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POTENTIAL IMPLICATIONS OF CLIMATE CHANGE ON THE WATER RESOURCES OF THE COLUMBIA RIVER BASIN

Jeffrey T. Payne
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Water Resources Series
Technical Report No.174
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ABSTRACT:

The potential effects of climate change on the hydrology and water resources of the Columbia River Basin (CRB) were evaluated using simulations from the U.S. Department of Energy and National Center for Atmospheric Research Parallel Climate Model (DOE/NCAR PCM). This study focuses on three climate projections for the 21st century based on a "business as usual" (BAU) global emissions scenario, evaluated with respect to a control climate scenario based on static 1995 emissions. Time-varying monthly PCM temperature and precipitation changes were statistically downscaled and temporally disaggregated to produce daily forcings that drove a macro-scale hydrologic simulation model of the Columbia River basin at ¼ degree spatial resolution. For comparison with the direct statistical downscaling approach, a dynamical downscaling approach using a regional climate model (RCM, was also used to derive hydrologic model forcings for 20-year subsets from the PCM control climate (1995-2015) scenario and from the three BAU climate (2040-2060) projections.

The statistically downscaled PCM scenario results were assessed for three analysis periods (denoted Periods 1-3: 2010-2039, 2040-2069, 2070-2098) in which changes in annual average temperature were +0.5, +1.3, and +2.1 °C, respectively, while critical winter season precipitation changes were -3, +5, and +1 percent. For RCM, the predicted temperature change for the 2040-2060 period was +1.2°C and the average winter precipitation change was -3 percent, relative to the RCM control climate. Due to the modest changes in winter precipitation, temperature changes dominated the simulated hydrologic effects by reducing winter snow accumulation, thus shifting summer and autumn stream-flow to the winter. The hydrologic changes caused increased competition for reservoir storage between firm hydropower and in-stream flow targets developed pursuant to the Endangered Species Act listing of Columbia River salmonids.

We examined several alternative reservoir operating policies designed to mitigate reservoir system performance losses. In general, the combination of earlier reservoir refill with greater storage allocations for in-stream flow targets mitigated some of the negative impacts to flow, but only with significant losses in firm hydropower production (ranging from -9 percent in Period 1 to -35 percent for RCM). Simulated hydropower revenue changes were less than 5 percent for all scenarios, however, primarily due to small changes in annual runoff.

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The U.S. Department of Energy's Accelerated Climate Prediction Initiative under Grant No. 354967-AQO provided funding for this research, performed at the University of Washington. This study was also supported by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement #NA17RJ1232, Contribution #922.

Chapter 1 - Introduction

Man's activities since the 1800's have unquestionably affected the chemical composition of the atmosphere. Concentrations of greenhouse gases (GHGs), especially carbon dioxide, have increased almost monotonically since the onset of major global industrialization. These changes are well documented, showing increases of about 25% in the atmospheric concentration of CO_2 during the period of instrumental record, which began less than 50 years ago. Although scientific opinions vary about the possible severity of changes in climate resulting from changes in atmospheric gas concentrations, there is a high certainty that changes have and will continue to occur as a result of increasing GHG concentrations. For instance, according to the Intergovernmental Panel on Climate Change (IPCC, Houghton and Ding, 2001):

> "For the end of the 21st century (2071-2100), for the draft SRES marker scenario A2, the global average surface air temperature change from [General Circulation Models (GCM)] compared with 1961 to 1999 is +3.05°C and the range is +1.3 to +4.5°C. ... These quantities are model dependant, and the previous range for this quantity [based upon $2xCO_2$ GCM results], widely cited as +1.5 to +4.5°C, still encompasses the more recent model sensitivity estimates."

The effects of global warming on U.S. are expected to be most profound in the West, where the hydrology and water resource systems are reliant, in large part, upon snow accumulation and melt patterns that are highly temperature dependant (Leung and Ghan, 1999). Further, many previous studies (e.g. Gleick and Chaleki, 1999; McCabe and Wolock, 1999; Hamlet & Lettenmaier, 1999; Lettenmaier, Brettmann, and Vail, 1992; Lettenmaier and Gan, 1990) indicate that even relatively small increases in temperature would result in a significant shift in runoff patterns (e.g. more winter runoff, an earlier peak snowmelt runoff, and reduction of summer and fall streamflow). The consequences of such shifts for managed water resources in the West could be substantial because snowpack influences summer streamflows, when a relatively small proportion of annual precipitation falls (e.g. Lettenmaier and Sheer, 1991).

This thesis evaluates how climate change might affect the water resources specific to the Columbia River Basin and investigates the value of several alternative reservoir operations in mitigating negative impacts. The primary focus of the work is on mitigating the climate-related impacts to hydropower production, flood protection, and fisheries protection and enhancement. Climate related impacts and the consequences of alternative operations to recreation and irrigation are also presented.

1.1: The Application of Climate Models

The presence of ongoing global climate change has been well documented in scientific literature and through various global and national reviews (IPCC, Houghton and Ding, 2001; IPCC, Houghton and Filho, 1996; Hansen, et al., 1998, Gleick and Chaleki, 1999; Cicerone, 2000). Many indications point to the anthropogenic production of greenhouse gases (CO_2, N_2O, CH_4, HFC, PFC, and SF_6) as primary contributors to global warming – particularly to CO_2 (United Nations: Framework Convention on Climate Change (UNFCCC), 1997). GCMs are the primary tool by which the effects of changing concentrations of GHGs are projected. They represent the interactions between the atmosphere, ocean, and land surface in a manner similar to that used by numerical weather prediction models (e.g. short-term weather forecasting models), that is, by solving the equations of fluid motion in the atmosphere, given land surface and ocean conditions as evolving boundary conditions, which are themselves represented by dynamic models.

Despite the understanding of the climate system represented in GCMs, the science of predicting climate change is in its early stages. Projections made for even the near future are subject to considerable uncertainty and cannot be considered to be forecasts in the commonly used sense. Several problems exist in making climate projections, including: representation of cloud physics in GCMs, the effects of the land surface on climate, and uncertainty associated with downscaling climate simulations to the river basin scale. However, climate projections based on GCM simulations of temperature, precipitation, and other variables can allow for the study of 'potential' hydrologic futures, which in turn can be used to assess sensitivities of water resource systems to changes future climate change, and to allow the feasibility of alternative adaptation strategies.

This thesis uses simulations performed at the National Center for Atmospheric Research (NCAR) from a state-of-the-art coupled land-atmosphere-ocean GCM, the U.S. Department of Energy (DOE)/NCAR Parallel Climate Model (PCM) (Barnett et al, 2001). PCM represents the evolution of climate specifically as it might be affected by increases in trace gas concentrations (Washington et al., 2000). Among various scenarios of future greenhouse gas emissions that have been evaluated using PCM is an ensemble of "business-as-usual" (BAU) projections (projecting CO_2 increases that fall between the 1995 IPCC A2 and B2 scenarios). The BAU emission scenario reflects the hypothesis that current GHG trends, practices, and abatement strategies will continue over the next century.

This study uses three PCM future climate ensembles with identical GHG emissions forcing, but with different atmospheric initializations: a process that allows the chaotic nature of the atmosphere and its interactions with the ocean and land to evolve differently. Thus, each ensemble presents a different future that could occur, consistent with the prescribed (deterministic) emissions scenario. The predicted western U.S. warming by the mid-21st century for these scenarios is approximately 1 degree Celsius relative to a "control run" that reflects recent conditions (1995). The climate control run, in turn, is about ½ °C warmer than the recent historical period, which reflects observed late-20th century conditions relative to the past.

In general, the amount of warming predicted by PCM (globally, as well as for the U.S. Pacific Northwest) is smaller than that predicted by most other climate models, such as those used in the recent IPCC and U.S. National Assessments (see IPCC, Houghton and Ding 2001, Gleick and Chaleki, 2000). The lower temperature sensitivity of PCM to greenhouse gas forcing relative to other GCMs is attributed by Barnett et al (2001) to more sophisticated representation of ocean-atmosphere coupling in PCM compared with other GCMs, the result of which is the storage of more heat in the ocean over the next century, and hence smaller increases in atmospheric temperature. The GCM and ensembles used in this study are presented in greater detail in Chapter 2.

1.2: The Columbia River System

The Columbia River Basin (CRB) covers portions of seven western states and the Canadian province of British Columbia (Figure 1). Most of the basin lies within Washington, Oregon, Idaho, and British Columbia. In total, the basin is approximately the size of Texas. From its headwaters in the Canadian Rockies, the Columbia flows 1,930 kilometers and drops 800 meters from its Columbia Glacier headwaters to the Pacific Ocean. Of the tributaries feeding the Columbia River, the largest is the Snake, which constitutes half of the Columbia River Basin in the US and flows over 1,770 kilometers from its headwaters in the Grand Tetons of Wyoming to its confluence with the Columbia in southeastern Washington.

Within the CRB, the annual precipitation varies from 150 to 2,800 mm, resulting in a unique range of vegetation and climate: from temperate rain forests to semi-arid plateaus. The highest precipitation falls along the mountainous fringes. Some of the interior is unsuitable for intense cultivation without irrigation. Despite the basin's need for irrigation, annual outflows are large. Annually, the Columbia River discharges an average 5,210 m^3/s at The Dalles (or 270 mm averaged over the drainage basin), and forms a 600 km long freshwater plume in the Pacific Ocean during the present regulated peak spring discharge.

Figure 1.1 – The Columbia River Basin (adapted from Corps media library)

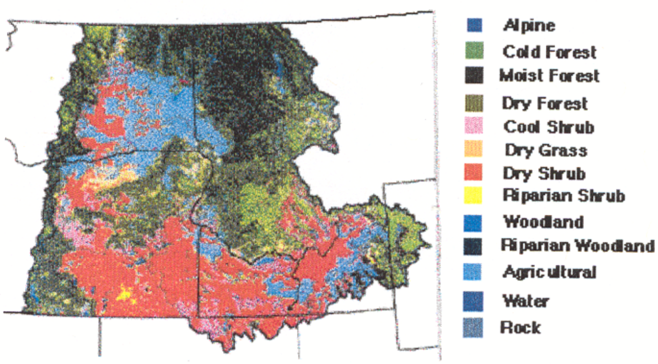


Figure 1.2 – Land cover in the CRB (Interior Columbia Basin Ecosystem Management Project, 2000)

The most significant aspect of the basin's geography, as it pertains to water resources, is its effect on both the regional climate and hydrology. The hydrology of the CRB is dominated by the winter snowfall and spring snowmelt cycle, which are byproducts of large winter snow accumulations in the Rocky and Cascade Mountain Ranges. Under the present climate, this cycle effectively stores large quantities of winter precipitation through the late spring. At The Dalles, nearly 60% of the runoff first accumulates as snow, and approximately one third of the annual discharge originates from the Canadian Rockies (Hamlet and Lettenmaier, 1999).

1.3: The Columbia River Reservoir System

Although the lower CRB underwent significant development in the 1800's (especially canal building and dredging projects), the current state of the system is dominated by infrastructure constructed during the 20th century. The convergence of various interests lead to the development of the CRB. These include, among others, public and private hydropower interests, irrigation projects, navigation interests, and work relief projects during the Great Depression. The resulting hydroelectric resources contributed directly to World War II, especially through development of an abundant supply of electricity that fueled aluminum plants, shipyards, and development of nuclear weapons at the Hanford Engineering Works near Richland, Washington. The boom in river development, which began with the construction of the largest dams in the 1930s and 1940s, ended in the late 1970's after the completion of Canada's Mica Dam and the four run-of-river projects on the lower Snake River. Despite the halt in development, the Columbia remains among the most densely developed hydropower sources in the world.

Table 1.1 – Columbia River dams contributing to flood protection at The Dalles, OR

ColSim Storage Dams	Reservoir Names	Location	Total Storage (billion m^3)	Nameplate Rating (MW)
Mica	Kinbasket	British Colombia	24.55	1,792
Keenleyside	Arrow Lakes	British Colombia	9.03	185
Duncan	-	British Colombia	1.76	0
Libby	Koocanusa	Montana	7.22	525
Corra Linn	Kootenai	British Colombia	1.01	559
Hungry Horse	Flat Head	Montana	4.50	428
Kerr	-	Montana	2.21	114
Albeni Falls	Pend Oreille	Idaho	1.87	43
Grand Coulee	F D Roosevelt	Washington	11.22	6,465
Upper Snake	*(Aggregated)*	Idaho	3.18	*120*
Mid Snake	*(Aggregated)*	Idaho	5.23	*107*
Brownlee	-	Idaho	1.75	585
Dworshak	-	Idaho	4.28	400
Total			**77.81**	**11,096**

The largest dams in the CRB (see Table 1.1) have a combined total storage capacity of nearly 62 billion cubic meters, which is managed to support a variety of purposes. Although dams are authorized individually for specific purposes, all of those listed in Table 1.1 provide a degree of flood protection, and all are operated to produce hydropower. Grand Coulee and the Snake River dams are operated to assist with the irrigation of over 5 million acres (2.02 million hectares) of farmland. The four lower Snake dams and the four lower Columbia projects have made Lewiston, Idaho the world's furthest inland sea-accessible port, 680 km from the ocean. A more thorough description of the CRB reservoir system and its operating purposes is provided in Chapter 3.

Hydropower provides, by far, the most significant economic benefit of the CRB reservoir system. Traditionally, the demands for electric power within the Columbia have been more or less consistent with flood control objectives on the lower Columbia – that is, large reservoir evacuations to provide storage for the spring runoff peak have coincided with the high-demand winter period. As a result, hydropower has de facto access to the largest portion of "active" storage in the basin (as compared with flood control, stream augmentation, and irrigation). Effective operation of the hydropower facilities is critical to the region, as they account for roughly 70 percent of the region's electrical capacity (Northwest Power Planning Council, 2001). This abundance of hydropower is one reason why the Pacific Northwest has the nation's cheapest electricity rates (BPA, 2001).

The enormity of the Columbia's hydropower capacity, however, did not come without a cost. The eleven run-of-river structures on the Columbia present a serious impediment to the survival of native fish and to the breeding cycles of anadromous species (most notably salmon) (National Marine Fisheries Service (NMFS), 2000). High spring runoff traditionally carried salmon smolt rapidly to the Pacific. However, the now-languid backwaters of the CRB reservoir system force salmon to make the trip without the benefit of naturally high stream velocities, resulting in greater in-stream mortalities.

In recent decades, both the Endangered Species Act (ESA) and court cases associated with tribal treaty rights have increased the priority of fish and wildlife management in reservoir operations and administrative budgeting. One result is that a significant portion of the Bonneville Power Administration's annual budget is allocated to researching ways to improve fish survival while minimizing effects on hydropower production (BPA, 2002). In the last 20 years, the BPA alone has invested nearly $3.5 billion in salmon recovery efforts (Northwest Power Planning Council, 2001).

1.4: Implications of Climate Change for CRB Water Resources

CRB water managers – principally the U.S. Army Corps of Engineers (COE), BC Hydro, the Bonneville Power Administration (BPA), and the U.S. Bureau of Reclamation (USBR) – have conflicting resource goals, intermittent (and politically fueled) changes in system priorities, and a dynamic natural hydrology. Reservoir managers routinely deal with interseasonal and interannual climate variability in mediating demands for flood protection and the need to maintain both reservoir storages and streamflows through the summer. In a sense, potential climate change is only one of many strains placed on CRB management. The major constraint in dealing with conflicting system demands (reservoir storage) is fixed, and there are few opportunities (either politically or geographically) to develop additional storage. Nevertheless, storage requirements for the Endangered Species Act and regional power consumption have been increasing (largely due to population growth; per capita power consumption has mostly been decreasing). Climate change complicates these trends by shifting the seasonal availability of runoff: a result that will increase competition for limited reservoir storages.

The direction, if not the magnitude, of climate change impacts on the Columbia River are reasonably well known. All climate scenarios indicate a general warming, a change that moves the spring discharge peak earlier in the year, and reduces summer and fall discharge (Hamlet and Lettenmaier, 1999). In addition, many sub-basins could be prone to increased winter flooding (Loukas, et. al., 2002), severe and frequent droughts, and significant decreases in summer flows. The latter effect will assuredly result in increased conflicts among summer lake recreation, instream flow for fish, irrigation withdrawals. On the other hand, there is some hope that improvements in reservoir management could help to mitigate some of these conflicts. For instance, Yao and Georgakakos (2001) studied the effect of climate change on the performance of Folsom Lake (a large reservoir in California) and found that both adaptive decision systems and dynamic operations would be able to benefit reservoir performance considerably under a changed climate.

1.5: Hypothesis

Given that climate change of some magnitude is likely due to ongoing increases in concentrations of GHG and inertia in both emissions control policies and the climate system, adaptation to climate change is required. Adaptation strategies have the potential to reduce many of the adverse impacts of climate change, although neither without cost nor without leaving residual damage (IPCC, Houghton and Ding, 2001). The central hypothesis of this thesis is that alternative operating policies for the CRB reservoir system could substantially mitigate impacts to reservoir system performance that otherwise would be expected due to climate change over the next century.

Chapter 2 - Research Approach

The research reported in this thesis was supported by the U.S. Department of Energy as part of its Accelerated Climate Change Prediction Initiative (ACPI). ACPI was created to study, among other things, the potential impact of climate change on the nation's energy supply. The ACPI addresses the national need for understanding climate processes:

> "[The] United States requires an unprecedented acceleration and extension of the modeling state of the art to reduce existing uncertainties about long-term climate change and provide regional specification in climate change projections to support national and international energy and environmental policies that must be formulated and implemented early next decade (DOE, 1998)."

The ACPI seeks to integrate three research pathways: the development and evaluation of GCMs, the publication of climate projections, and the assessment and analysis of hydropower impacts related to the projections.

This thesis is associated with the third pathway. Specifically, it assesses climate impacts on the performance of federal hydropower projects within the Columbia River Basin. This assessment used the DOE/NCAR PCM, the Variable Infiltration Capacity (VIC) macroscale hydrology model (Liang et al, 1994; Liang et al, 1996b), and the Columbia Simulation Model (ColSim) (Hamlet, et al, 1999). Four PCM ensembles were constructed and run by NCAR: three transient climate change ensembles spanning the 21st Century and a 52 year control ensemble representing the atmospheric conditions of 1995 (see Section 2.1). Atmospheric data, including temperature, precipitation, and information on near-surface energy balances were downscaled and bias corrected from the PCM ensembles to match with the temporal and spatial resolution of the VIC model. The downscaling and bias correction methods used to transform PCM outputs into VIC inputs are described in detail by Wood, et al. (2002a; b), and are summarized in Section 2.2. The VIC model, described in Section 2.3, was used to generate naturalized, or unregulated, hydrographs at 15 river stations in the CRB that correspond with the projected PCM climate changes over the next 100 years. These hydrographs were used directly as input into the ColSim reservoir operation model, where experiments were conducted to establish the impact of projected hydrology changes on the Columbia River's operational reliability. Alternative operating policies were then pursued in ColSim to develop the sensitivity of system performance to reservoir operations. Finally, an assessment was conducted to maximize system operations considering a combination of several operating alternatives and conservative system constraints. (See Section 2.4.)

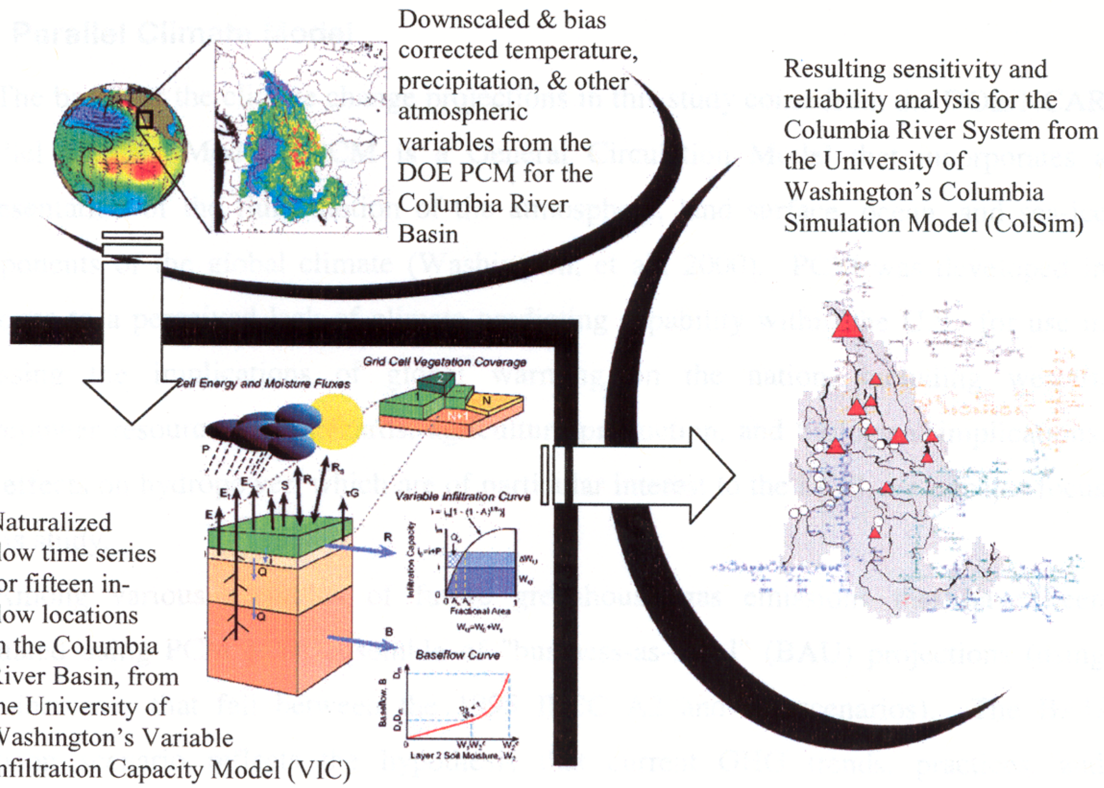


Figure 2.1 – The underlying relationship between the PCM, VIC, and ColSim models in this study

Figure 2.1 illustrates the basic process integrating results from PCM, VIC, and ColSim. This has become a common method of assessing the results of GCMs on regions and river basins. Lettenmaier and Gan (1990) developed the basic approach for investigating of the effect of climate change in California's Central Valley, as part of an

EPA Report to Congress (Smith and Tirpack, 1989). The method has since been applied several times to the CRB to determine the system's sensitivity to various GCM projections of climate change (e.g. Hamlet and Lettenmaier, 1999; Cohen, et al, 2000), and to determine the economic value of long-lead forecasting in countering climate change (Hamlet, et al, 2002). For the present study, the approach was expanded to evaluate the water resource implications of a true transient GCM global warming scenario, and to investigate the potential for mitigating system losses with reservoir operations (constrained to conservative assumptions for future system demands).

