace resident species, especially those that are currently rare and endangered. One of these is the white sturgeon (Beamish et al., 1997), which has already been the subject of legal actions that have led to changes in hydropower operations (see "Interjurisdictional Aspects"). There is also concern for future survival of salmon (Kokanee, in the Canadian portion of the basin), which prefer cold water.

From the perspective of the Columbia basin's salmon stocks, the projected impacts of global warming in some ways resemble the effects of development of the system for hydropower and other purposes. The dams have both raised water temperatures and have shifted the seasonal peak flow of the mainstem (as noted in Figure 4). Volkman describes the effect of storage operations as follows:

> The spring freshet has been reduced and pushed back a month. So, the freshet that historically flowed in June now flows in May. In late summer and fall, water in the reservoirs is warmer than it would be if it were a free-flowing stream. (1997: 57)

Projected declines in late spring and early summer flows may make it more difficult to meet the minimum streamflow requirements set forth in the 1995 NMFS Biological Opinions for fishery protection. In the MPI scenario, the reliability of meeting these requirements for McNary Dam on the main stem of the Columbia dropped from 85 percent in the base case to 76 percent in 2020 and 2050 (Figure 7). For the UKMO and GFDL scenarios, reliability in 2050 would be 80 percent and 81 percent, respectively (Hamlet et al., 1998).

The projected changes in flows and water temperatures are broadly consistent with Chatters et al. (1991), who used a Mid-Holocene (8,000–6,000 years ago) analogue to develop a scenario of the effects of a warmer climate on streamflow, water temperatures, and salmon habitat for the Yakima basin. Temperatures in the region were approximately 2°C warmer than today. There was less total precipitation, but the seasonal distribution of precipitation was approximately the same as in the current climate. Streamflows were less than 70 percent of modern; water temperatures were higher; and the spring peak flow (freshet) ended three to four weeks earlier than it does today (Chatters et al., 1991).

Incorporating these hydrologic changes in a salmon production model resulted in projected declines of 60 percent in the number of returning adult spring chinook salmon in the Yakima. Chatters et al. (1991) noted that the impacts of such a climate change would not be the same for all species and stocks of salmon and that some stocks could be helped by climate change. For the drier parts of the Columbia basin, however (where the effects of dam operations and irrigation withdrawals on salmon are now so problematic), they concluded that salmon stocks would decline if the climate of the future resembles