2.1: Parallel Climate Model

The basis for the climate change projections in this study come from the DOE/NCAR Parallel Climate Model. PCM is a General Circulation Model that incorporates a representation of the fluid motion of the atmosphere, land surface, ocean, and sea-ice components of the global climate (Washington, et al., 2000). PCM was developed in response to a perceived lack of climate predicting capability within the U.S., for use in assessing the implications of global warming on the nation, including western hydropower resources, fire hazards, agriculture production, and biological implications. The effects on hydropower, which are of particular interest to the DOE, are a major focus of this study.

Among various scenarios of future greenhouse gas emissions that have been evaluated using PCM is an ensemble of "business-as-usual" (BAU) projections (using CO_2 increases that fall between the 1995 IPCC A2 and B2 scenarios). The BAU emission scenario reflects the hypothesis that current GHG trends, practices, and abatement strategies will continue, at least over the next century. This study is based on three PCM ensembles, each of which uses the same BAU greenhouse gas emission scenario, but in which the atmosphere was initialized differently so as to allow the chaotic nature of the atmosphere (and its interactions with the ocean and land) to evolve differently. The generation of the three ensembles is performed in a manner similar to that routinely used in weather forecasting; each of the three ensembles represents a different future that could occur, consistent with the prescribed (deterministic) emission scenario. For the purposes of this study, the three ensembles are treated as equally probable scenarios.

The three BAU climate ensemble members (Table 2.1) used in this study are denoted B06.44, B06.46 and B06.47, and span the period 1995-2099. A shorter (1995-2048) control simulation, denoted B06.45, in which GHG emissions are fixed at roughly year 1995 levels is also used in this study, as is part of a historical simulation (130 years), for which GHG emissions were fixed at pre-industrial levels. In particular, the historical simulation (B06.28) is used to derive statistics needed for bias-correcting the PCM control and climate change runs.

Table 2.1 – PCM Simulations used in this study

Run	Description	Period
B06.28	Historical (CO_2+aerosols at pre-industrial levels)	1870-2000
B06.45	Climate Control (CO_2+aerosols at 1995 levels)	1995-2048
B06.44	Climate Change (BAU6, future scenario forcing)	1995-2099
B06.46	Climate Change (BAU6, future scenario forcing)	1995-2099
B06.47	Climate Change (BAU6, future scenario forcing)	1995-2099

The results reported here are based on segments of the BAU ensembles for three 30-year periods: 2010-2039, 2040-2069, and 2070-2098. Our assessment approach is based on full transient assessment of these warming scenarios within the VIC hydrology model, rather than the more common "quasi-transient" approach (Lettenmaier et al., 1999), in which segments of the warming scenarios (e.g. decades) are averaged and used to adjust historic observations to reflect decadal changes in means relative to a control climate run.

Figures 2.2 and 2.3 show the temperature and precipitation trends of the three transient runs for the CRB, compared with the control run. Averages of the historic and control climates are included as horizontal lines. The average 1995 temperature is noticeably higher than the historic temperature, which is expected and confirms the increases in temperature that have already occurred in the Pacific Northwest (Mote, et al, 1999).

As part of other studies (Wood, et al, 2002c; Hamlet, et al, 1999; Maurer, et al, 1999), several other GCM runs have been downscaled and used in the VIC model, including runs from the Max Planck Institute (MPI) and the U.K. Hadley Center (HC2). Figure 2.3 displays the resulting of hydrographs (routed through VIC) for each of the GCMs used to date. The PCM results are notable in that they have smaller temperature rises than most other models, primarily due to their higher rates of ocean sequestration of greenhouse gasses. It is worth noting that among the three models there is relatively less disparity in the projections for early in the 21st century, primarily because the initial climate condition exerts considerable control early in the simulations.

A critical aspect of the approach is the use of a chain of models – including the GCM and the resultant ensembles, a downscaling approach to produce from the GCM ensembles input at the appropriate spatial and temporal resolution, the VIC hydrology model, and the ColSim reservoir simulation model. The downscaling approach is summarized in the following section. The VIC hydrology model and the ColSim reservoir model are described briefly in the following sections. More information on the PCM, its development, and its regional application in the ACPI is available in Washington (2002), Barnett et al. (2001), and Leung, et al. (2002).

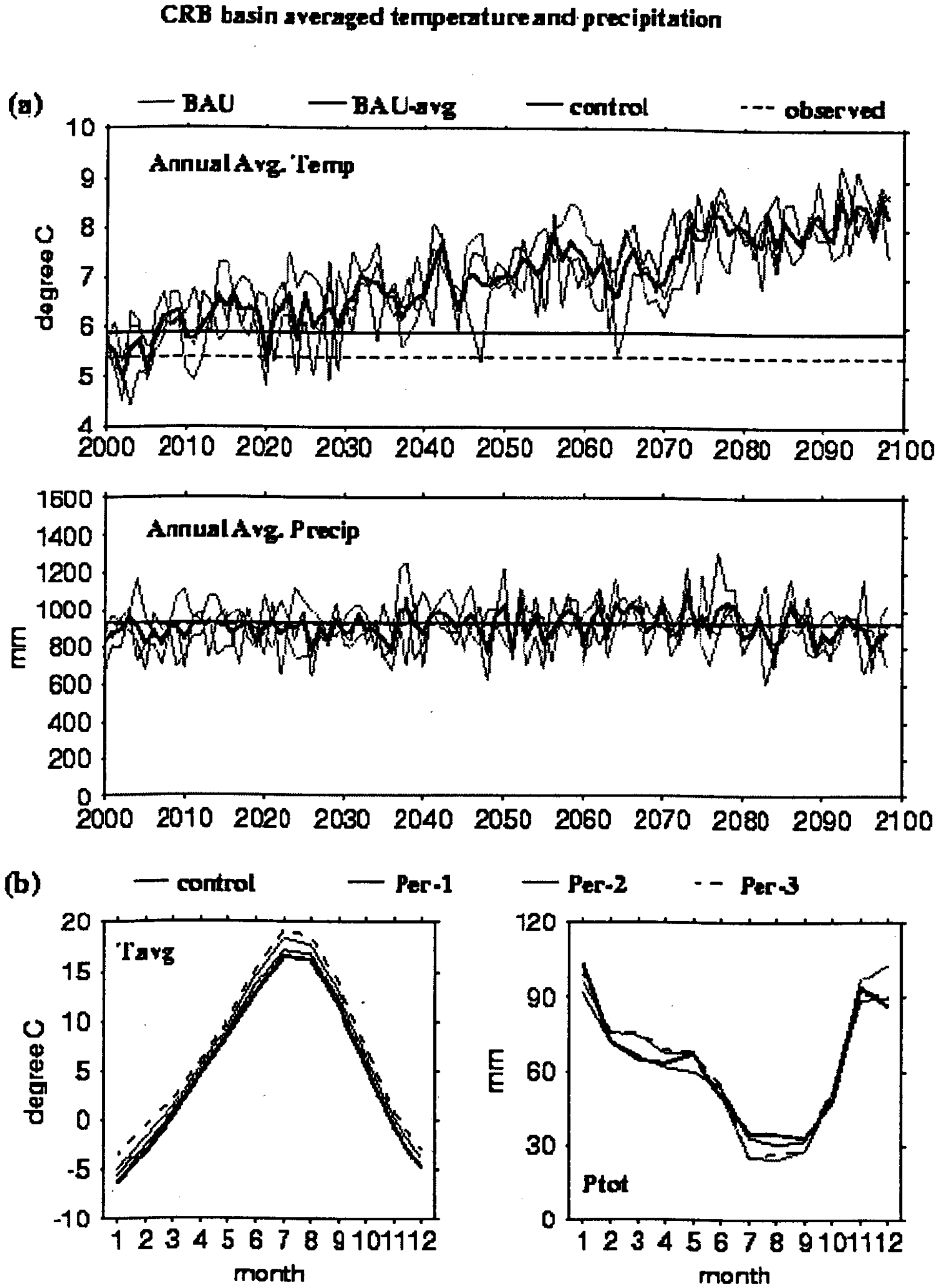


Figure 2.2– (a) Downscaled CRB-average annual total precipitation and average temperature; and (b) CRB-average monthly total precipitation and average temperature

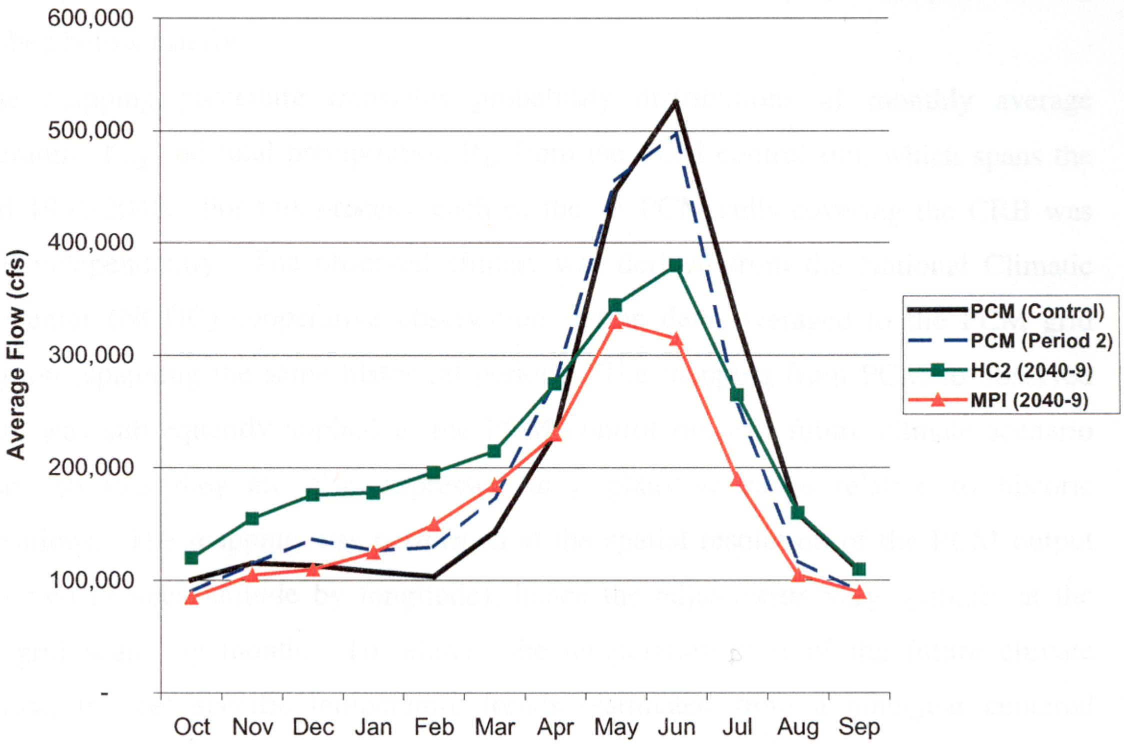


Figure 2.3 – A comparison of projected naturalized annual hydrographs about the year 2045 at The Dalles, OR. Represented are projections from the Max Planck Institute (MPI) the U.K. Hadley Centre (HC2) for the 2040 decade (the closest approximation of Period 2 from previous studies, i.e. Hamlet, 1999) and the DOE/NCAR Parallel Climate Model (PCM), which is used as the Control (current climate) and displays the average results from Period 2 (2040-2069).

2.2: Downscaling Approach

In order to transform PCM outputs into naturalized runoff hydrographs, biases in the climate model outputs had to be removed and downscaled to meet the spatial and temporal requirements of the hydrology model. The method of bias-correction used is based on a quantile mapping method developed by Wood et al. (2002a), which was originally designed for application to streamflow forecasting driven by multi-month climate ensembles. Its application to downscaling of the PCM climate ensembles is described in Wood et al (2002b). The basic procedure is to map observed probability distributions of average monthly temperature (T_{avg}) and total precipitation (P_{tot}) to probability distributions for the simulated GCM ensemble output. The procedure is described below briefly.

The mapping procedure translates probability distributions of monthly average temperature T_{avg} and total precipitation P_{tot} from the PCM control run, which spans the period 1995-2048. For this process, each of the 13 PCM cells covering the CRB was treated independently. The observed climate was derived from the National Climatic Data Center (NCDC) cooperative observation station data, averaged to the PCM grid resolution (spanning the same historical period). The mapping from PCM to observed climate was subsequently applied to the PCM control run and future climate scenario outputs, so that they are also expressed in a plausible range relative to historic observations. The mapping was performed at the spatial resolution of the PCM output (about two degrees latitude by longitude); hence the adjustments vary spatially at the PCM grid scale, by month. To address the temperature shift of the future climate scenarios, the cell-specific temperature trends (estimated from a nine-year centered moving average) were removed before, and replaced after the bias-correction step.

Following bias correction, the climate change ensembles were disaggregated from the PCM cells (thirteen cells of T62 resolution, dimensions 1.91° latitude by 1.87° longitude) to the ¼-degree latitude-longitude resolution of the hydrology model. This was achieved by imposing a random daily pattern of T_{avg} and P_{tot} (from the historic record, at the resolution of the VIC hydrology model) so as to reproduce the interpolated PCM monthly fields. The reader is referred to Wood et al., (2002a; b) for details of the procedure.

2.3: Variable Infiltration Capacity Hydrology Model (VIC)

The Variable Infiltration Capacity (VIC) macroscale hydrologic model (Liang et al., 1994; 1996; 1999) was used to generate the naturalized streamflow hydrographs for the Columbia River. VIC simulates land-atmosphere interactions via a multi-layered grid cell mosaic representation of the land-surface. Within each grid cell, sub-grid spatial variability in precipitation, infiltration, and vegetation cover are represented, with the sub-surface represented by three soil layers. Lateral movement of water from grid cell to grid cell is represented via a channel routing post-processor. Land-atmosphere fluxes of moisture and energy are assumed to be entirely vertical. VIC has been applied to such large continental rivers as the Columbia (Nijssen et al., 1997), the Arkansas-Red (Abdulla et al., 1996), and the Mississippi (Maurer et al. 1999; Cherkauer and Lettenmaier, 1999), and, as part of the Land Data Assimilation System (LDAS) project (Mitchell et al, 2000), to the continental U.S. (Nijssen, et al., 2001). The model has performed consistently well in comparisons with observations conditions (e.g. Liang 1998; Lohmann 1998). Figure 2.5 illustrates how VIC translates surface meteorological and radiative forcings (precipitation, temperature, wind, humidity and downward solar and long wave radiation) into runoff.

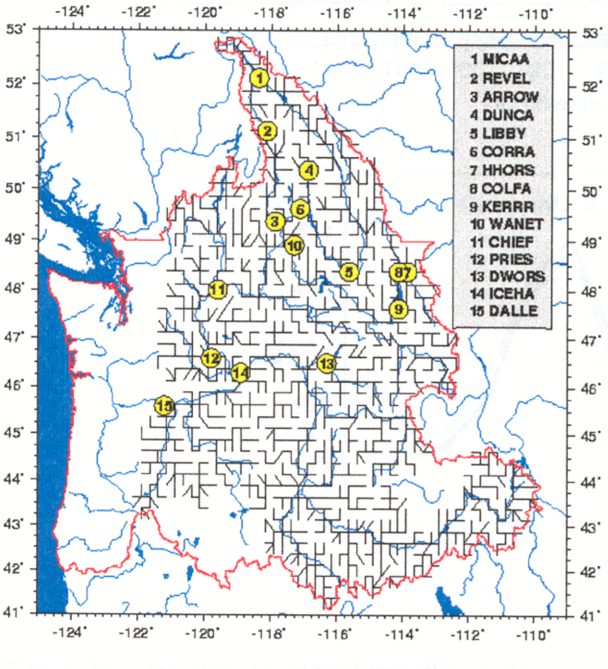


Figure 2.4 – The ¼ degree VIC routing network for the CRB, with the fifteen designated streamflow stations used as input into the ColSim reservoir operation model

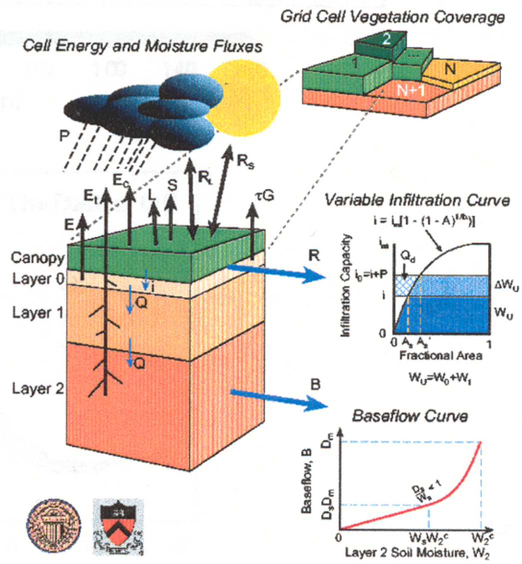


Figure 2.5 – A general schematic of the VIC macroscale hydrologic model (Lettenmaier, 2002)

The naturalized daily VIC outputs were routed through the stream network to 15 nodes corresponding with stream gauge locations along the Columbia River and its tributaries, as shown in Figure 2.4. For the ColSim reservoir model, each streamflow time series was produced on a daily time-step by VIC and was then aggregated into a monthly flow volume to fit with the water resources model.

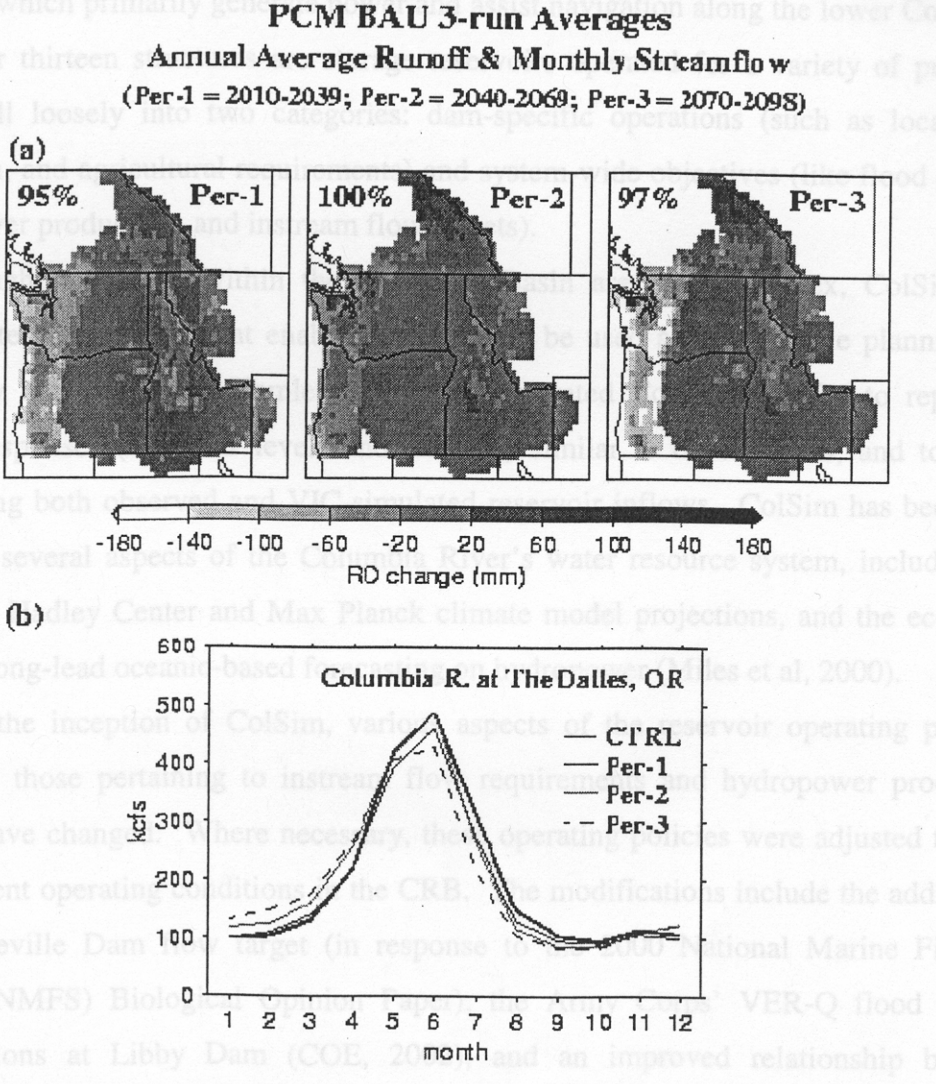


Figure 2.6 – (a) average annual runoff and (b) mean monthly hydrograph for The Dalles, OR

2.4: Columbia River Simulation Model (ColSim)

ColSim was developed by Hamlet (1999) to provide a relatively simple tool to evaluate the implications of hydrologic changes associated with climate, vegetation, and other large-scale changes represented by the VIC macroscale hydrology model on performance of the CRB reservoir system. ColSim simulates the operations and outputs of thirty-three dams in the Columbia River basin. Twenty of these dams are run-of-river projects, which primarily generate power and assist navigation along the lower Columbia. The other thirteen structures are storage reservoirs operated for a variety of purposes, which fall loosely into two categories: dam-specific operations (such as local flow, recreation, and agricultural requirements) and system-wide objectives (like flood control, hydropower production, and instream flow targets).

Although operations within the Columbia Basin are quite complex, ColSim uses appropriate assumptions that enable the model to be used as an effective planning and sensitivity analysis tool. Hamlet (1999) demonstrated ColSim's ability to reproduce system responses (reservoir levels and releases) similar to observations, and to do so when using both observed and VIC-simulated reservoir inflows. ColSim has been used to assess several aspects of the Columbia River's water resource system, including the effects of Hadley Center and Max Planck climate model projections, and the economic value of long-lead oceanic-based forecasting on hydropower (Miles et al, 2000).

Since the inception of ColSim, various aspects of the reservoir operating policies, especially those pertaining to instream flow requirements and hydropower production targets, have changed. Where necessary, these operating policies were adjusted to meet with present operating conditions in the CRB. The modifications include the addition of the Bonneville Dam flow target (in response to the 2000 National Marine Fisheries Service (NMFS) Biological Opinion Paper), the Army Corps' VER-Q flood control modifications at Libby Dam (COE, 2002), and an improved relationship between agricultural applications and return flows in the Snake River Plain. A more detailed description of the operations at each dam is provided in Chapter 3.

ColSim is used here to evaluate possible changes in the CRB reservoir operating policies that might mitigate effects of global warming as predicted by the PCM ensembles. Altering regulatory requirements within the ColSim model provided the means for these evaluations. Specifically, alterations in the required winter flood control evacuation, shifts in the timing of refill, changes in the demand curve for firm energy, and increases in the total allocated storage for instream flow requirements were evaluated. Details of the specific evaluations performed are described in Chapter 4.

Chapter 3 - Representing Columbia River reservoir operations: ColSim

ColSim is a monthly time-step, object-oriented model designed to evaluate the performance of the Columbia River reservoir system, as it would be affected by either changes in reservoir inflows (associated with changes in climate, and/or land cover) or reservoir operation. ColSim replicates the key features of the present reservoir system and its current operating policies while maintaining a principle of limited complexity, or Occam's razor. Details of the physical system and its operation are included in ColSim only to the extent that they substantially affect the overall system's performance.

ColSim explicitly represents eleven major storage reservoirs, two aggregated storage reservoirs, and hydropower production at 20 run-of-river facilities within the system. Although representation of hydropower generation is a key objective, the model also represents performance of the system with respect to the other major purposes of system operation, including flood damage mitigation, environmental flow targets, Snake River Plain irrigation, and recreation at Lake Roosevelt. Each of these multiple purposes are monitored in terms of their overall monthly performance and, when possible, in economic terms.

For this study, the primary focus is on the relationships among flood control, hydropower, and instream flow targets. Ultimately, this work is concerned with answering, "Can negative climate change impacts be mitigated by altering reservoir operation policies?" This requires an understanding of how individual reservoir functions are most affected by both changes in natural inflows and alternative operation policies. Performance measures (also called metrics of performance, or metrics) were developed to highlight the system's sensitivity within ColSim's monthly time-step environment. The sensitivity results are used in formulating several alternative policies and a final, combination alternative, designed to maximize the performance of the water resource system within each of the three 30-year analysis periods.

3.1: Flood Control

All dams within the CRB have one of five classifications with respect to flood control, as designated by the U.S Army Corps of Engineers (COE, 1991): (1) Headwater reservoirs operated with fixed releases; (2) reservoirs operated for tributary protection; (3) major lakes operated for flood control; (4) reservoirs operated with variable releases for downstream flood control; or (5) run-of-river projects. Of these, (1) and (4) are the most important to short-term system regulation. Category 4 reservoirs in particular (Arrow, Grand Coulee, and John Day) require continual adjustment during the spring runoff to achieve flood control in the lower Columbia (COE, 1991).

ColSim reduces this complexity into three elements; 1) run-of river dams with no flood operations, 2) operations at individual dams for local targets, and 3) conjunctive operations for protection of the lower Columbia River. The majority of dams modeled by ColSim are represented as run-of-river structures, including John Day, which is modeled as a run-of-river structure because its storage is nominal in relation to flooding events that occur on a monthly time-step. Individual operations include provisions for protection against local flooding, such as in the reaches below Mica and Corra Linn Dams. Many of the existing local operations, such as ramping rates (restrictions pertaining on the rate by which the instantaneous releases from dams can be altered) and maximum daily releases, are obscured at the monthly time-step used by ColSim and are therefore not represented.

Table 3.1 – The relationship between flows at The Dalles and Portland-Vancouver flood conditions (COE, 1991)

Outflow at The Dalles		Corresponding Vancouver Stage		Flood condition at Portland	Annual Exceedance Frequency
(cfs)	(cms)	(feet)	(m)		
450,000	13,000	16	5	Bankfull	10%
500,000	14,000	19	6		5%
600,000	17,000	22.5	7	Minor Damage	2%
750,000	21,000	26	8	Major Damage	0.2%
950,000	27,000	30	9	Levee Overtopping	0.05%

Protection of flood control levees in the Portland area is indexed by flows at The Dalles (a point also used by the COE in more detailed flood analyses), and requires the conjunctive regulation of flows at all thirteen ColSim storage reservoirs. ColSim represents these operations by attempting to maintain average monthly releases at The Dalles below the bankfull value of approximately 450,000 cfs (13,000 cms). Table 3.1 defines the relationship between Dalles outflow and Portland-Vancouver flood conditions used in this study. The contribution of ColSim storage projects to Dalles flood control is achieved in different manners, depending upon their COE flood control designation. Generally, all dams have evacuation requirements based on forecasts of spring snowmelt, which are simulated in ColSim as error-free (perfect fore-knowledge of future inflows). Arrow and Grand Coulee (as category 4 dams) are the only two in the model with the ability to manage flows on the lower Columbia River. This is a result of travel time limitations at the other storage reservoirs. The remaining storage projects (Mica, Duncan, Libby, Hungry Horse, Noxon, Brownlee, Dworshak, and the two aggregated Snake River reservoirs) provide flood control either incidentally or through COE developed variable draft schedules, published as Storage Reservation Diagrams (SRD).

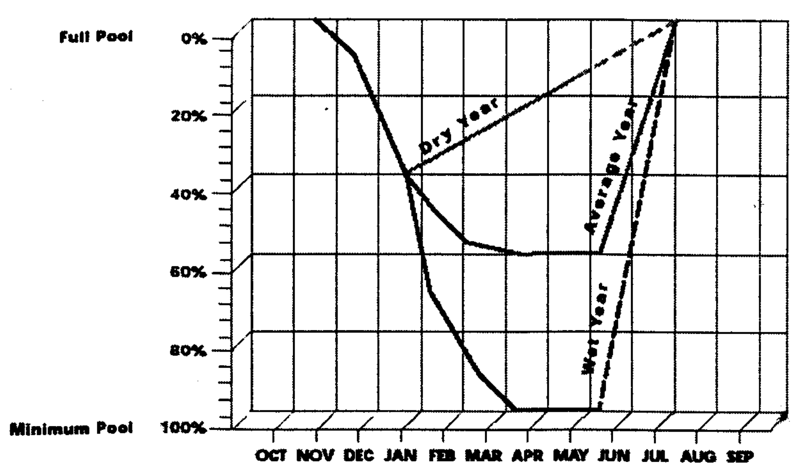


Figure 3.1 – Typical Storage Reservation Diagram. SRDs provide guidelines for drafting flood storage based upon projections of snowpack and flooding potential. (BPA, 2001a)

SRDs provide release schedules, which include a fixed rule curve until January 1st, and then a variable rule curve, which is a function of forecast inflow between January 1st and July 1st (conceptualized in Figure 3.1). The aggregated Snake River projects (which represent Jackson Lake, the Palisades, Anderson Ranch, Arrowrock, and Lucky Peak Reservoirs) are operated in ColSim for the protection of nearby tributaries and agricultural demands. According to the COE (COE, 1991), they provide only incidental flood protection for the lower Columbia.

SRDs and release ratios were adjusted to be consistent with the monthly time-step of ColSim, which is generally sufficient to simulate drawdown and release in a manner consistent with observations (Hamlet, 1999). The SRDs utilized in ColSim were developed in the *Columbia River Treaty Flood Control Operating Plan* (COE, 1972), and then reiterated in the COE 1991 flood control review (COE, 1991). Generally, little adjustment was required to adapt the published flood control operations for a monthly time-step simulation. SRDs pertaining to ColSim are provided in Appendix A.

Notwithstanding the ability of ColSim to represent major aspects of conjunctive flood operation, the monthly time-step introduces a degree of uncertainty in the representation of flood risks at The Dalles. Figures 3.2 and 3.3 show the relationship between average monthly streamflow and peak daily flows at The Dalles for the months April through August for two conditions; 1) the regulated historic record for water years 1974 to present (conditions since the construction of Mica Dam; effectively representing completion of the present flood control system), 2) the unregulated VIC model flows simulated for historic conditions (1975-2000), routed to The Dalles.

These two ratios are relatively close. The regulated historical ratio between average monthly outflow and peak daily flow is 1:1.28 and the same relationship for naturalized (unregulated) simulated flows over the same period produces a ratio of 1:1.33, about five percent larger than the regulated value based on observed flows. The smaller, historic regulated index (1.28) was used for three reasons: 1) there was little difference in the projected damage levels between the two indices, 2) flood control would undoubtedly reduce expected ratios despite the proposed operations changes tested herein, and 3) the smaller index overestimated the ratio between daily peak and monthly average flows for the highest points in the scatter-plot (which are of the most concern in flood control), thereby adding an extra level of safety in the calculations. (The process of converting discharge values into dollar damages is discussed in detail later in this chapter: see Section 3.6.1.)

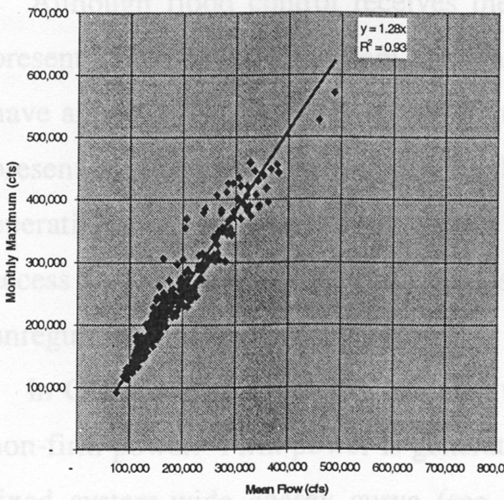


Figure 3.2– The historic relationship between the regulated monthly mean and daily maximum flows at The Dalles, OR during the flood and refill season [April-August] from 1974 to 1999

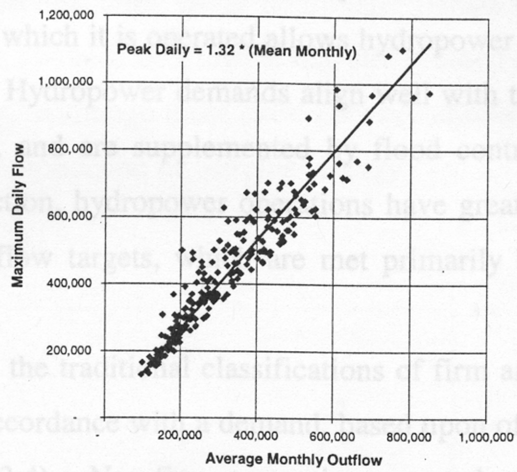


Figure 3.3 – Relationship between naturalized flows from the meteorological record. This is VIC data, processed at 1/4th degree. Index = 132%

The 1.28 factor relating monthly average flows to peak daily flows at The Dalles is an estimate subject to some uncertainty. This uncertainty could be reduced, for instance, through use of a hydraulic routing model, facilitating a detailed assessment of property value in the floodplain. Such an effort was beyond the scope of this study. However, the computed flood damages are relatively insensitive to the specific index estimate, especially in comparison with economic implications to other system operating objectives, hydropower in particular. For instance, an index value of 2.5 is needed to increase annualized flood damages by a factor if 10, which still would considerably less than hydropower gains or losses associated with changes in reservoir operating policies (see Section 3.2). The relatively simple indexing approach appears able to produce estimates of economic (and not political) outcomes within the range of those reported by the COE (1992).

3.2: Hydropower Production

Although flood control receives the highest operating priority for operations in the present Columbia River system, the manner in which it is operated allows hydropower to have almost equal access to reservoir storage. Hydropower demands align well with the present flood evacuation and refill schedules, and are supplemented by flood control operations. As will be shown later in this section, hydropower operations have greater access to reservoir storage than do instream flow targets, which are met primarily by unregulated outflows.

In ColSim, hydropower is modeled through the traditional classifications of firm and non-firm power. Firm power is generated in accordance with a demand, based upon of a fixed system-wide energy curve (see Figure 3.4). Non-firm power is generated and marketed under two conditions: 1) when releases from reservoirs for other operations generate electricity in surplus of firm power demands, or 2) when non-firm demands (Figure 3.4) are not satisfied by preliminary releases, and reservoirs hold storage in excess of the Energy Content Curve, or the non-firm energy draft limitation (Figure 3.5).

Firm power is contracted through the BPA for periods up to 30 years in advance. Generally, firm power follows the regional demand curve for electricity, which is highest in the winter when space heating is highest. Power demands in the CRB are lower during the late spring, summer and fall because temperatures seldom rise to levels that require air-conditioning. Firm power has traditionally held a higher market value (in comparison to non-firm power) because of its guaranteed nature, and dams are operated in a manner that preserves storage for early winter generation. This results in a family of rule curves, which are annually formulated by the BPA, COE, and USBR to preserve multiple basin objectives at the maximum value to hydropower.

There are four general rule curves at each storage dam: Flood Evacuation, Critical, Assured Refill, and Variable Energy Content Curves (Figure 3.5). The flood evacuation curve provides the upper bound on storage at each dam, as expressed in the SRDs. The critical curve constrains drafts to help fulfill late fall contracts. This is achieved by hedging against the worst one-year hydrologic period on record – presently September 1936 through April 1937 (BPA, 2001a). The assured refill curve is a desired storage goal providing for autumn refill by hedging against the third worst hydrologic period on record. The variable energy content curve (ECC) bounds non-firm drafts, and is based on projections of runoff for the spring and summer. Although these curves are not absolute, they are the guidelines that generally govern the production of 'surplus' energy.

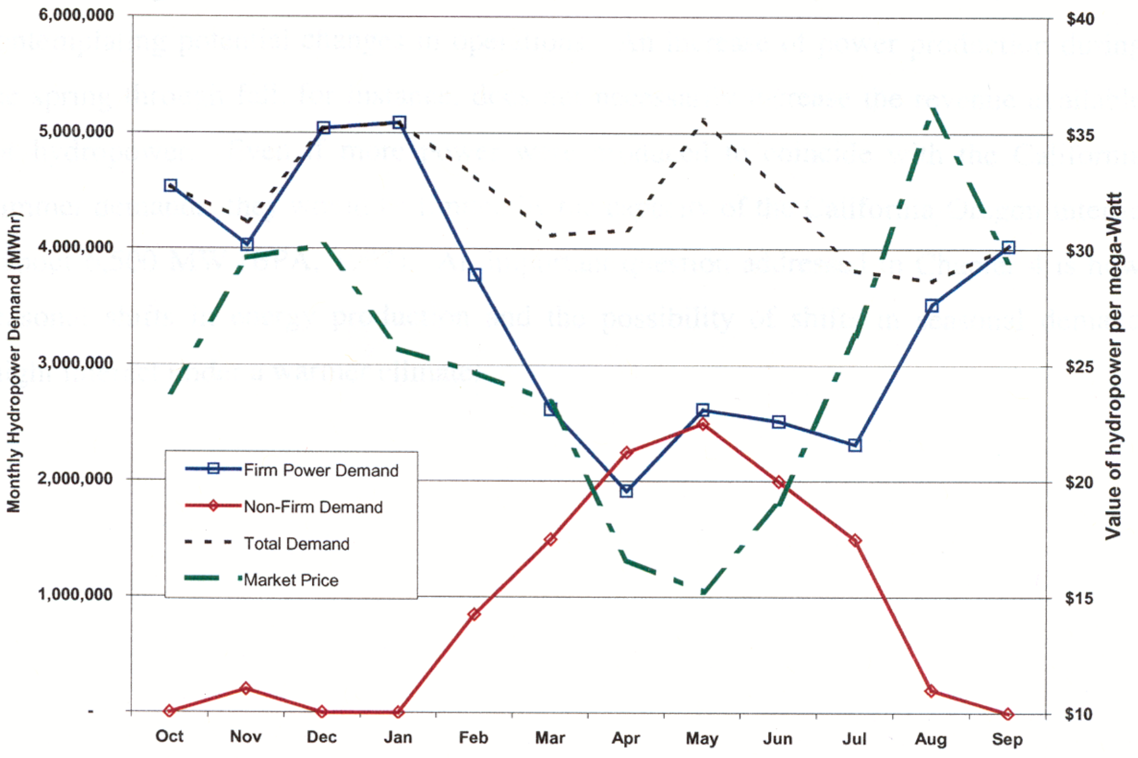
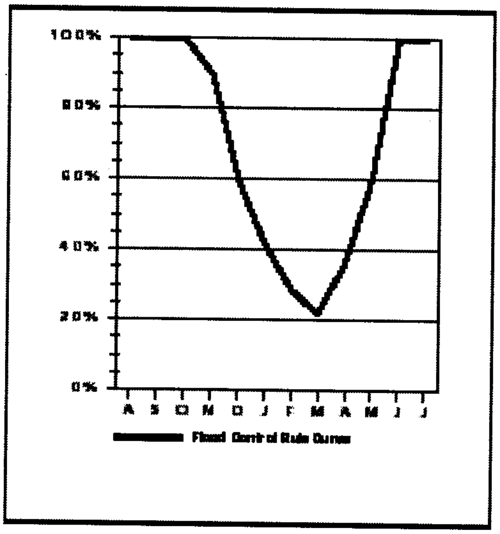


Figure 3.4 – Summary of ColSim hydropower demands used to govern releases for generation & typical curve about the present spot-market price for non-firm power (applied here to both firm and non-firm power) (BPA, 1994)

Non-firm power is produced through incidentally by releases for other operations (flood control evacuations, instream targets, navigation releases, etc.) or to accommodate spot market demands, contingent upon storages above the ECC. ColSim models non-firm demands with a peak during the summer, corresponding to spot market sales via the California Intertie, which meet summer demands for air-conditioning. It could be argued that the difference between firm and non-firm power used in ColSim has become less distinct in practice, as a result of market responses to recent energy shortages and impending deregulation. However, the quantification of a 'safe yield', represented well by firm power capacity, is still a valuable indication of the hydropower system's overall value. The blurred distinction between firm and non-firm power is acknowledged in this study by using equivalent pricing for both production classifications (Figure 3.4).

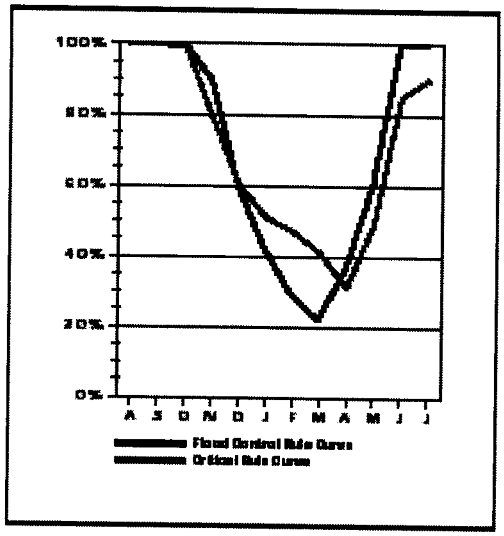
The divergent cycles for firm and non-firm demand are important to consider when contemplating potential changes in operations. An increase of power production during the spring through fall, for instance, does not necessarily increase the revenue available for hydropower. Even if more power were produced to coincide with the California summer demands, they would be limited by the capacity of the California-Oregon Intertie - about 6,500 MW (BPA, 1997). An important question addressed in Chapter 4 is how seasonal shifts in energy production and the possibility of shifts in seasonal demand might interact under a warmer climate.

Flood Control Rule Curve



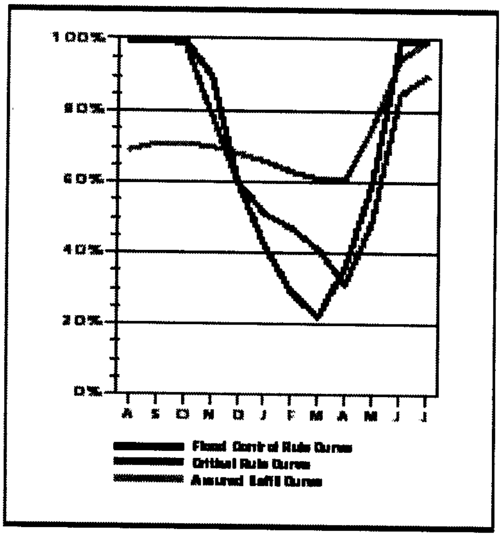
This curve is an absolute upper bounds on storage, and is defined by forecast of runoff at the Dalles, OR.