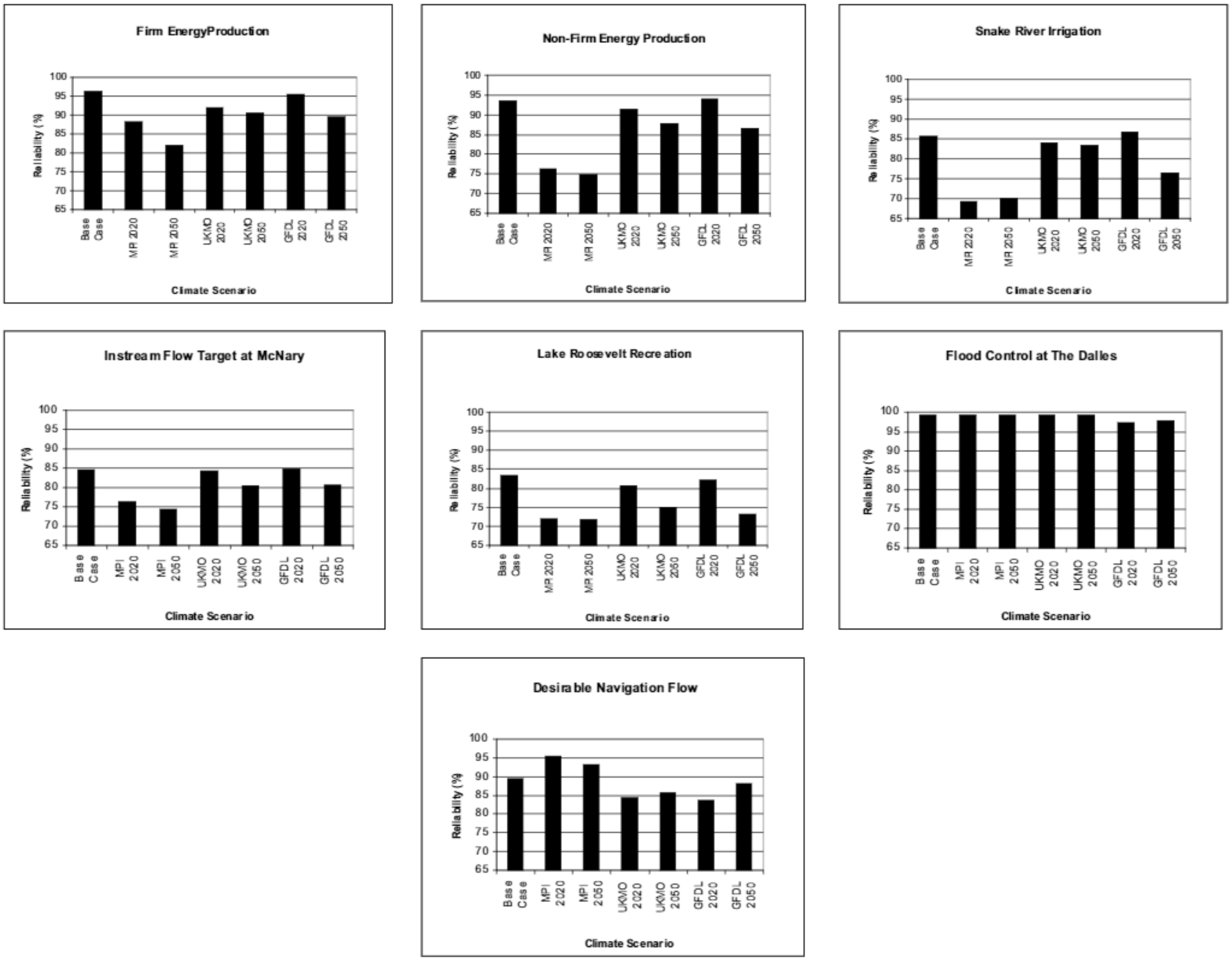

Figure 7. Reliability of Columbia basin reservoir system uses for 2020 and 2050. Source: Hamlet et al., 1998.

the Mid-Holocene analogue.

The results of that modeling exercise do not assume any changes in the marine environment. However, there has been a growing recognition that variations in sea surface temperatures, coastal upwelling, offshore transport, and shifts in the abundances of predators and food species have significant impacts on the ocean survival, growth, and subsequent fecundity of salmon (Nickelson, 1986; Pearcy, 1992; Blackbourn, 1993; Mantua et al., 1997). El Niño-Southern Oscillation (ENSO) warm events in the Pacific have had large detrimental impacts on Columbia basin salmon. It is not yet clear if global warming will alter the ocean environment in ways that resemble El Niño impacts.

Recent El Niños, particularly since 1990, have contributed to sharp declines in Columbia basin salmon stocks, resulting in a virtual collapse of salmon production off the Oregon and Washington coast. The estimated population of Columbia basin Pacific salmon declined from 4 to 5 million in 1980 to the current population of less than 1 million, of which only 75,000 are wild (see review by Pulwarty and Redmond, 1997). Meanwhile, salmon production in Alaska has been at historical highs (Miller, 1996; Mantua et al., 1997). The declines in southern salmon abundance, coupled with increasing Alaskan harvests, contributed to a collapse of international cooperation on joint management of U.S. and Canadian salmon harvests under the Pacific Salmon Treaty (Miller, 1996). The resulting "fish war" further jeopardized the Columbia's fragile salmon stocks.

Irrigated Agriculture

If water availability should decline as a result of climate change, the senior priority structure of water rights will largely determine the allocation of the impacts of the decline on the U.S. side of the border. Those irrigators with very senior water rights are likely to continue to have access to water, while the most junior parties may be obligated to either do without water or obtain it by purchasing or renting water rights from senior right holders. In addition, if unappropriated water is available in the high runoff season, they could provide for their needs by investing in additional storage capacity.

A longer growing season would provide new agricultural opportunities, but higher temperatures are likely to increase the demand for irrigation water. In heavily allocated subbasins, such as the Snake and the Yakima, there may be little water available to serve increasing demands. By 2050, reliability of flows for Snake River agriculture would be reduced from 85 percent to 70 to 75 percent in the three scenarios (Figure 7).

Current state moratoria on new irrigation diversions in the U.S. part of the basin seem likely to remain in force, particularly if climate change leads to new endangered species listings or causes further deterioration of the Columbia's salmon stocks. However, total consumptive use of water on irrigated land could still increase. This is due to the fact that existing water rights typically specify an allowable rate or total quantity of water to be diverted, but the proportion that is consumptively used (e.g., lost to evaporation and crop evapotranspiration) would likely increase under warmer conditions (Miller et al., 1997). In addition, possible declines in groundwater levels (Vaccaro, 1992) could lead to increased seepage losses from unlined irrigation ditches. To the extent that instream flows continue to be treated as junior to irrigation diversions, they would have to absorb the impact of any increases in consumptive use caused by climate change.