Critical Rule Curve
with Flood Control Rule Curve



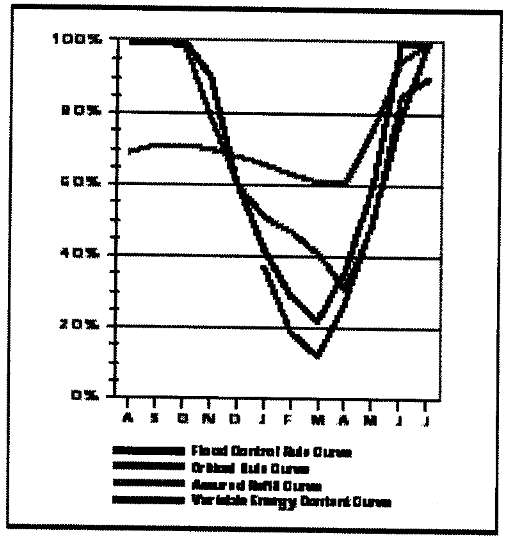
Defined by the worst year on record, this curve is a lower limit on drafts to assure firm power production (flood control will go below the critical curve in most winters)

Assured Refill Curve
with Flood Control & Critical Rule Curve



Defined by the third worst year on record, this curve is based on the Coordination Agreement refill test.

Variable Energy Content Curve
with Flood Control Rule Curve, Critical Rule Curve & Assured Refill Curve



The ECC is also based on projections for inflow, and limits non-firm energy production

Figure 3.5–Variable Rule Curves provide limitations for operations (BPA, 2002).

3.3: Instream Flow Targets

In the past decade, tremendous attention has been given to the decline of various fish and wildlife species within the Columbia River basin and their causes. Anadromous fish, such as salmon and steelhead trout, have been the most significantly impacted. Most of the losses have been attributed to the so-called "4-H's": harvesting, hatcheries, habitat loss, and hydropower (Federal Caucus, 1999). Although various federal and state agencies have attempted to find economically viable solutions to the dwindling salmon runs, the process itself has been criticized by non-government organizations for lacking clear performance objectives, accountability, and the fragmented responsibilities for planning, funding, and implementation.

Over the past two decades, the BPA alone has invested nearly $3.5 billion in salmon recovery, including the installation of fish ladders, smolt barging operations, physical improvements to dams and turbines, seasonal spills, hatcheries, and habitat research (Northwest Power Planning Council, 2001). This amount increases when spending by other federal agencies (e.g. COE, USBR, EPA) and state governments is considered, although the predominant amount of state spending is funded through the BPA. During this same period, several plans were implemented to restore salmon runs, although early emphasis was placed on hatcheries (one of the 4 H's) instead of wild salmon runs. The discontinued Water Budget was intended to set aside a block of storage which fish managers could access on an "on-call" basis. Several issues contributed to the eventual discontinuation of the water budget, primarily the endangered listing of Snake River salmon under the ESA in 1991.

Three authorities play the most important roles in salmon recovery plans: the Council, the U.S. Fish & Wildlife Service (FWS), and the National Marine Fisheries Services (NMFS). The Council is a regional administrative body, which was authorized by Congress and funded through the BPA. The Council's mandate is to protect, mitigate, and enhance fish and wildlife while providing "adequate, efficient, economical, and reliable" power for the region. In response to its mandate, the Council publishes a Fish and Wildlife Plan, which reflects the opinions of state and federal fisheries. The Plan itself holds no funding or implementation authority, however the Council does allocate some BPA funding in support of 200 or so specific projects in association with the Plan. FWS and NMFS are authorized and funded under the Endangered Species Act (ESA) to publish Biological Opinion Papers (BiOP) suggesting minimum recovery standards for both anadromous (NMFS) and resident (FWS) fish species. NMFS's limited political authority, however, somewhat countermands their legal authority, and their BiOPs (including the most recent suggestion to augment Lower Granite targets with an additional 1 million acre feet of storage) are fiercely debated as both insufficient and extreme (Columbia River Inter-Tribal Fish Commission, 2000; USBR, 1999).

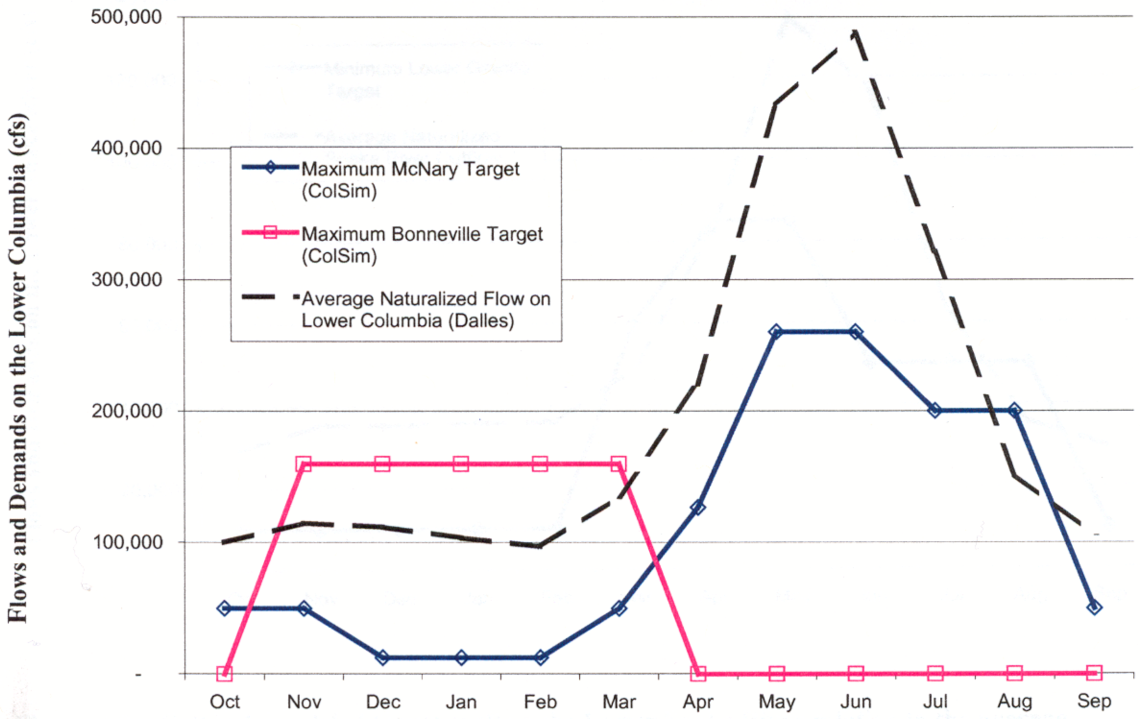


Figure 3.6 – ColSim's modeled target outflow for Lower Columbia relative to the average naturalized outflows at The Dalles Dam (PCM control)

Recent BiOPs have resulted in three significant instream targets (see Figures 3.6 and 3.7) for salmon spawning cycles and reallocations of flood storage to improve resident fish habitat (e.g., the COE VAR-Q). The three BiOP targets concern the middle and lower Columbia, where the run-of-river dams have created a veritable staircase to the Pacific Ocean. In an effort to increase velocities through the reservoirs, outflow requirements are occasionally higher than the pre-reservoir conditions for all three targets. The intent of the target flows is not to replicate historic discharges, but to reduce travel times through the reservoir system, thereby reducing the period during which young salmon passing downstream are exposed to predators.

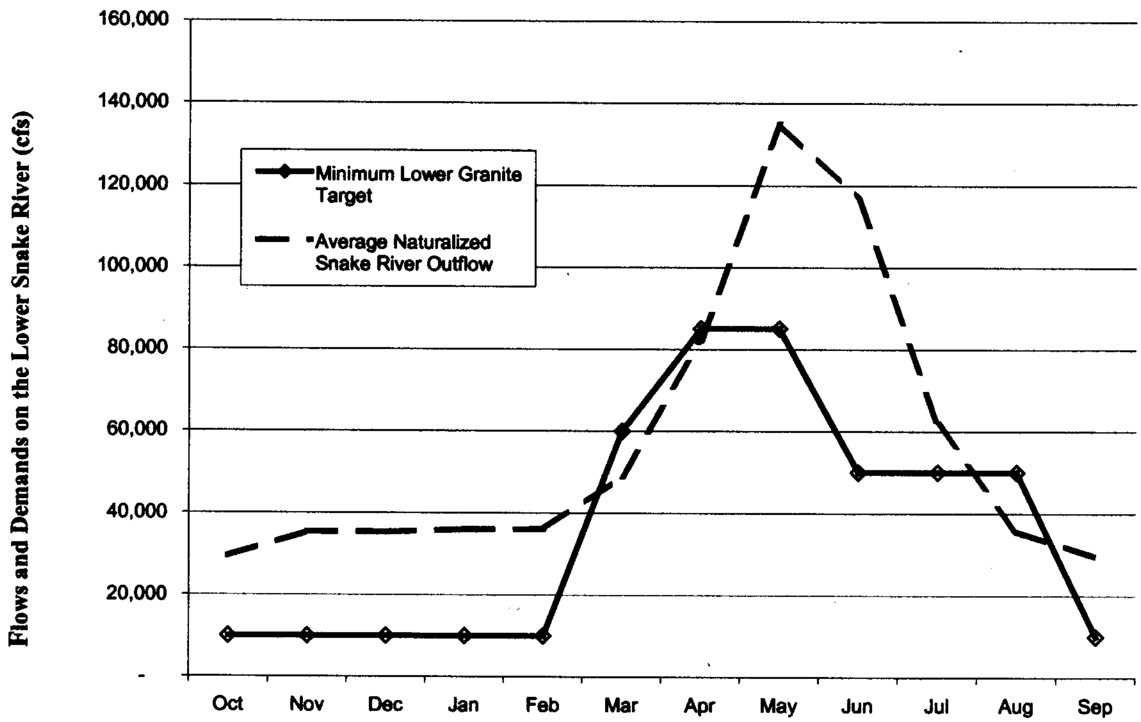


Figure 3.7 – ColSim's modeled target outflow the Lower Snake River relative to the average naturalized outflow at Ice Harbor Dam (PCM control).

ColSim represents instream flow targets in much the same way the system is intended to provide for them under the NMSF Biological Opinion. Responsibility for meeting the two lower Columbia River targets is assigned to Grand Coulee Dam, although supplemental operations exist at both Hungry Horse and Libby Dams. As mentioned in Section 3.1 on flood control, Grand Coulee is the only U.S. dam with a large enough storage and a short enough travel time (lead times less than about a month.) to affect flows along the middle and lower Columbia River. As per the USBR (2001), Grand Coulee apportions available storage in April through August for meeting the lower Columbia BiOP targets at McNary and Bonneville Dams. Withdrawals for firm power, however, may diminish these allocations, resulting in a reduced ability to meet the BiOP targets with high frequency or sufficient flows in the later summer months of all simulations.

The 1995 NMFS BiOP suggested augmenting discharges through Lower Granite by an amount up to 427,000 acre-feet in order to increase salmon smolt survival. The targets for this flow were set between 85,000-100,000 cfs from April 10 to June 20 and 50,000-55,000 cfs from June 21 to August 31, depending on projections for the entire water year. Dworshak Dam is primarily responsible for providing flow augmentation at Lower Granite Dam. Some assistance is provided from other sources, including the Idaho Water Bank – a state operated entity allowing irrigators to transfer "excess" water between federal projects without violating either the perpetual or beneficial-use clauses (see Section 3.4) of their rights – and other year-to-year resources (e.g. negotiated supplements with USBR storage facilities). These supplemental resources are not modeled within ColSim, however a small storage allocation of about 200,000 acre-feet (250 million m^3) at Brownlee Dam is modeled for responses to deficits at Lower Granite Dam. This storage augments the Lower Granite Dam target in April via shifts in basin-wide changes in from Grand Coulee to dams upstream of Brownlee (Nielson, 1998).

Approximately seven percent of the total system's storage above Grand Coulee is allocated to meeting these three instream flow targets. However, the storage available for flow augmentation is subject to draft limitations at the uppermost portion of each dam – i.e. if the system fails to refill entirely, the allocation for instream flows is reduced below the nominal seven percent.

3.4: Irrigation

Irrigation in the Columbia River Basin is protected by the legal doctrine of 'Prior Appropriation'. Prior appropriation allows private landowners to claim usufructory rights on public waters (i.e. deed holders have the right of use, but no ownership of the water). Water rights are contingent upon applications being perpetual (uninterrupted) and beneficial (usually defined in broad terms, e.g. agriculture). These rights are protected by state laws, and dedicated by seniority: the oldest deed has the first right to the water. The status of "rights" for instream habitat relative to appropriated agricultural withdrawals remains a contentious issue; in practice appropriated water rights have taken precedence, with the possible exception of instream flows related to endangered species. In any event, on the main stem of the Columbia, agricultural withdrawals are insignificant in relation to the required supplements for instream flow targets. Agriculture in the Snake River Plain (SRP) of Idaho, however, uses a great enough portion of natural flows (especially in summer) to interfere with habitat goals.

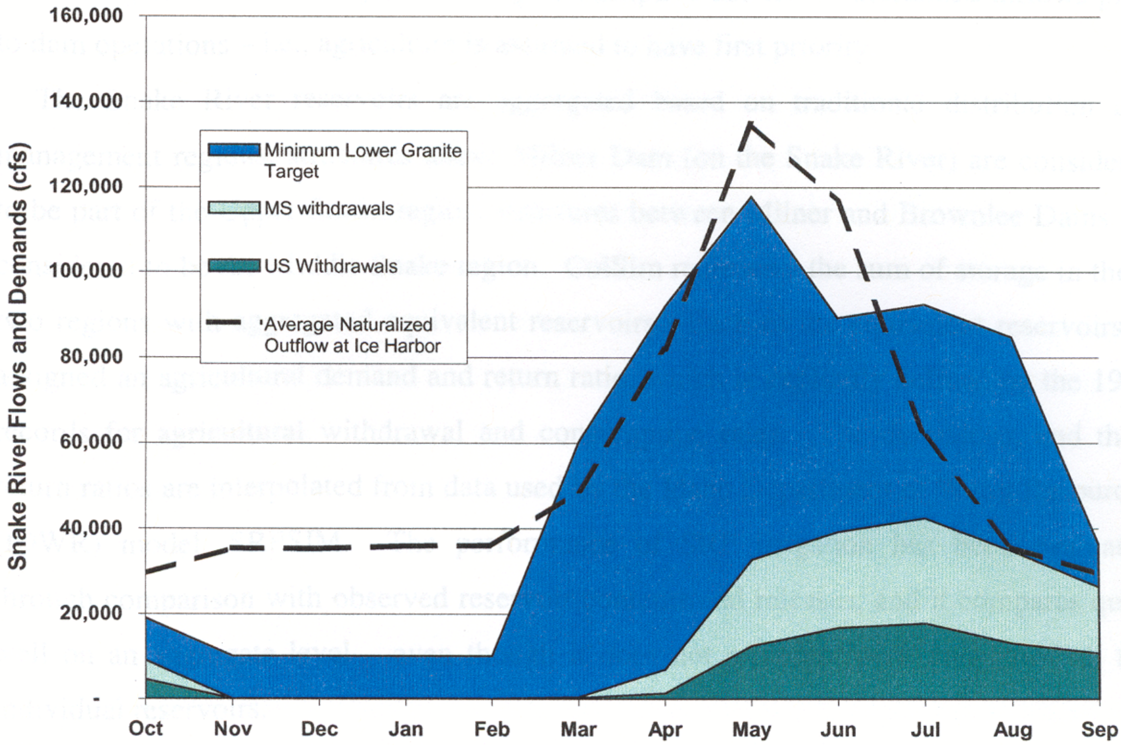


Figure 3.8 – Average Snake River flow (at Ice Harbor Dam) plotted against a stacked area graph of SRP agricultural demands and the NMFS BiOP requirement at Lower Granite Dam (as represented in ColSim) [Note: typical returns from agricultural withdrawals (which vary on the order of withdrawals between five and fifteen percent) are not represented]

Approximately 8.4 million acres (3 million hectares) are irrigated within the Columbia River Basin. The largest individual project, the USBR Columbia Basin Project, irrigates almost 650,000 acres (260,000 hectares) with diversions from Lake Roosevelt. Net withdrawal of the Columbia Basin Project constitutes about 3% of the mean annual flow at Grand Coulee. In comparison, the SRP supports about 4.1 million acres (over 1.7 million hectares) of irrigated agriculture with a network of dams. The SRP agriculture consumes and delays a significant enough portion of water that there would be substantial impacts on irrigated agriculture if the Lower Granite Dam BiOP target were given priority over senior water rights. For these reasons, ColSim explicitly models the agricultural withdrawals in the Upper and Middle Snake River Plain. All other Columbia

Basin irrigation is treated by subtracting consumptive use from naturalized inflows prior to dam operations – i.e., agriculture is assumed to have first priority.

The Snake River reservoirs are aggregated based on traditional distribution and management regions: structures above Milner Dam (on the Snake River) are considered to be part of the Upper Snake region, structures between Milner and Brownlee Dams are considered to be the Middle Snake region. ColSim represents the sum of storage in these two regions with aggregated equivalent reservoirs. Each of the equivalent reservoirs is assigned an agricultural demand and return ratio, which is explicitly defined by the 1989 records for agricultural withdrawal and consumption rates. The diversions, and their return ratios are interpolated from data used by the Idaho Department of Water Resources (IDWR) model: SRPSIM. The performance of SRP irrigation has been evaluated through comparison with observed reservoir contents and releases, and it compares quite well on an aggregate level – even though it does not represent performance of all the individual reservoirs.

3.5: Recreation

The most significant recreational facility within the Columbia River reservoir system is Lake Roosevelt, formed by Grand Coulee Dam. Operations at Grand Coulee are managed to maintain a high stage through the summer until Labor Day. ColSim represents this objective by lowering the priority of energy production at Grand Coulee during the months when high levels are desired. This is accomplished by a system of weighted priority, where other dams are drafted for firm energy before Grand Coulee: when a firm power shortfall occurs, Grand Coulee is the last to be drafted down to its dead pool.

3.6: Measures of Performance

3.6.1 Flood Control

The Portland-Vancouver metropolitan area is the only instream control point represented by ColSim for flood operations. All other flood prevention sites in the

Columbia lie along tributary streams, and are not resolved by the model. Flows at Portland are indexed to flows at The Dalles, OR, as described in Table 3.1. For this study, an index was also needed to compare the severity and magnitude of flood damages between climate conditions and operating periods. It was decided that an economic description of flood damages in the Portland-Vancouver area would be the best way of presenting these data for comparison.

The economic metric for flood control was created in three steps. The first step was to index monthly flows at The Dalles to typical maximum daily flows, based upon the linear relationship between regulated monthly averages and daily peak flows at The Dalles, OR. (See Equation 1.)

*(Peak daily flow at Portland) = (Mean monthly outflow at Dalles) * 1.28* (1)

The second step was to relate the indexed values for peak daily flows to stage and damage levels in Portland. This index requires a piecewise relationship that relates the linear increase of damages until flooding exceeds the COE-defined threshold for major damage (about 9 m at Vancouver, corresponding to the more highly developed portions of the floodplain). Above this threshold, damages increase exponentially. This scheme is based upon a published estimation of both unregulated flows at Vancouver and prevented damages between 1974 and 1988 (COE, 1991), and is illustrated in Equation 2. Exceedances of the 9 m threshold, and damages corresponding with the exponential portion of the equation, are considered to be both realistic and appropriate signals of relative flood risk, where higher exceedances begin to carry more weight beyond a certain point. This study does not account for basin development that occurred between the COE assessments of prevented damages and present day, nor did it project development that may occur in the future.

Equation 3.1 - – The three part equation relating peak flows (Q_P) to damages (D) occurring in relation to the Minor Damage (Q_{ND}) and Major Damage (Q_{MD}) thresholds. [Q was measured in terms of 1000* cubic feet per second, damages are measured in dollars.]

No Damage	$D = 0$	for	$Q_P < Q_{ND}$	
Minor Damage	$D = 0.1466 * (Q_P - Q_{ND})$	for	$Q_{ND} \leq Q_P < Q_{MD}$	*(2)*
Major Damage	$D = 0.3825 * e ** (0.0139 * (Q_P - Q_{ND}))$	for	$Q_P \geq Q_{MD}$	

Q_P	= Peak daily flows (1000* cfs)	- from Equation 1
D	= Damages ($ million)	
Q_{ND}	= Minor damage threshold	600,000 cfs
Q_{MD}	= Major Damage threshold	750,000 cfs

The third step was to express flood damages as expected annual losses, by averaging the estimated losses over the period of analysis (51 years in the case of the control run, 30 years for the three study periods for the future climate ensembles).

3.6.2 Hydropower Production

Hydropower is evaluated in terms of economic value and reliability. The economic valuation is straightforward. Hydropower production is recorded throughout the simulation in terms of firm and non-firm generation. Both classifications of production are multiplied by the same approximation of current regional market price ($25 per megawatt-hour), and by an index reflecting the traditional seasonal variation of value on the spot market, shown in Table 3.2 (BPA, 1994). This pricing structure reflects the assumption that firm pricing contracts will have approximately equal value with spot market prices in the evolving era of deregulation

Firm energy is 'guaranteed' system production, and ColSim allows the entire system to be drafted to the dead pool to insure its generation if need be. As such, firm power is a good surrogate for the "safe yield" of the hydropower system, and at least for planning purposes will likely to hold some significance in the near future. Therefore, shortfalls to firm power are likely to receive close scrutiny, even under a deregulated power structure – especially given existing contracts for delivery of firm power. A successful operating policy will need to consider both the desirability of maximizing revenues, and of avoiding failures in firm power deliveries.

A general set of performance metrics is used to monitor firm power. Months where the firm power target is not met are recorded as shortfalls. The overall reliability of firm power is computed as the percentage of months where the target is fully met. However, firm power shortfalls are significant mostly because they indicate long periods of storage decline, which compromises the multi-purpose nature of the system. Therefore, firm shortfalls are also compiled by month.

Table 3.2–Monthly hydropower price index and values (percent & dollars per megawatt-hour)

	Oct	Nov	Dec	Jan	Feb	Mar
Index:	95%	118%	121%	103%	99%	94%
Price:	$23.77	29.58	30.13	25.68	24.68	23.41
	Apr	May	Jun	Jul	Aug	Sep
Index:	66%	61%	76%	105%	144%	118%
Price:	$16.61	15.25	19.06	26.32	36.03	29.49

3.6.3 Instream Flow Targets

Shortfalls for the three BiOP flow targets – Lower Granite, McNary, and Bonneville (see Section 3.3) – were monitored in terms of their volumes and frequencies. Seasonal reliability (the number of months where the targets were met) and deficit (the volume of water by which the target was not satisfied) were monitored in the months when the target was most significant. The performance season for Lower Granite was March-August; for McNary it was April-August: and for Bonneville November-March. As with firm power, a monthly breakdown of shortfalls and reliabilities was also developed to indicate the sensitivity of particular months to climate change and mitigation strategies.

3.6.4 Irrigation

Because Snake River irrigation is the only consumptive agriculture demand that is large enough to affect performance of the system with respect to instream flow targets and hydropower production, it is the only project represented explicitly in ColSim. The chosen metric for agriculture is the volume of water available for irrigation relative to prescribed targets, which are based on known water rights. A volumetric approach to monitoring agriculture in the Snake River Plain was chosen because irrigation supply failures are difficult to evaluate in dollar terms. Variations in prices, the possibility of crop substitution (which can significantly alter consumptive use), along with the macro-scale resolution of ColSim, preclude the evaluation of economic impacts, especially under conditions where the physical climate would have both direct effects on agricultural productivity (e.g., due to carbon fertilization effects) and implications for water availability.

3.6.5 Recreation

ColSim monitors recreation storage only at Lake Roosevelt. The desirable recreation pool at Lake Roosevelt is 1,280 feet (mean sea level: 390 m) between June and August, which corresponds to 8.3 million acre-feet of storage (10 billion m^3) or about 15% of the total possible evacuation. ColSim monitors the monthly stage of Lake Roosevelt during the summer recreation season, and reports shortfalls in terms of reliability (defined as the number of months where targets were met divided by the total number of months in the recreation season over the period of simulation).

Chapter 4 - Experimental Design

As discussed in Chapter 2, this thesis explores operating alternatives for mitigating hydrologic changes associated with projected climate change over the next century, as represented by the DOE-NCAR Parallel Climate Model (PCM). Briefly, a set of experiments was designed to evaluate the sensitivity of basin operations to the PCM projections; to test how changes in reservoir operation, power demand cycles, and the quantity of storage allocated to BiOP targets affects CRB operations; and finally, to evaluate the potential for mitigating changes in CRB system performance associated with climate change by changing reservoir operating procedures.

4.1: Evaluating Reservoir System Performance

The sensitivity of reservoir system performance to the climate change scenarios was evaluated by comparing performance for the control PCM hydrology with current operations (the 'control scenario') and three approximately 30-year climate ensembles for which corresponding hydrologic ensembles were produced using the VIC hydrology model [2010-2039, 2040-2069, and 2070-2098]. The three periods are used in most of the work that follows (referred to as Periods 1, 2, and 3). For each hydrologic ensemble, system performance was evaluated for present operating conditions, and for three other operating alternatives, which are described in the remainder of this chapter.

4.2: Flood Evacuation and Refill Modifications

This operating alternative provides greater hydropower by changing flood operations in response to changes in future seasonality of runoff (see Figure 2.3) so as not to create greater de facto hydropower drafts or further compromise BiOP targets. An array of five flood evacuation policies was combined with a set of three system refill dates, creating fifteen combinations of operating policies within this general category. The required flood evacuations at each dam, as defined in the SRDs, were multiplied by the following factors [0.80, 0.90, 1.00, 1.10, 1.20] (see Figure 4.1). The 80% alternative requires 20% less draft than the present system does; 100% represents current operations. The refill timing was changed by reducing the duration of the flood evacuation pool in three intervals [zero, 2-weeks, 1-month] (see Figure 4.2). For this experiment set, the 1-month interval allows each dam to entirely refill one month earlier, the 2-week option allows each dam to refill 50% of the total current draft requirement in the final month of their flood evacuation schedule, and zero represents current refill schedules. Combinations of changes in timing and flood evacuation volume were used to create tradeoff curves for evaluation of system performance (see Chapter 6).

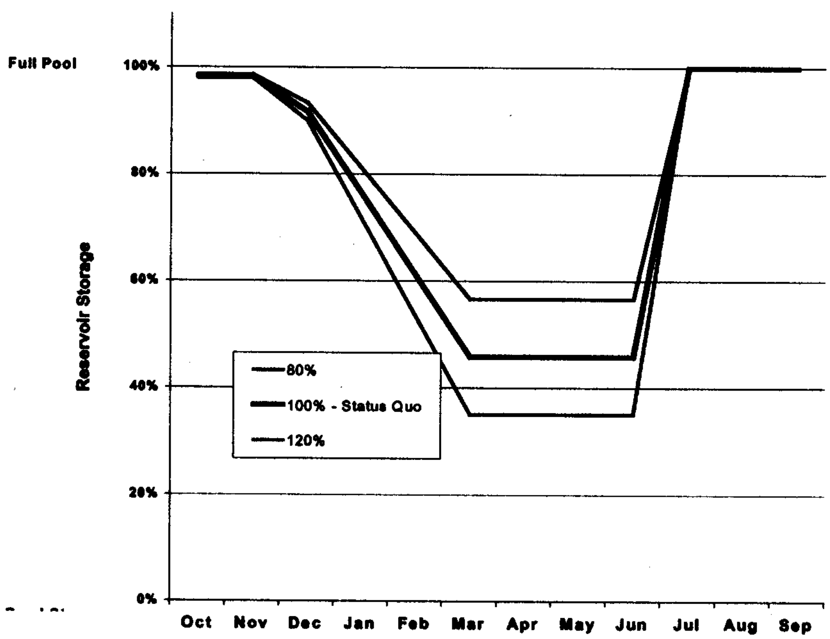


Figure 4.1 – Examples of modifications to flood evacuation requirements studied

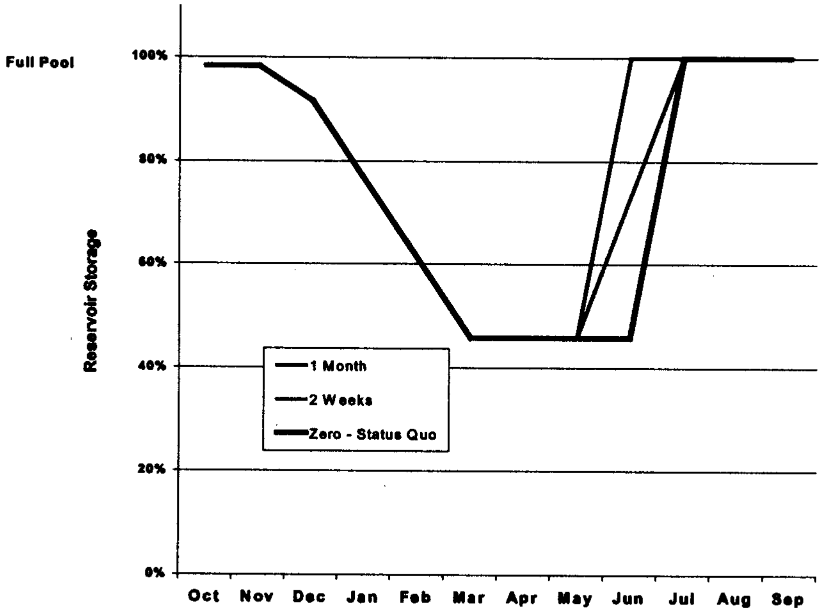


Figure 4.2 – Evaluated shifts in the timing of system refill

4.3: Energy Demand Shifts

Energy demand shifts are likely under a generally warmer climate, as a result both of reduction in winter heating demands, and increases in summer air conditioning. Although it is difficult to predict future prices and demands, a set of experiments was designed to reveal the sensitivity of basin operations to shifts in the present firm energy curve. Shifts in firm power demands were designed to move production from the winter through to the summer in accordance with arbitrarily assigned temperature elasticities for power demand. Demands were adjusted in equal increments of 5% (e.g., 110%, 105%, 95%, 90%, and 85%) relative to the current index, a monthly load factor (Figure 4.3). The 85% option, for instance, allocates 15% of the typical winter firm power load to the summer, as demonstrated in Figure 4.3 and by Table 4.1.

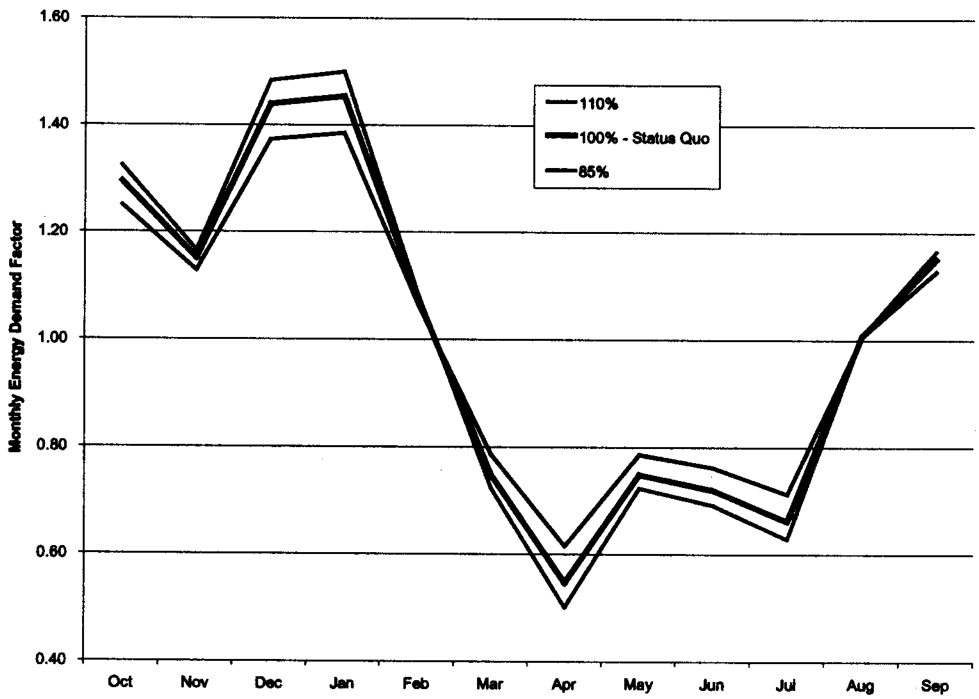


Figure 4.3 – Flattening the energy demand curve

Table 4.1 – Monthly load factors, and an example of the 85% experiment described above

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Normal Monthly Load Factor	0.98	0.98	0.92	0.76	0.61	0.46	0.46	0.46	0.46	1.00	1.00	1.00
Experimental Monthly Demands (85% option)	0.99	0.99	0.93	0.80	0.67	0.54	0.54	0.54	0.54	1.00	1.00	1.00

4.4: Augmenting BiOP Storage Allocations

Present reservoir allocations for instream flow targets are relatively small in comparison with the magnitude of the seasonal release requirements for instream flows (storage makes up only about seven percent of the average target), therefore unregulated inflows are relied upon to meet demands rather than with the limited storage allocations. Seasonality shifts in reservoir inflows predicted by the PCM evaluation used in this study (see Figure 2.4) reduces both summer baseflow and spring melt volumes, requiring greater supplements from limited storage allocations. This set of experiments was constructed to explore the effects of augmenting the two lower Columbia River BiOP targets (McNary and Bonneville) with greater reservoir storage allocations (see Table 4.2). Storage augmentation in the Snake River for the Lower Granite BiOP target was not pursued because it would necessitate evaluating tradeoffs with agriculture demands, which ColSim currently is incapable of handling on a suitable scale for beneficial analysis.

Table 4.2 – Breakdown of experimental changes for upper Columbia storage allocations to augment instream flows in the lower Columbia River

Total US Storage Allocation	Total Canadian Storage Allocation	Grand Coulee		Arrow		Mica		Libby, Duncan, & Hungry Horse	
		MAF	Billion m^3	MAF	Billion m^3	MAF	Billion m^3	MAF	Billion m^3
7%	0%	0.8	1.0	0.0	0.0	0.0	0.0	1.5	1.2
15%	0%	1.2	1.5	0.0	0.0	0.0	0.0	2.1	2.6
25%	15%	1.2	1.5	0.4	0.5	0.4	0.5	2.3	2.8
40%	20%	1.5	1.8	0.8	1.0	0.8	1.0	2.9	3.6
50%	25%	2.0	2.5	1.2	1.5	1.2	1.5	4.0	4.9

4.5: Combined Multiple Alternatives

Finally, a heuristic alternative was developed that combined flood evacuation and refill alternatives with augmented storage for BiOP minimum streamflows and prescribed changes in the firm power demand curve. Absent an optimization model, the combination alternative was not intended to reach an optimum reservoir operation policy. Instead, this final experiment evaluates the interrelated effects of shifting operations and demonstrates tradeoffs that must be considered in any climate change mitigation strategy.

This alternative is structured to increase hydropower revenues, constrained by both flood control and the current level of provision for summer instream flow targets. To do so, operations were calibrated independently within each of the three analysis periods and each of the three changed climate runs. The calibration process began with the selection of instream storage allocations that decreased McNary average annual deficit to levels equivalent or below the control scenario level. Next, both flood evacuations and system refill timing were altered such that hydropower revenues were maximized. The maximization of hydropower revenues was constrained by Portland-Vancouver flood control losses and firm power reliability. A reduction in firm power capacity, or the occurrence of Dalles outflow above 500,000 cfs was cause for rejection of an alternative. These constraints were adopted because increased flood control storage has a policy effect equivalent to increasing winter firm power demands, which in turn result in summer reliability losses for both firm power and instream flow targets. Having chosen operations that maximized revenue production, firm power was then reduced to a level that could be supported at 100% reliability. If the result produced a deficit at McNary greater than the control, the iterative procedure was repeated until an acceptable solution was reached.

Chapter 5 - Results

5.1: System Sensitivities to Climate Change.

Following the general strategy outlined in Chapter 4, implications of changes in the hydrologic forcings and accompanying system operation were evaluated for segments of the three PCM ensembles described in Section 2.1. The ensembles are evaluated in three approximately 30-year segments, referred to as Periods 1, 2, and 3, and corresponding to 2010-2039, 2040-2069, and 2070-2098, respectively. For each of these periods, the implications of hydrologic changes were evaluated for current operations, and for four sets of reservoir operating alternatives. Briefly, the four alternatives can be described as; 1) changes in the flood evacuation and system refill requirements, 2) changes in the required firm power generation, 3) changes in the total allocation of storage for instream flow targets, and 4) the combination of the above three alternatives to create a non-optimized mitigation scheme.

For current operations under a changed climate, reliabilities (Figure 5.1) were sensitive to the modest (relative to other GCM scenarios reported by the IPCC (1995; 2001) and U.S. National Assessment (Gleick, 1999)) changes in flow regime resulting from the BAU climate scenarios (Table 5.1). Overall, the number of Dalles spring flood control exceedances (set at 450,000 cfs in ColSim) decreased for all three periods. However, flood control damages were significantly higher for all three periods, and exceedances in Periods 2 and 3 began to occur in the late winter (February and March), a time of year when flood control has traditionally not been a problem in the CRB. Average annual flood damages (see Table 5.2) increase dramatically in relation to the control run, for two reasons: 1) the seasonality of inflows shifts, so flows are larger during an earlier time of the year, and 2) the maximum naturalized flows present in the climate change ensembles exceed the flows produced by the control run during normal flooding periods. Despite the larger magnitude of flows produced in the climate change ensembles, the largest naturalized June outflow at The Dalles, OR (900,000 cfs, see Figure 5.2) is well within the historic record of naturalized flows.

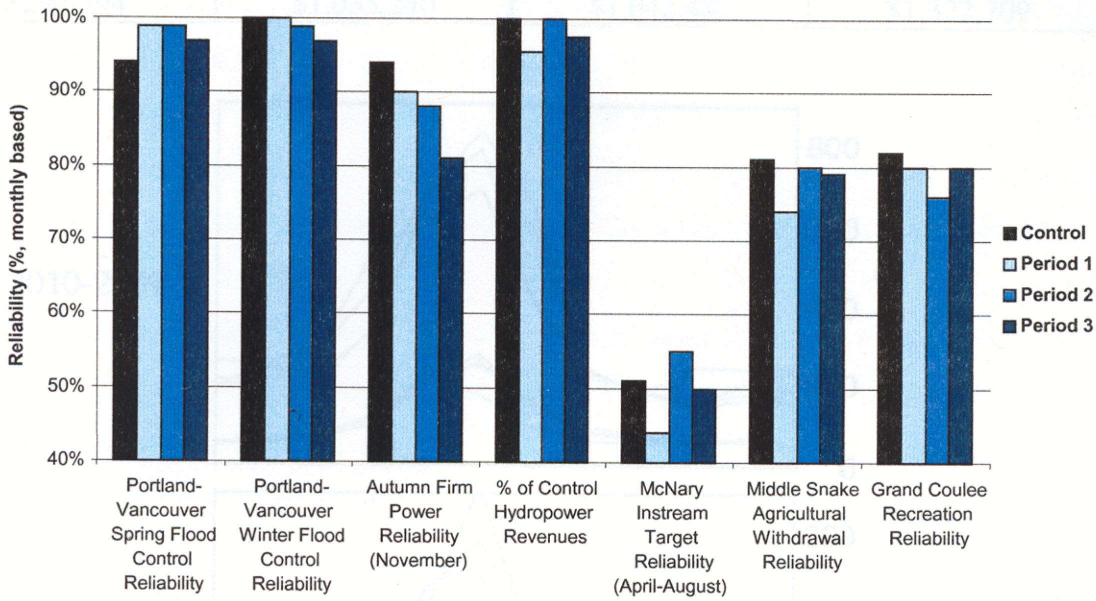


Figure 5.1 – Base effects of climate on CRB resources

Table 5.1 – General hydrologic trends from PCM affecting reservoir operations

	Period 1	Period 2	Period 3
DJF precipitation (% of control, B06.45)	95%	102%	98%
JJA precipitation (% of control)	97%	83%	87%
DJF Temperatures (difference from control)	+0.6°C	+1.3°C	+2.4°C
April 1st Snow accumulation (% of control)	85%	91%	79%

Table 5.2– Average Annual Flood Damages at the Portland-Vancouver levees between the control and three climate change analysis periods

Control	Period 1	Period 2	Period 3
$292,394	$1,033,240	$1,042,487	$1,322,709

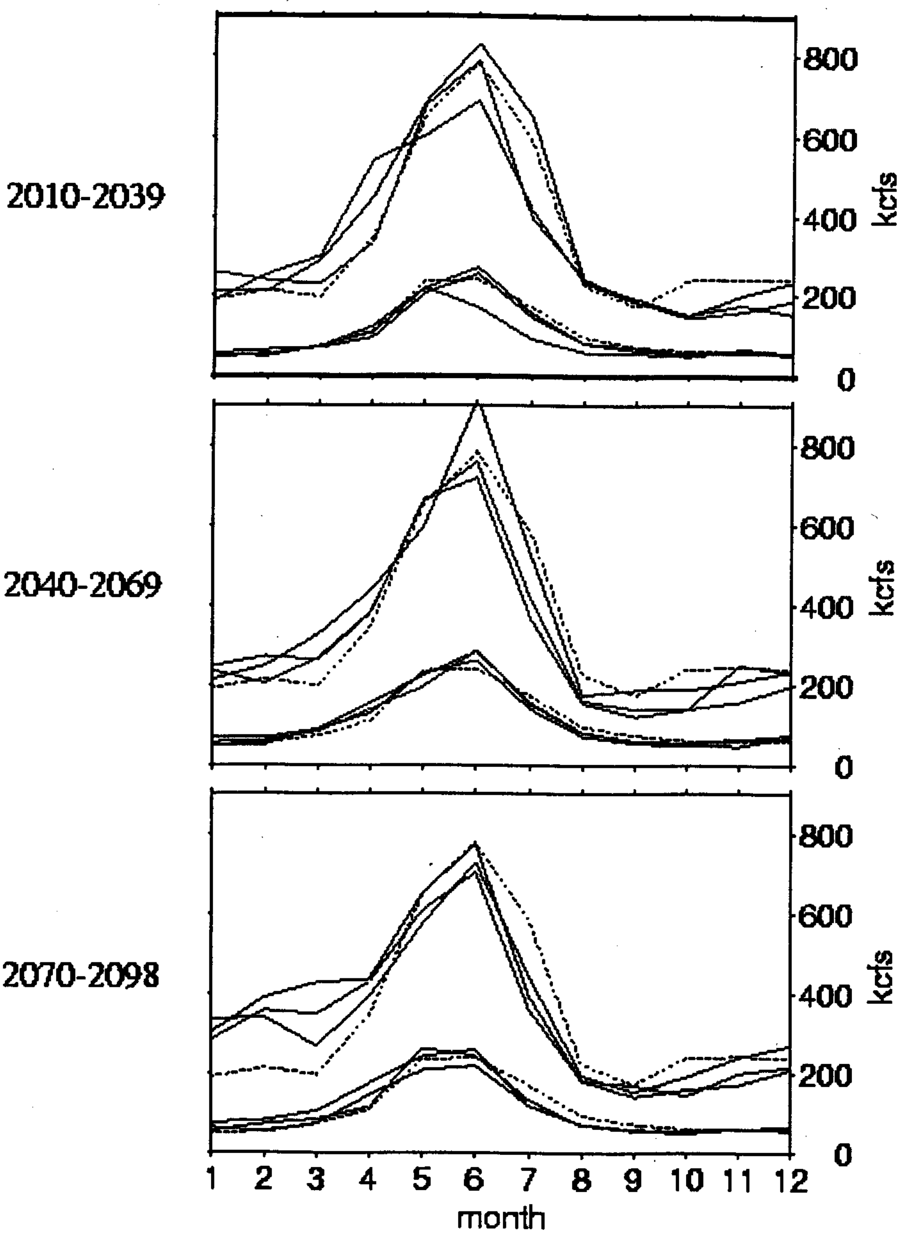


Figure 5.2 – Control run (dashed) and 3 PCM ensembles (solid): maximum and minimum naturalized monthly flows at The Dalles, OR [x-axis reports calendar months; Jan=1, etc.]