While water allocation policy can effectively trade impacts between irrigators and fish, substantial impacts to one or both cannot be avoided all the time, even under current climate. A changed climate, like that represented in the scenarios, can only exacerbate this conflict over water allocation priority due to lengthening of the summer season, reduced summer and fall streamflow, and higher irrigation demand.

In Canada, irrigation is an important feature of horticultural production (apples, grapes, peaches, etc.) and forage production (alfalfa, hay) in the arid regions of the Okanagan and Similkameen subbasin. So, in a scenario of climate warming, demand for irrigation water will increase. Suitable climatic conditions for fruit growing could expand to higher latitudes and elevations, including Kamloops and the Shuswap (Zebarth et al., 1997). Should such a land use change occur (i.e., agricultural expansion), there could be side effects on the hydrologic cycle, but these have not been investigated in the scenario studies. This would also be the case for other changes in managed landscapes (e.g., commercial forestry) and unmanaged landscapes (e.g., alpine tundra), with effects occurring at various rates throughout the region (Harding and McCullum, 1997; Krannitz and Kesting, 1997; Evans and Clague, 1997; Marks et al., 1993).

Navigation

Evidence of the possible magnitude of the impacts of lower summer streamflows on commercial navigation on the Columbia and Snake Rivers can be gleaned from assessments of the impacts of reservoir drawdowns to assist the outmigration of salmon smolts. At the high end, some studies assume that grain now transported in barges would be transported by the next-higher-cost mode of transportation during the assumed two-month drawdown period. Martin et al. (1992) report that one such study concluded that such drawdowns would cost shippers US$60 million annually. The Martin et al. analysis points out that the cost of holding grain in storage is very small compared with the cost of shipping by an alternate mode. They argue that grain shippers could easily accommodate a two-month period in which reservoir levels were too low to allow barge movement by shipping at other times of the year. Doing so would entail cost increases on the order of US$0.05 per bushel or less (compared with the US$0.17–0.86 bushel increases that would be incurred by switching to rail or truck transport).

If lower summer flows extended the period during which barge traffic were halted on the lower Snake and Columbia Rivers, the impacts would likely exceed those estimated by Martin et al., while the cost of using alternate modes of transportation would provide an upper bound on the navigation impacts.

Flood Management

While the MPI scenario suggests lower average annual flows for the Columbia, several scenarios suggest higher winter flows, and the GFDL 2 x CO_2 scenario suggests a 22 percent increase in average annual runoff. Under the MPI scenario, Lettenmaier et al. (1996) found a substantial decrease in flood vulnerability in the lower basin. On the other hand, they found substantial increases in flood vulnerability for the GFDL and GFDL 2 x CO_2 scenarios in which there were increases in peak monthly flow (Figure 7). They concluded that "the possibility of substantial increases in flood flows . . . may, given present reservoir capacity, represent serious risk to life and property, particularly in the densely populated lower Columbia River flood plain" (Lettenmaier et al., 1996: xv). They note, however, that the monthly time steps used in their analysis are too long to give an accurate picture of changes in flood risks. Any changes in flood risks along the lower mainstem of the Columbia are likely to have implications for the operation of the Canadian storage facilities.

In addition, heavier winter precipitation and warmer temperatures suggest an increased likelihood of large rain on snow events, which would tend to increase winter flooding risks particularly in unregulated tributary watersheds. This may have transboundary environmental implications if it leads to calls for the construction of new dams or other flood control works in the tributary watersheds.

Structured Interviews

Further insights on the possible consequences of climate change for the Columbia basin can be gleaned from the concerns of the various stakeholders who were interviewed as part of this project. Structured interviews were carried out with 31 key stakeholders in the upper Columbia basin. Concerns related to current conflicts and the indirect impacts of future climate change are evident in the interview results. Structured interviews with key stakeholders have been used in previous studies of climate issues in the Columbia (Pulwarty and Redmond, 1997; Miles, personal communication). Those interviews, however, focused on operations and the use of weather and ENSO forecasts in the lower Columbia. In the case study described here, our intention was to generate a picture of indirect impacts of future climate change and to highlight concerns raised in the upper Columbia through interviews with individuals directly involved in resource operations, marketing, and management in this region. In the following discussion, stakeholder perspectives are compared with the reservoir reliability model results described above.

Research Methodology

Thirty-one key stakeholders in the upper Columbia were interviewed for this research. They included members of environmental nongovernment organizations (ENGOs), government officials (federal, provincial, and regional), and private sector employees. Interviews normally took between one to two hours, and sessions were recorded and transcribed for later analysis. Interviews were carried out during the months of July, August, and September 1997.

Participants in the research were asked a series of 20 questions about approaches to water management and the potential impact of climate change in a one-on-one interview situation. The questions were broken into four segments: tasks and responsibilities, water management issues, climate change issues, and organizational interaction.

When discussing climate change issues, participants were presented with the MPI scenario, including temperature, precipitation, and natural streamflow changes. This scenario was chosen because it was the only one available at the time of the interviews. Future research should incorporate additional scenarios.

Analysis of the interviews was carried out using computer-aided qualitative data analysis software entitled ATLAS/ti. ATLAS/ti is one of a wide variety of such software that allows the user to qualitatively analyze textual, graphical, or audio data. In this case, transcribed interviews were coded using selected categories as would normally be done by hand. These categories consisted of climate variables, various impacts of recent climate variations, water resources issues, conflicts between stakeholders, and potential responses to the University of Washington scenario work. ATLAS/ti then allows for the extraction and comparison of codes in a variety of ways that help to add insight to the analysis. For a more detailed discussion of the uses and advantages/disadvantages of computer aided qualitative data analysis software, see Crane et al. (1997).

Results of Survey of Stakeholders

The following discussion reflects stakeholders' comments on the following topics: direct impacts of the hypothesized climate change, indirect impacts on current conflicts, potential new conflicts, and possible effects on institutional arrangements. A summary of stakeholders' comments is shown in Table 2. We cannot assign a probability to the scenario of outcomes indicated by our sample of stakeholders, and the small size of this sample precludes any meaningful computation of statistics.

Direct and Indirect Impacts

Stakeholders identified possible problems in adjusting the operation of the storage dams to an earlier spring peak and more rain on snow events. They noted that the big storage dams (e.g., Keenleyside) operate on a four-year cycle, so they have the ability within that cycle to absorb interseasonal variations and influences, but changes that exacerbate extreme high or low flows will lead to operational problems. In addition, flood risk is not necessarily reduced, even in a scenario of a lower spring peak (such as MPI), since upstream storage facilities may be releasing high discharges for other reasons.

For example, changes in Libby Dam's operations would affect Kootenay Lake levels. The seasonal cycle of flood control requirements could shift from spring to winter. Reservoir filling would have to begin sooner, and it could prevent operators from getting reservoir levels down to prescribed minimum levels.

They also noted that if there is less water overall, there would be less flexibility in how hydroelectricity is produced. Winter electricity demands would be reduced due to less demand for heating. Summer demands would increase for air conditioning and irrigation, and this would lead to greater difficulties in sharing the resource for fisheries needs. Under reduced flow conditions, utilities might have to buy more electricity at various times rather than use available storage to produce electricity. If this purchase would be from fossil fuel sources, it would affect the region's ability to meet greenhouse gas emission targets (see "Stakeholder's Views on Potential New Conflicts").

Respondents identified possible benefits to agriculture in the Canadian portion of the basin because of warmer and longer growing seasons. It might become possible, for example, to expand grape production to Kamloops. This would lead to increased demands for irrigation water. The Osoyoos region already includes the

Table 2. Summary of Impacts of the MPI Climate Change Scenario on the Columbia Basin