The ability to meet firm power diminishes as seasonality shifts progress. As exemplified by the November reliability of firm power in Figure 5.1, the late summer/early winter firm power targets, which are predominantly governed by storage drafts, steadily decline with diminishing snow accumulation and lower summer inflows. Failures are computed as a percentage of months in which there was no shortfall. Because all failures to firm power targets occur in the autumn, an annual calculation window for firm reliability was inappropriate. Therefore, the firm power reliability analyses focused on the autumn.

An investigation was performed in each period to determine how much firm power could be supported without causing shortfalls. The results of this investigation are termed 'sustainable firm power' (i.e., safe yield) and are described as percentages of the control climate (with current operations) firm power demand. Climate change resulted in a 7, 5, and 7 percent loss in sustainable firm power, for each of the three periods, respectively (see Figure 5.1). Hydropower revenues, which rely more upon the volume of annual outflows than seasonality shifts, were relatively insulated from the effects of the climate projections on the seasonal hydrographs. Although average annual hydropower revenues do not indicate severe economic impacts under a changed climate, the system's political responsibilities to provide instream habitat could force operations to further diminish firm power. As a result, the shortfalls occurring to firm power and instream flow targets indicate a system cost that is not reflected in power revenues (sales).

The volume of spring runoff predominantly governs environmental flow target reliabilities (as demonstrated by the McNary Dam target), whereas the ability of the system to reduce deficits to environmental targets is more constrained by storage allocations and summer inflows. This is because reliabilities require that monthly targets be met *entirely*, which happens mostly during periods of high inflow in the spring, and less frequently as the summer progresses. Deficits, however, are a function of the system's ability to restore the limited storage allocated to environmental targets by the late spring and maintain them through the summer low flow period. During the summer, instream allocations can be reduced by drafts for firm hydropower, which diminish the "would be" environmental reserves upstream of Grand Coulee. So while the reliability of the McNary target closely follows the volume of spring runoff at Grand Coulee, the cumulative deficits increase considerably as seasonality shifts lower both spring and summer runoff: +30%, +20%, and +40% in all three periods, respectively, rising highest in Period 3 when seasonality shifts have diminished spring refill the most.

The same relationships with spring runoff volume and reservoir carryover hold true for Snake River irrigation, where reliabilities in the spring months closely follow the volume of spring runoff, but the ability to reduce late summer deficits relies heavily upon snowpack to maintain reservoir storages until the middle of summer. For reasons mentioned earlier, particularly the inability of ColSim to resolve tradeoffs between agriculture and instream flow targets within the Snake River Plain, it was not feasible to evaluate operations alternatives for the SRP. Therefore, current operating policies were assumed to remain constant in this portion of the basin.

The ability to meet recreation targets, which require the maintenance of storage through Labor Day for most dams, depends mostly on summer runoff to keep elevations at a suitable level. Hence, even though Period 3 is the warmest, with the greatest change in the seasonality of runoff, the low summer inflows of Period 2 (demonstrated in the low summer precipitation) cause the greatest loss of recreation reliability (as represented by Lake Roosevelt).

5.2: Changing flood evacuation and refill timing

Changes in flood evacuation and refill timing (see Section 4.2) were pursued as a potential adaptation to the increased winter flows and earlier annual runoff associated with progressive seasonality shifts. Two actions have been suggested as likely adaptations to climate change (Martin, 2001); 1) lower flood evacuation requirements and 2) earlier refill schedules. Although earlier refill and reduced flood evacuations might be expected to improve the reliability with which McNary instream targets could be met, their benefit under the PCM climate scenarios was minimal because instream flow deficits were more constrained by reservoir draft limitations than by the frequency of dam refill. As found earlier, the system's ability to refill under the PCM climate scenarios has little impact on its ability to remain full through the summer until November, when the environmental targets drop-off and firm power demands are highly susceptible to shortfalls.

Generally, lower flood control evacuations yielded the most significant benefit to McNary, but their effectiveness was compromised by a reduction in flood control, and was steadily diminished as seasonality progressed. The 80% designation, corresponding to a 20% reduction in required evacuation, reduced McNary deficits by 15%, 12% and 9% and increased the targets reliability by 3%, 2%, and 1% (for Periods 1-3, respectively). However, this measure was ruled out as a potential adaptation policy because it produced little to no benefit for hydropower and increased average annual flood control damages by 50%, 156%, and 259% (in Periods 1-3, respectively).

The use of early refill dates resulted in the most positive benefits for the system as a whole by increasing the frequency and magnitude of spring refill. This benefited operations reliant upon carryover storage (like non-firm revenues and firm power capacity) without significantly impacting flood control. However, draft limitations constrained environmental targets from accessing much of the refill volumes, resulting in an overall performance decline at McNary (Figures 5.3). Changes in refill timing seemed only to displace average deficits in the early spring, with minimal effect on the late summer: which is the most difficult to meet because hydropower can diminish environmental reserves. This reinforces the finding that the present allocation limitations for environmental flows are the limiting performance constraint, and may need reconsideration in the event of seasonality shifts.

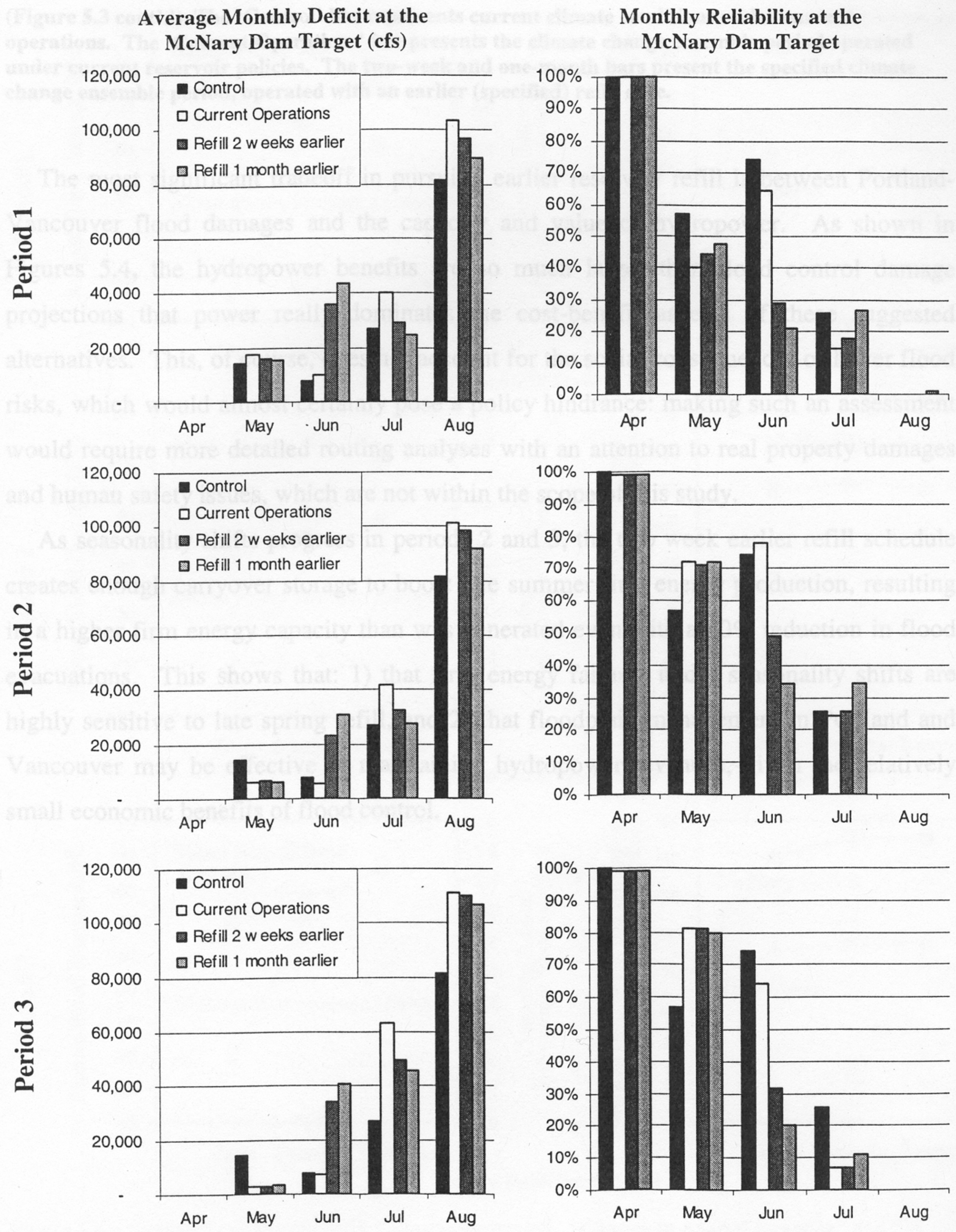


Figure 5.3 – Monthly effects of earlier refill on McNary environmental target (deficit and reliability).

(Figure 5.3 cont'd) The 'Control' bar represents current climate conditions under current operations. The 'Current Operations' bar presents the climate change ensemble period operated under current reservoir policies. The two-week and one-month bars present the specified climate change ensemble period, operated with an earlier (specified) refill date.

The most significant tradeoff in pursuing earlier reservoir refill is between Portland-Vancouver flood damages and the capacity and value of hydropower. As shown in Figures 5.4, the hydropower benefits are so much larger than flood control damage projections that power really dominates the cost-benefit aspects of these suggested alternatives. This, of course, does not account for the social consequences of lower flood risks, which would almost certainly pose a policy hindrance: making such an assessment would require more detailed routing analyses with an attention to real property damages and human safety issues, which are not within the scope of this study.

As seasonality shifts progress in periods 2 and 3, the two week earlier refill schedule creates enough carryover storage to boost late summer firm energy production, resulting in a higher firm energy capacity than was generated even with a 20% reduction in flood evacuations. This shows that: 1) that firm energy failures under seasonality shifts are highly sensitive to late spring refill, and 2) that floodplain management in Portland and Vancouver may be effective in maintaining hydropower revenues, given the relatively small economic benefits of flood control.

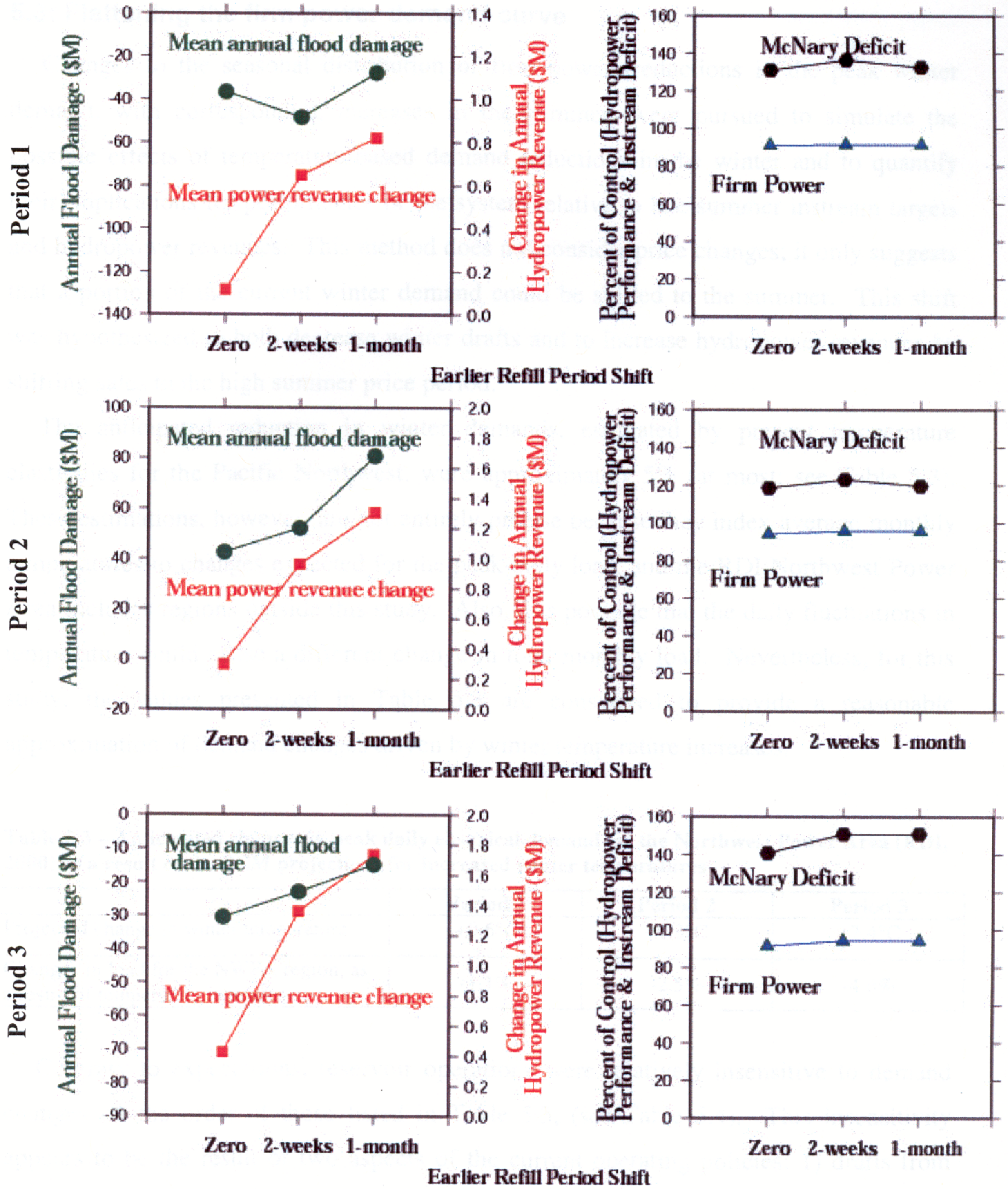


Figure 5.4 – Sensitivity of system refill timing experiments. "Change in Annual Revenue" and "% Firm Power Sustainable" are relative to values produced under the control climate with current operations.

5.3: Flattening the firm power demand curve

Changes to the seasonal distribution of firm power (reductions in the peak winter demand, with corresponding increases in the summer) were pursued to simulate the possible effects of temperature-based demand reductions in the winter and to quantify their implications for performance of the system relative to late summer instream targets and hydropower revenues. This method does not consider price changes; it only suggests that a portion of the current winter demand could be shifted to the summer. This shift was hypothesized to both decrease winter drafts and to increase hydropower revenues by shifting sales to the high summer price period.

The anticipated reduction in winter demands, estimated by present temperature elasticities for the Pacific Northwest, were approximately 5% (at most: see Table 5.3). These estimations, however, are not entirely precise because they index average monthly temperatures to changes expected for the peak daily load, and the RDI Northwest Power Area includes regions outside this study. Also, it is possible that the daily fluctuations in temperature could cause a different change in total monthly load. Nevertheless, for this study, the values presented in Table 5.3 are considered to provide a reasonable approximation of demand changes driven by winter temperature increases.

Table 5.3 – Anticipated changes in peak daily electrical demand for the Northwest Power Area (RDI, 2000) as a result of the PCM projections for increased winter temperatures

	Period 1	Period 2	Period 3
Projected change in winter temperature	+0.6°C	+1.3°C	+2.4°C
Changes in load for the NWPA region, as a result of temperature increases	-1.1%	-2.5%	-4.6%

Contrary to expectations, reservoir operations were relatively insensitive to demand changes on the order of those listed in Table 5.3, (see Table 5.4). This insensitivity appears to be the result of two aspects of the current operating policies: 1) drafts from reservoirs in the winter for firm power effectively regulates releases during years with the lowest runoff, and 2) flood control requirements, which are designed to assist in firm production, continued to force large releases during the winter despite lower firm power targets during this time of year.

Table 5.4 – Sensitivity of operations to reallocations of power from winter to summer months. All italicized percentages are based on a relationship with the control hydrology with current operations

		Hydropower revenues	Sustainable Firm Power	Flood Damages	McNary Deficits	McNary Reliability
Period 1	Current Operations	*95.5%*	*93%*	$1,033,000	*131%*	43.8%
	15% reallocation	*95.5%*	*94%*	$1,033,000	*131%*	43.8%
Period 2	Current Operations	*99.9%*	*96%*	$1,042,000	*119%*	54.7%
	15% reallocation	*100%*	*99%*	$1,042,000	*119%*	54.7%
Period 3	Current Operations	*97.5%*	*93%*	$1,323,000	*141%*	50.2%
	15% reallocation	*97.5%*	*96%*	$1,323,000	*141%*	50.2%

When the firm energy demand curve was entirely flattened (i.e. 100% reallocation of winter energy demands above the mean to the summer), such that each month demanded the same quantity of hydropower from the system, there was an average nine percent increase in sustainable firm energy (Figure 5.5). However, the added benefit of this shift would likely be offset by the cost of replacing such a large amount of winter energy, as demand reductions associated with warmer winter temperatures was much smaller, and the lost winter energy would have to be purchased from outside suppliers at a price that likely would be higher than its current production cost.

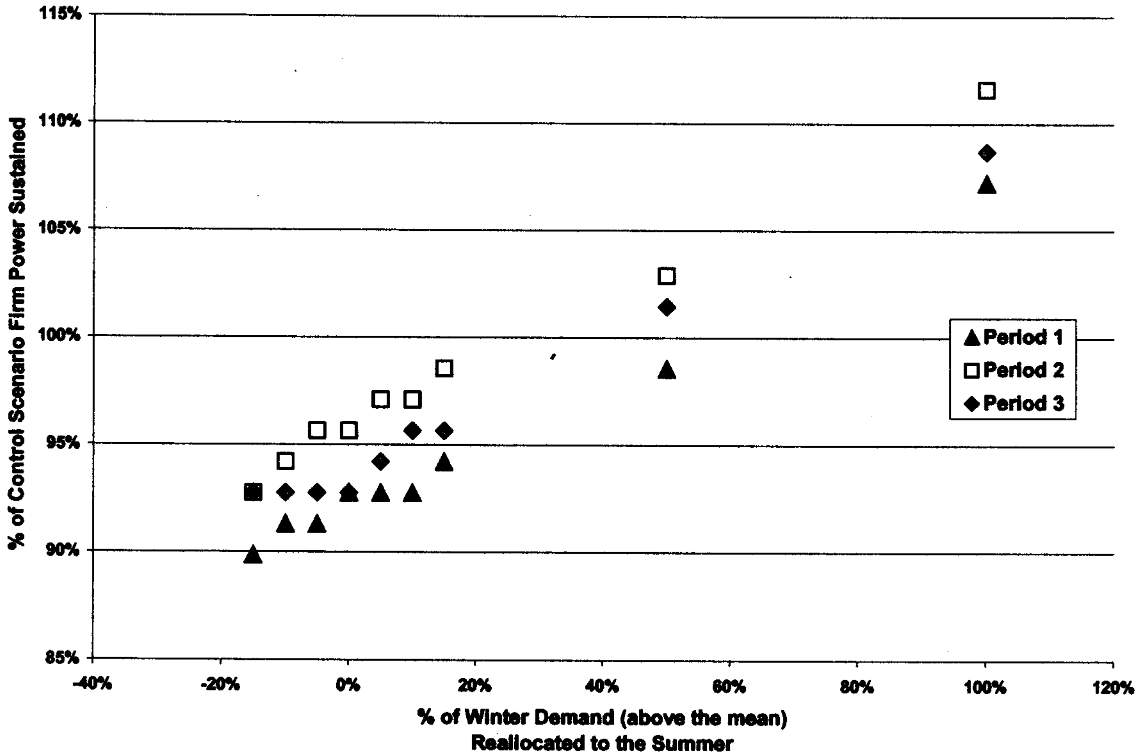


Figure 5.5 – Changes in Firm Power Sustainability in relation to the reallocation of winter firm energy demands to the summer. The control scenario was able to sustain 3.45 million megawatt-hours of production per month.