	Direct Impacts	*Indirect Impacts*
Agriculture	Longer growing season; opportunities for expansion Increased irrigation demand Increases in consumptive water use, despite moratoria on new diversions in U.S. states Possible shortfalls in water supply - falling	Increased conflict with urban uses and fisheries in arid regions Increased demands for water transfers from agriculture to other uses, with opportunities for further development of water banking arrangements mostly on junior right holders, on U.S. side.
Fisheries	Increased risk for cold water species due to warmer water and lower summer flows Further pressure on endangered or threatened salmon stocks	Increased conflict between sport fishery and advocates of ecosystem approach In U.S., Endangered Species Act could be used more aggressively to reduce (or modify the use of) other vested water rights
Flood Control	Shift from spring snowmelt peak to rain-dominated winter peak Begin annual storage earlier in the year Increases in winter/spring flooding risks in tributary watersheds	Prescribed minimum levels not attained as often; impacts on shoreline property maintenance Conflicts between possible new tributary flood control infrastructure and fisheries/ ecosystem preservation
Forestry	Longer growing season Increased fire risk Some species could expand to higher elevations; others could lose niches Shorter harvesting period	Impacts on reforestation strategies not known Increased conflict with riparian water users, fisheries (increased water temperatures, lower minimum flows)
Hydroelectricity	Reduced demand for winter heating Increased demand for summer cooling and irrigation services; power demand increases when water supply decreases Changes in total hydropower output, seasonal timing of production, and availability of hydropower to meet peaking demands, with consequences for hydropower firm load carrying capacity and hydropower value	Changes in entitlements Dependent on operations for fisheries and flood control Changes in electricity market; potential increase in purchase of energy and/or use of thermal power sources
Navigation	Earlier start to low flow period Increases in commodity transportation costs possible with shorter season open to barge traffic	Lower summer flows could increase conflicts between recreational users and commerical traffic

Source: Stakeholder interviews in the upper Columbia (Cohen et al., 1998; Miller, 2000).

highest irrigation users in North America on a per hectare (or acre) basis because of its sandy soils and arid climate.

They also identified possible adverse impacts on forestry (moisture stress, fire hazard, and greater difficulty in harvesting trees during wetter winters) and on resident fish populations (direct impacts of warmer temperatures, adverse effects on spawning of sturgeon, extension of the range of exotic species, and changes in the balance of warm water vs. cold water species). One interviewee stated that

> the general view has been expressed in . . . meetings is that global climate change is another substantial obstacle in an already obstacle ridden effort to restore salmon populations and other fish populations . . . we've got a number of exotic species that have been introduced and are thriving under current conditions and we also have a number of the native species, which are primarily cold water species . . . trout, etc. . . . that . . . are already stressed.

Reduced streamflows were also projected to exacerbate conflicts between agriculture and fishery interests and to adversely affect water quality.

Stakeholders' Views on Institutional Arrangements

Direct and indirect effects of climate change could also affect management structures, including binational instruments, national and regional instruments, and commercial agreements. These arrangements may be based on a historic data set of climate or streamflow, which may have been the basis for defining certain guidelines or targets. The evaluation of the performance of such arrangements may have been based on the explicit assumption that climate would not change during the lifetime of the agreement.

For example, if Libby Dam continues to be operated to protect white sturgeon, it is possible that there might be a requirement to augment releases during conditions of lower flows. As long as Kootenay Lake elevations are not increased beyond what would have occurred under natural conditions, such releases would not violate the current IJC Order. It therefore hinges on how natural flow is defined, and since the IJC Order was written before the construction of Libby and Duncan Dams, hydrologic changes due to climate change represent one more incentive to revisit the order.

Hydropower operations are dependent on how major storage facilities would operate, so entitlement agreements might be revisited in light of hydrologic changes. Within the Columbia River Treaty, there is a lump sum payment for flood control until 2024. After 2024, payments would be on a flood event basis. Power benefits are based on historic records. If global warming changes the hydrologic cycle, this may require a new basis for calculation of flood and power benefits. Interviewees have indicated the possibility that this would lead to future legal challenges.

There is also the question of how competitors would react to climate change. For instance, if the competition assumes more water in winter, they might market aggressively and the price would drop. Another issue is how demand for air conditioning would change, particularly in California. Concerns about market competition have also been reflected in an earlier survey on seasonal climate forecasts in which power marketers noted that benefits of such forecasts can be derived from observing what competitors do with the same information (Pulwarty and Redmond, 1997).

WKP (and perhaps other utilities) regularly track electricity sales by adjusting them for variations in winter (heating degree-days) and summer (cooling degree-days) temperatures. The current warming trend has led WKP to revise its definition of "normal" period from 50 years to 20 years. Shortening the normal period reduced the estimate of normal heating degree-days by 2.3 percent, which reduced "normalized" sales in 1995 by 20 GW.hours (1.4 percent). This redefined normal period also showed a shift in the expected peak demand from January to December as degree-days in the two months are becoming more similar (Isherwood, 1996).