An approach to exploit this interaction would be the simultaneous reduction of flood control evacuations in the winter (thereby reducing the mandatory winter generation) with the reallocation of firm demand to the summer. However, experimental reductions in flood evacuation (described in the previous section) resulted in a large increase in flood control exceedances during the winter for Periods 2 and 3. A more detailed study of flood damages in the Portland-Vancouver area (than was possible with the monthly time-step ColSim model) would be required to evaluate in sufficient detail the flood damage implications of such policies. For this reason, they were not pursued further in conjunction with the reallocation of firm power.

5.4: Increasing storage allocations for environmental targets

As demonstrated earlier, the performance of the McNary instream flow target was not improved by policies that were otherwise successful in enhancing hydropower performance. This stems from two factors: 1) the storage allocations are more quickly depleted under the PCM climate scenarios because summer inflows (i.e. summer snowmelt) is lower and 2) the first priority allocation for firm power production is capable of further diminishing the effectiveness of instream storage allocations by requiring larger summer drafts to accommodate for lower system inflows. In short, deficits at the McNary dam target have been constrained by reservoir draft limitations. Increasing the storage allocations for environmental flows was pursued as a response to this constraint and was highly successful in reducing annual deficits at McNary. However, there was a corresponding loss to firm power, which indicates that the competition must be resolved between summer storage uses under a seasonality shifted hydrograph.

Generally, a 4.3 million acre-foot (5.3 billion m^3) storage allocation was adequate to bring the cumulative annual deficit at McNary (for all three Periods) to a value approximately equivalent to the control (Figure 5.6). However, the reliability of June and July targets is still overwhelmingly tied to spring inflows, which prevents the McNary target from matching that of the control, even when instream targets are given 100% access to storage (i.e. 33.3 million acre-feet, 41 billion m^3). The McNary reliability, which is a function of meeting early targets with spring inflows, is not improved by greater storage allocations. This results, in part, from greater winter drafts for the Bonneville dam target, which subsequently lower flood damages.

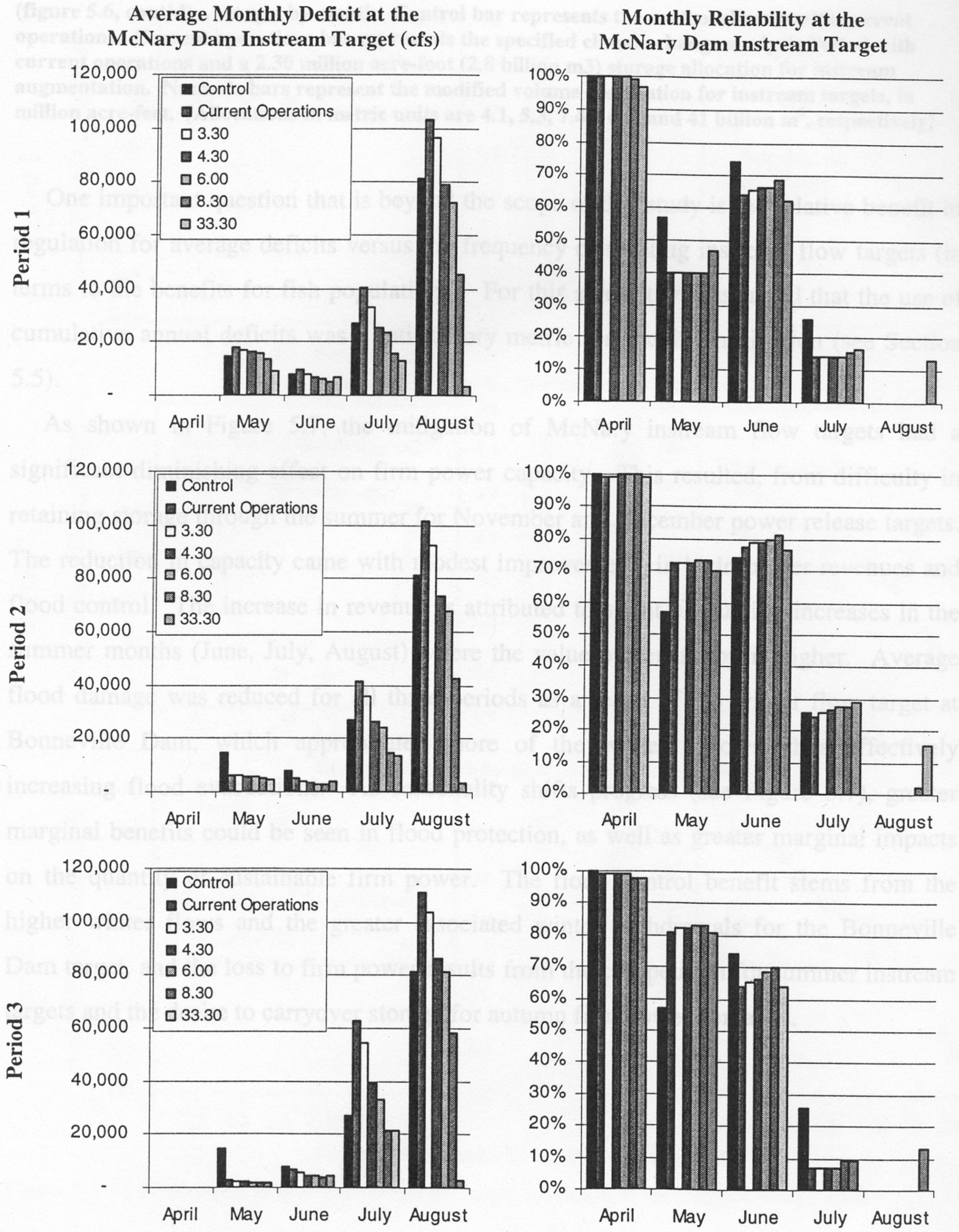


Figure 5.6 – Effects of greater storage allocations for environmental flows upon the McNary Dam

(figure 5.6, cont'd) ...target by month. Control bar represents the control climate with current operations. Current operations bar represents the specified climate change analysis Period with current operations and a 2.30 million acre-foot (2.8 billion m3) storage allocation for instream augmentation. Numeric bars represent the modified volume designation for instream targets, in million acre-feet. [Allocations in metric units are 4.1, 5.3, 7.4, 10.2, and 41 billion m^3, respectively]

One important question that is beyond the scope of this study is the relative benefit of regulation for average deficits versus the frequency of meeting instream flow targets (in terms to the benefits for fish populations). For this study it was assumed that the use of cumulative annual deficits was a satisfactory metric for gauging mitigation (see Section 5.5).

As shown in Figure 5.7, the mitigation of McNary instream flow targets had a significant diminishing effect on firm power capacity. This resulted, from difficulty in retaining storage through the summer for November and December power release targets. The reduction in capacity came with modest improvements in hydropower revenues and flood control. The increase in revenue is attributed to slight production increases in the summer months (June, July, August) where the value of generation is higher. Average flood damage was reduced for all three periods as a result of the winter flow target at Bonneville Dam, which appropriated more of the winter inflows, thus effectively increasing flood evacuations. As seasonality shifts progress (see Figure 5.7), greater marginal benefits could be seen in flood protection, as well as greater marginal impacts on the quantity of sustainable firm power. The flood control benefit stems from the higher winter flows and the greater associated winter withdrawals for the Bonneville Dam target, and the loss to firm power results from the competition for summer instream targets and the desire to carryover storage for autumn firm power demands.

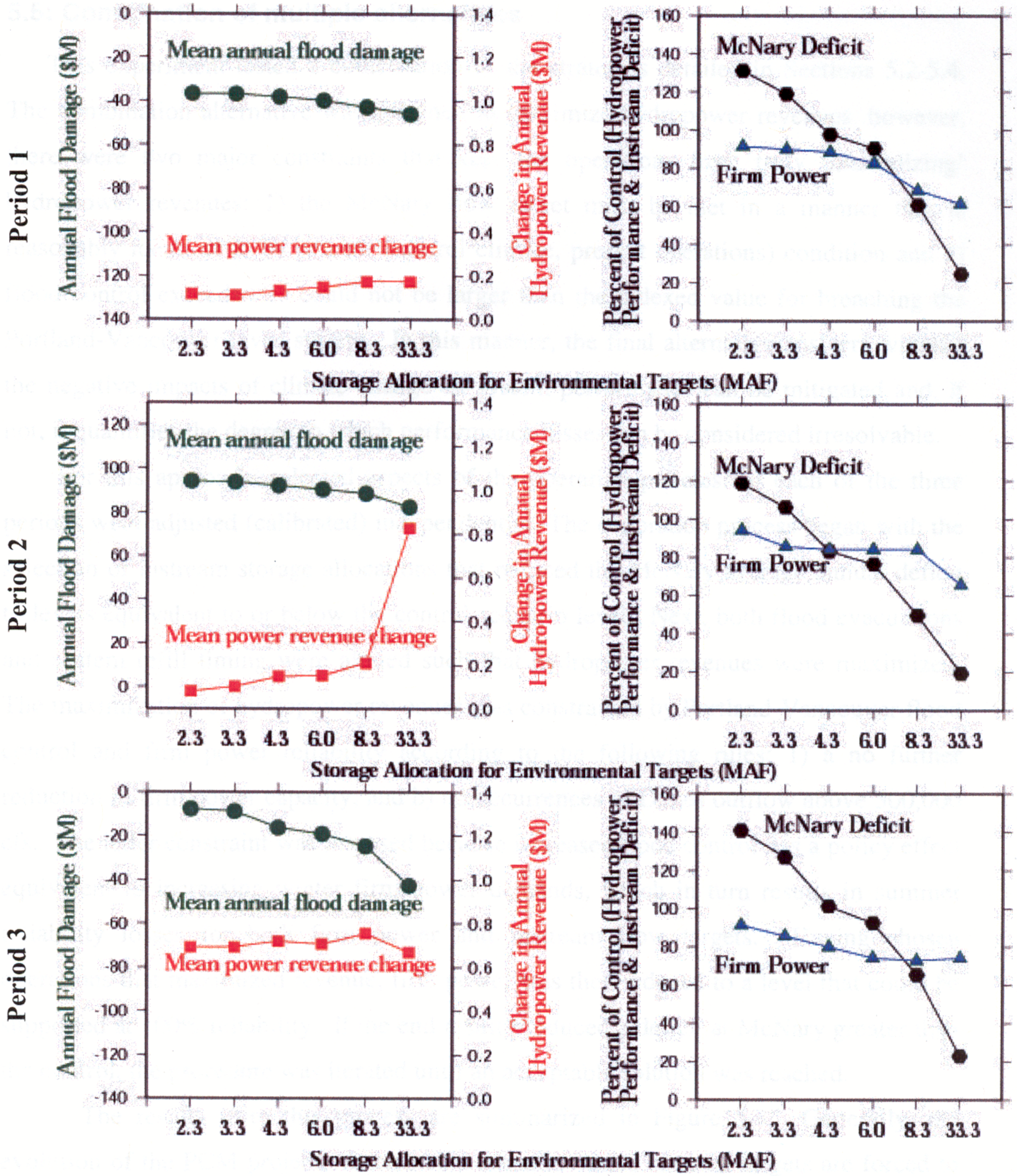


Figure 5.7 – Sensitivity to an increased instream target allocation in the Upper Columbia Basin.

5.5: Combination of multiple alternatives

This experiment tested a combination of the strategies detailed in Sections 5.2-5.4. The combination alternative was designed to maximize hydropower revenues, however, there were two major constraints that kept the operations from truly 'maximizing' hydropower revenues: 1) the McNary flow target must be met in a manner that is reasonably identical to its present (control climate, present operations) condition and 2) flood control exceedances could not be larger than the indexed value for breaching the Portland-Vancouver levee system. In this manner, the final alternative answers whether the negative impacts of climate change on system performance can be mitigated and, if not, it quantifies the degree to which performance losses can be considered irresolvable.

For this approach, selected aspects of the operating policies for each of the three periods were adjusted (calibrated) independently. The calibration process began with the selection of instream storage allocations that reduced the McNary average annual deficit to levels equivalent to or below the control scenario level. Next, both flood evacuations and system refill timing were altered such that hydropower revenues were maximized. The maximization of hydropower revenues was constrained by Portland-Vancouver flood control and firm power reliability according to the following rules: 1) a no further reduction in firm power capacity; and b) no occurrences of Dalles outflow above 500,000 cfs. The latter constraint was imposed because increased flood control has a policy effect equivalent to increasing winter firm power demands, which in turn results in summer reliability losses for both firm power and instream flow targets. Having chosen operations that maximized revenue, firm power was then reduced to a level that could be supported at 100% reliability. If the end result produced a deficit at McNary greater than the control, the procedure was iterated until an acceptable solution was reached.

The results from this process are summarized in Figure 5.8. Generally, the evolution of the PCM projections creates a scenario where summer targets are forced to rely more upon storage allocations than inflows. This causes an obvious tradeoff between targets that currently have storage allocations and those that do not. This tradeoff is apparent in the interaction between firm power capacity and the McNary average annual deficit. As seen in the results (Figure 5.8), the reduction of McNary annual deficits to levels equal to the control climate condition requires the reduction of firm capacity in Periods 2 and 3. Period 1 does not display this tradeoff because the seasonality shift of the annual hydrograph is minimal.

A second tradeoff lies in a less risk-adverse policy toward flood control along the lower Columbia. A two-week earlier refill date benefits the refill reliability and hydropower revenue considerably for all three periods, at a noticeable cost to flood control exceedances. Although the benefit to hydropower seems small, the relative economic benefit of hydropower is much larger than the expected flood damages (see Section 5.2, Figure 5.4). The implicit assumption of the tradeoff analysis is that the economic benefit of hydropower would provide justification for greater frequency of modest floods in the floodplain in the Portland-Vancouver area, so long as the levees were not breached.

Table 5.5 – Resulting operational policies for the CRB, as determined by the heuristic processes presented above.

	Current Operations	Period 1	Period 2	Period 3
Sustainable Firm Power Demand (average million megawatt hours per month)	3.5	3.2	3.0	3.0
Desirable allocation of storage for environmental flows: million acre feet (billion m^3)	2.3 (2.8)	4.3 (5.3)	4.3 (5.3)	6.0 (7.4)
Desirable timing of refill	Current timing	2-weeks early	2-weeks early	2-weeks early
Assigned reallocation of firm power demand (winter to summer). Based on liberal assumptions of temperature elasticity on the market	0%	0%	5%	10%
Desirable flood evacuation (as a percent of current Army Corps of Engineer's requirements)	100%	100%	100%	100%

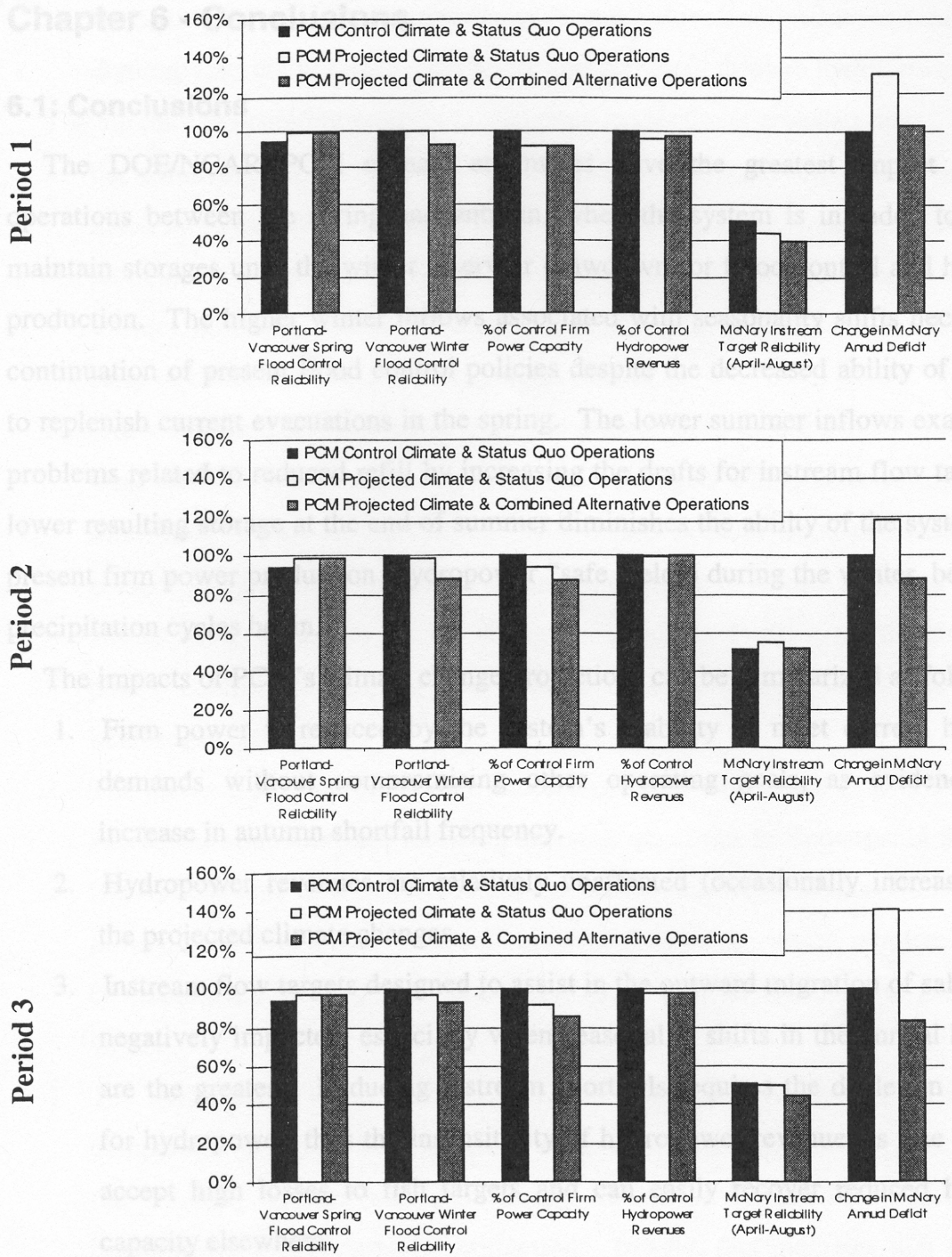


Figure 5.8 – Combined effects of changes to flood evacuation and refill timing, firm demand distribution, and instream storage allocation [black is control climate & current ops, white is climate change with current operations, gray is climate change with heuristic operations.]

Chapter 6 - Conclusions

6.1: Conclusions

The DOE/NCAR PCM climate ensembles have the greatest impact on system operations between the spring and autumn, when the system is intended to refill and maintain storages until the winter reservoir drawdown for flood control and hydropower production. The higher winter inflows associated with seasonality shifts necessitate the continuation of present flood control policies despite the decreased ability of the system to replenish current evacuations in the spring. The lower summer inflows exacerbate the problems related to reduced refill by increasing the drafts for instream flow targets. The lower resulting storage at the end of summer diminishes the ability of the system to meet present firm power production (hydropower "safe yield") during the winter, before major precipitation cycles begin.

The impacts of PCM's climate change projections can be summarized as follows:

1. Firm power is reduced by the system's inability to meet current hydropower demands without compromising other operating goals, as evidenced by an increase in autumn shortfall frequency.
2. Hydropower revenues are relatively unaffected (occasionally increasing) under the projected climate changes.
3. Instream flow targets designed to assist in the outward migration of salmonids are negatively impacted, especially when seasonality shifts in the annual hydrograph are the greatest. Reducing instream shortfalls requires the depletion of reserves for hydropower, thus the insensitivity of hydropower revenues is true only if you accept high losses to fish targets and can easily recover reduced hydropower capacity elsewhere.
4. Although the monthly time step used in this study makes it impossible to explicitly state the projected changes in flood risk, the opportunity costs associated with maintaining the same general flood control policy seem significantly higher than the associated benefits. This study suggests that the

reconsideration of flood control needs and values and under seasonality shifted hydrographs could create a major economic benefit through hydropower.

The alternative operating policies investigated in this thesis revealed that:

1. For achieving spring refill goals, the use of earlier reservoir refill schedules was much more beneficial than a reduction in flood control evacuations. Early refill is particularly good because it 'adapts' to the shift in the hydrograph caused by a warmer climate. Lower flood evacuations cannot provide the same volume as early refill without compromising flood control.
2. Shifts in firm energy demand from the current peak in the winter to the summer were unsuccessful in providing summer flow targets with greater volumes and had little other impact on the system. This results because flood evacuations, which presently align with hydropower demands, continue to require the same quantity of winter withdrawals despite the change in demand. Further, the demand for firm power controls the timing and volume of releases only under the lowest of hydrologic conditions.
3. The increase of reservoir storage allocations for instream flow targets was the most successful alternative for reducing shortfall quantities to Endangered Species Act (ESA) instream flow requirements for salmonids. The reallocation of storage, however, came at a cost to the reliability of firm power, which requires storages to be maintained through the summer for generation during the late fall and early winter.
4. The combination of all the alternatives in this thesis was successful in attaining comparable levels of instream flow volumes for summer ESA targets. However, the resulting system was increasingly unable to sustain the present level of commitment to firm energy production. Briefly, this indicates that the climate changes projected by PCM exacerbate the level of competition for reservoir storages in the summer. This competition, in the real world, is couched between the immediate economic interest of hydropower providers and consumers and the

political mandates for instream habitat, which have economic consequences that are less immediate and more difficult to quantify.