The change in the way power is bought and sold will complicate the relationship between climate and energy and make it difficult to identify the proportion of a utility's financial performance affected by climate, i.e., was a long-term change in profitability of a utility influenced by climate change? One possible example provided by interviewees is the arrangement between BC Hydro and WKP regarding construction and operation of the Kootenay Canal Plant. When the canal plant was constructed on the Kootenay River in 1975, some water could be diverted to a canal parallel to the river, thereby providing flow through this more efficient facility instead of through four older WKP facilities. This canal bypasses the four WKP plants and discharges back into the Kootenay River downstream. It was therefore agreed that WKP would receive an entitlement of energy, regardless of where the energy was generated or whether the region was experiencing a high or low water year. The entitlement is based on the power that the four plants, plus two others in the area, could have produced under conditions of natural flow (i.e., before construction of Libby and Duncan). This provides BC Hydro with incentive to optimize its output because there is a fixed amount of energy going to WKP. When the canal plant agreement is renegotiated in 2005, there would be questions related to energy entitlement for WKP given the 1975–2005 record and, perhaps, projected changes in streamflow due to climate change.

Table 3. Comparison of Stakeholder Interview and Reservoir Model Results for the MPI Scenario

	Upper Columbia Interviews	*Reservoir Model (Results for 2050)*
Agriculture	Possible shortfalls in irrigation supply	Snake River agriculture—reliability reduced from 85 to 70 percent
Fisheries	Increased risk for cold water species due to warmer water and lower summer flows	McNary River biological flow—reliability reduced from 85 to 74 percent
Flood Control	Change in procedures needed, e.g., begin annual storage earlier in the year; prescribed minimum flows not attained as often	No change in reliability
Hydroelectricity	Changes in availability of hydroelectricity May need to purchase thermal power	Firm energy—reliability reduced from 96 to 82 percent Non-firm energy—reliability reduced from 94 to 75 percent

Source: Cohen et al.; 1998, Hamlet et al., 1998.

Another regional example could be the entitlement agreement for Keenleyside Power Plant being negotiated between Columbia Power Corporation (Columbia Basin Trust) and BC Hydro. The terms would depend on anticipated operations of Keenleyside's treaty (power, flood control) and nontreaty (fish, natural flows) storage. What natural flows would be assumed, and would climate change be part of this?

Stakeholders' Views on Potential New Conflicts

Respondents indicated that new regional conflicts might arise from international agreements on global climate change. The 1992 United Nations Framework Convention on Climate Change and 1997 Kyoto Protocol established greenhouse gas emissions targets for the U.S., Canada, and other countries. In the MPI scenario, it is possible that hydroelectric production would be affected by whatever system of emission credits is established for various energy types. If the region's utilities were forced to reduce hydroelectric production because of fish protection or other needs, shortfalls in electric power demand could be met by thermal sources inside the basin or purchased energy from thermal sources outside the basin. If established hydropower facilities are not given emission credits, there could be an increase in gas turbine facilities, thereby increasing regional emissions.

Conclusion

There are several key issues that are common to the stakeholder interviews and the reservoir model results reported by Hamlet et al. (1998). Table 3 provides a comparison for agriculture, energy, fisheries, and flood control. The stakeholders' narratives and model results show similar tendencies, i.e., increased risks and reduced reliability in the MPI scenario for agriculture, hydropower, and fisheries. Both suggested little or no change in flood control risk, but stakeholders suggested that changes in procedures would be needed.

Climate change has the potential to increase the level of current conflicts and to create new ones (e.g., changing entitlements for power benefits). The "bottom line" message is that even in a highly developed and highly managed watershed, climate change impacts could still occur.

It is important to note, however, that this assessment is preliminary and based on a limited published literature, reservoir model results, and a set of interviews with a small group of stakeholders. Important research issues have been identified. The next step is to broaden the research and consultation process so that a more rigorous assessment of scenarios of climate change can be considered. We hope that we can follow up on this work in the near future with additional scenarios and a broader consultation of regional stakeholders.

In the upper Columbia, the Columbia Basin Trust has outlined a series of environmental issues and opportunities as it prepares its management plan (Columbia Basin Trust, 1997). Among the issues are (a) limited understanding of the region's ecosystems; (b) difficulties in moving towards integrated management of natural systems and resources, in part due to jurisdictional complexity and increasing specialization; (c) habitat loss, alteration, and degradation; (d) harvesting practices that may not be maintaining the ecological viability of the basin; (e) impacts of population growth and infrastructure development; and (f) the need for more widespread public awareness of issues and involvement in management and planning.

Global climate change is an external force that could influence all of these regional issues. At the same time, any projections of climate change impacts and assessments of regional response options will depend on our collective abilities to understand how this global scale force may play out in the context of this region. This case study is only a small step in this process.

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