6.2: Recommendations

The results reported here could be extended by several refinements. These include: 1) the use of shorter (e.g. one-week) reservoir model time-step (note that the monthly time-step is fixed in the current version of ColSim), 2) increased resolution of the Snake River Plain reservoirs, and associated agricultural withdrawals and return flows, and 3) the development of fish survival metrics in place of deficit and reliability statistics for the assessment of environmental flow targets. Each of these is discussed briefly below.

6.2.1 The implementation of a one-week time-step

A one-week time-step would allow exploration of several important aspects of reservoir operations that were not possible with the present version of ColSim, including 1) a better assessment of flood control at the Portland-Vancouver levees, 2) the observation of climate change effects on the weekly timescale of flood control, and 3) the inclusion of travel time for reservoir releases.

6.2.2 Implications for the Snake River

Better resolution on Snake River Plain agriculture would be provided by a one-week time-step. An explicit representation of reservoirs and agricultural districts, which are currently represented in aggregate, would allow for the evaluation of tradeoffs between agriculture and the Lower Granite Dam flow target. Further, this would allow for the assessment of market-based strategies to reallocate water between hydropower, agriculture, and environmental flows, and their potential benefit under projected future climate and hydrology.

6.2.3 Development of fish survival metrics

This study relied heavily upon the assumption that present deficits at the McNary target would continue to provide present levels of endangered species protection in the lower Columbia River. This is somewhat misleading, as the goal of the flow targets are the preservation of sea-bound salmon smolt. The development of better metrics from the biological community, which relate factors of concern in maintaining viable salmon populations as a function of recommended flow target performances, would allow a more useful assessment of hydrologic changes and reservoir operations on fish populations.

Glossary

Selected Acronyms:

BAU – business as usual

BiOP – Biological Opinion Paper

BPA – Bonneville Power Administration

COE – U.S. Army Corps of Engineers

CRB – Columbia River Basin

DOE – U.S. Department of Energy

ESA – Endangered Species Act

GCM – general circulation model

GHG – greenhouse gasses

HC2 – UK Hadley Center (GCM research center)

IDWR – Idaho Department of Water Resources

IPCC – Intergovernmental Panel on Climate Change

MPI – Max Planck Institute (GCM research center)

NCAR – National Center for Atmospheric Research

NMFS – National Marine Fisheries Service

PCM – the Department of Energy's Parallel Climate Model

SRD – Storage Reservation Diagram (a.k.a. Flood Rule Curves)

SRES – the IPCC Special Report on Emissions Scenarios

SRP – Snake River Plain

USBR – U.S. Bureau of Reclamation

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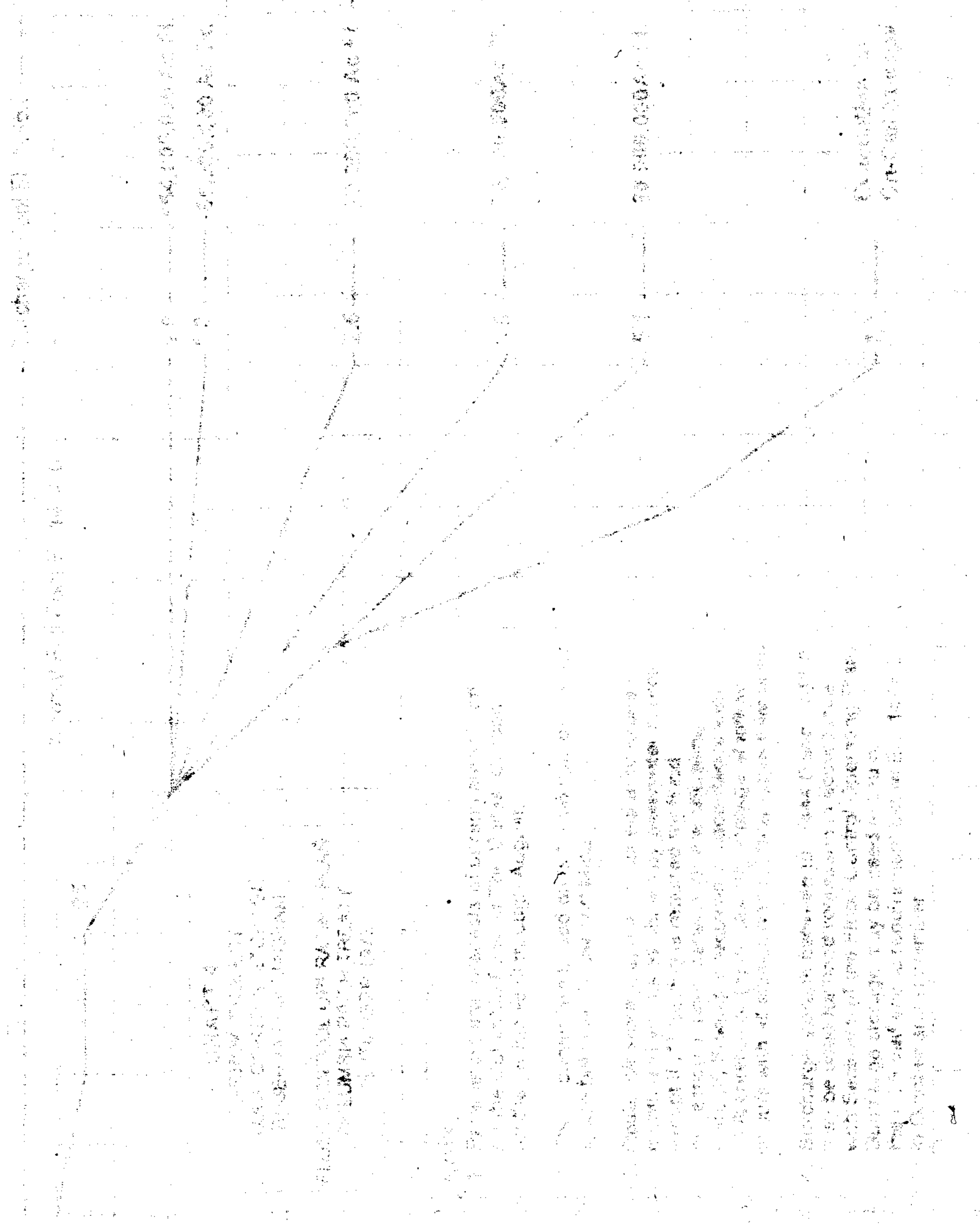
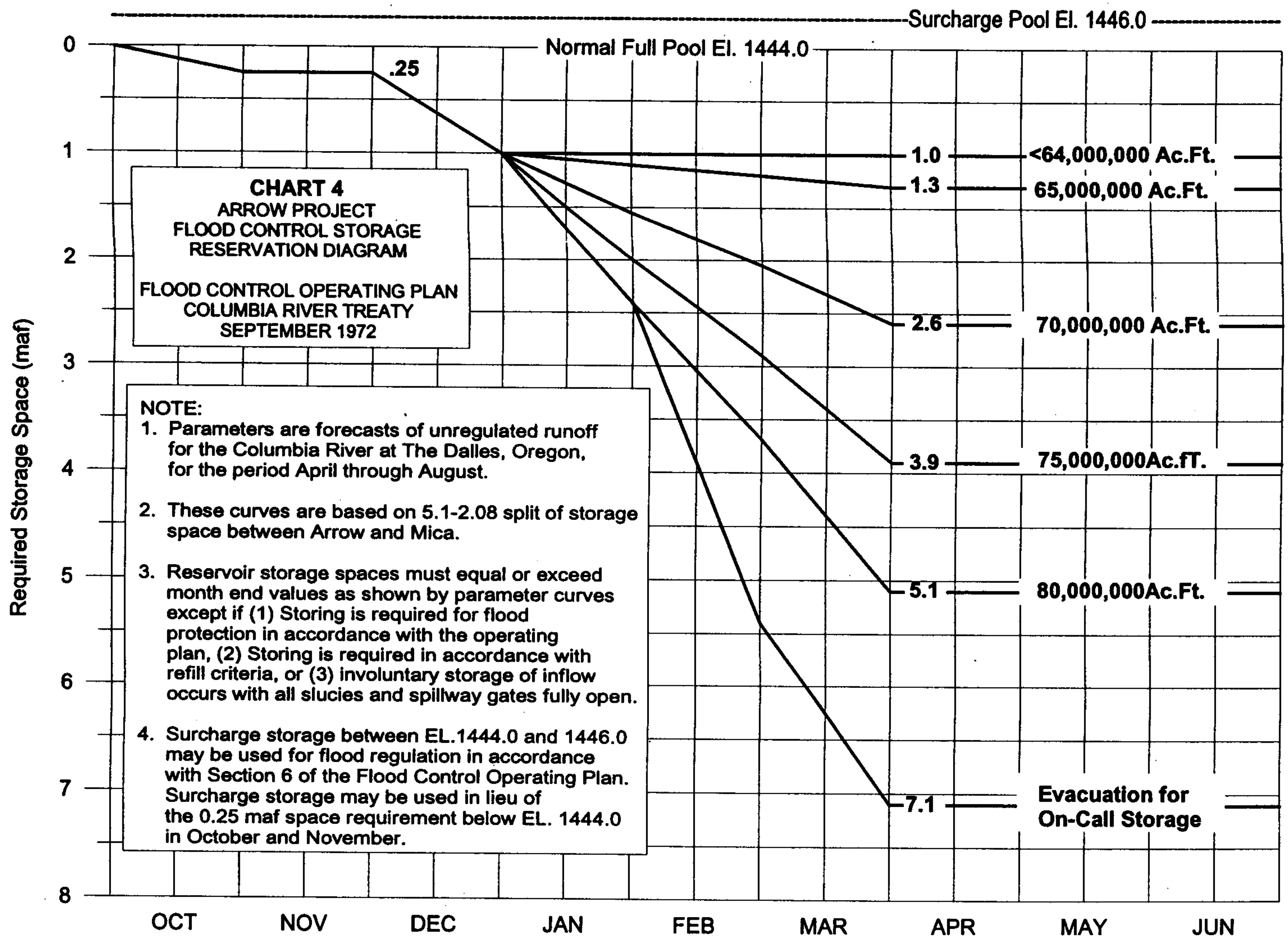
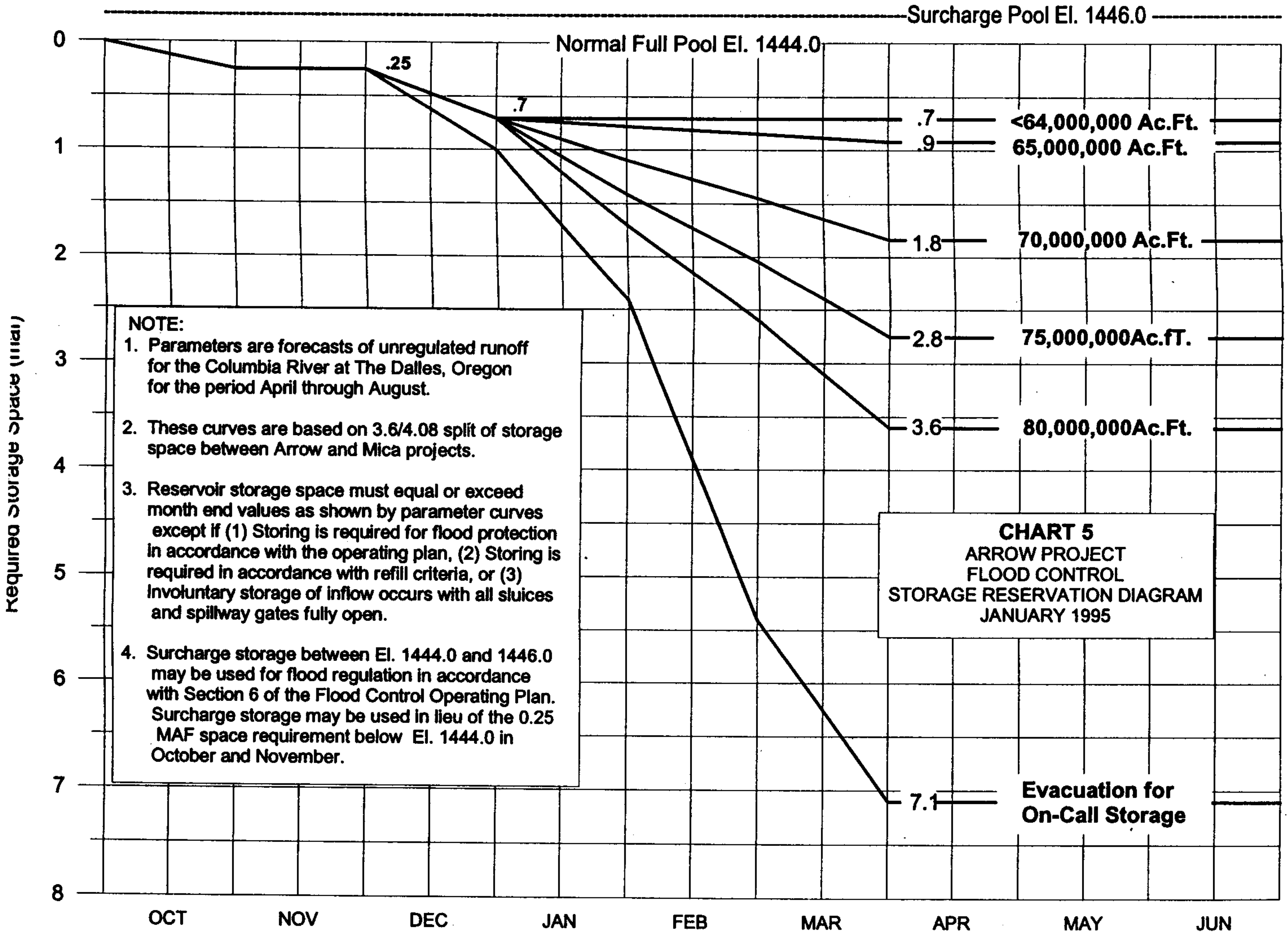
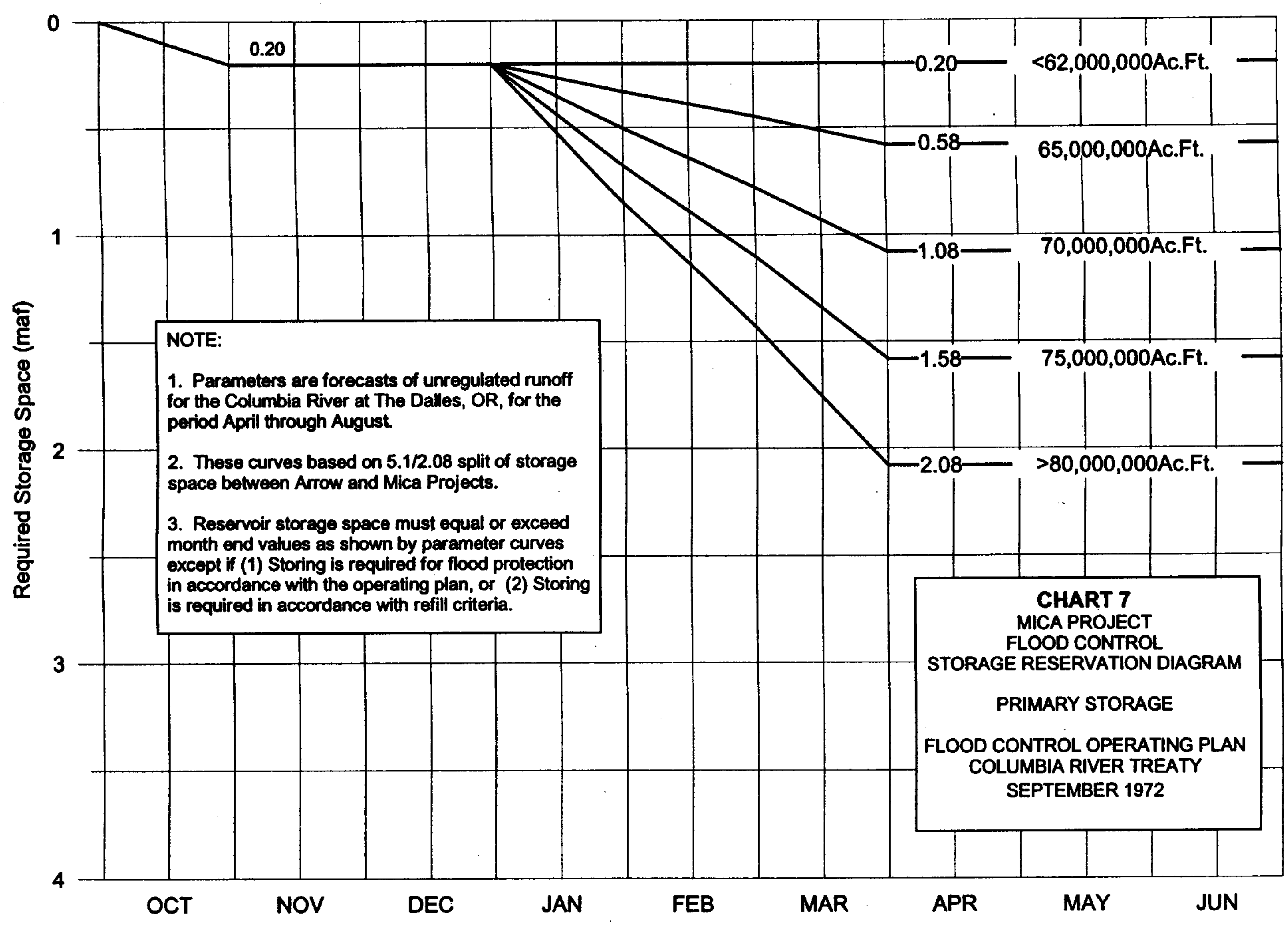
Appendix A:
Storage Reservation Diagrams





Surcharge Pool El. 1446.0
Normal Full Pool El. 1444.0
CHART 4
ARROW PROJECT
FLOOD CONTROL STORAGE
RESERVATION DIAGRAM
FLOOD CONTROL OPERATING PLAN
COLUMBIA RIVER TREATY
SEPTEMBER 1972
NOTE:
1. Parameters are forecasts of unregulated runoff for the Columbia River at The Dalles, Oregon, for the period April through August.
2. These curves are based on 5.1-2.08 split of storage space between Arrow and Mica.
3. Reservoir storage spaces must equal or exceed month end values as shown by parameter curves except if (1) Storing is required for flood protection in accordance with the operating plan, (2) Storing is required in accordance with refill criteria, or (3) involuntary storage of inflow occurs with all slucies and spillway gates fully open.
4. Surcharge storage between EL.1444.0 and 1446.0 may be used for flood regulation in accordance with Section 6 of the Flood Control Operating Plan. Surcharge storage may be used in lieu of the 0.25 maf space requirement below EL. 1444.0 in October and November.
.25
1.0
<64,000,000 Ac.Ft.
1.3
65,000,000 Ac.Ft.
2.6
70,000,000 Ac.Ft.
3.9
75,000,000Ac.fT.
5.1
80,000,000Ac.Ft.
7.1
Evacuation for
On-Call Storage
Required Storage Space (maf)
0
1
2
3
4
5
6
7
8
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN


Surcharge Pool El. 1446.0
Normal Full Pool El. 1444.0
Required Storage Space (maf)
0
1
2
3
4
5
6
7
8
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
.25
.7
.7
.9
1.8
2.8
3.6
7.1
<64,000,000 Ac.Ft.
65,000,000 Ac.Ft.
70,000,000 Ac.Ft.
75,000,000Ac.fT.
80,000,000Ac.Ft.
Evacuation for
On-Call Storage
NOTE:
1. Parameters are forecasts of unregulated runoff for the Columbia River at The Dalles, Oregon for the period April through August.
2. These curves are based on 3.6/4.08 split of storage space between Arrow and Mica projects.
3. Reservoir storage space must equal or exceed month end values as shown by parameter curves except if (1) Storing is required for flood protection in accordance with the operating plan, (2) Storing is required in accordance with refill criteria, or (3) Involuntary storage of inflow occurs with all sluices and spillway gates fully open.
4. Surcharge storage between El. 1444.0 and 1446.0 may be used for flood regulation in accordance with Section 6 of the Flood Control Operating Plan. Surcharge storage may be used in lieu of the 0.25 MAF space requirement below El. 1444.0 in October and November.
CHART 5
ARROW PROJECT
FLOOD CONTROL
STORAGE RESERVATION DIAGRAM
JANUARY 1995


0
1
2
3
4
Required Storage Space (maf)
0.20
0.20
<62,000,000Ac.Ft.
0.58
65,000,000Ac.Ft.
1.08
70,000,000Ac.Ft.
1.58
75,000,000Ac.Ft.
2.08
>80,000,000Ac.Ft.
NOTE:
1. Parameters are forecasts of unregulated runoff for the Columbia River at The Dalles, OR, for the period April through August.
2. These curves based on 5.1/2.08 split of storage space between Arrow and Mica Projects.
3. Reservoir storage space must equal or exceed month end values as shown by parameter curves except if (1) Storing is required for flood protection in accordance with the operating plan, or (2) Storing is required in accordance with refill criteria.
CHART 7
MICA PROJECT
FLOOD CONTROL
STORAGE RESERVATION DIAGRAM
PRIMARY STORAGE
FLOOD CONTROL OPERATING PLAN
COLUMBIA RIVER TREATY
SEPTEMBER 1972
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN

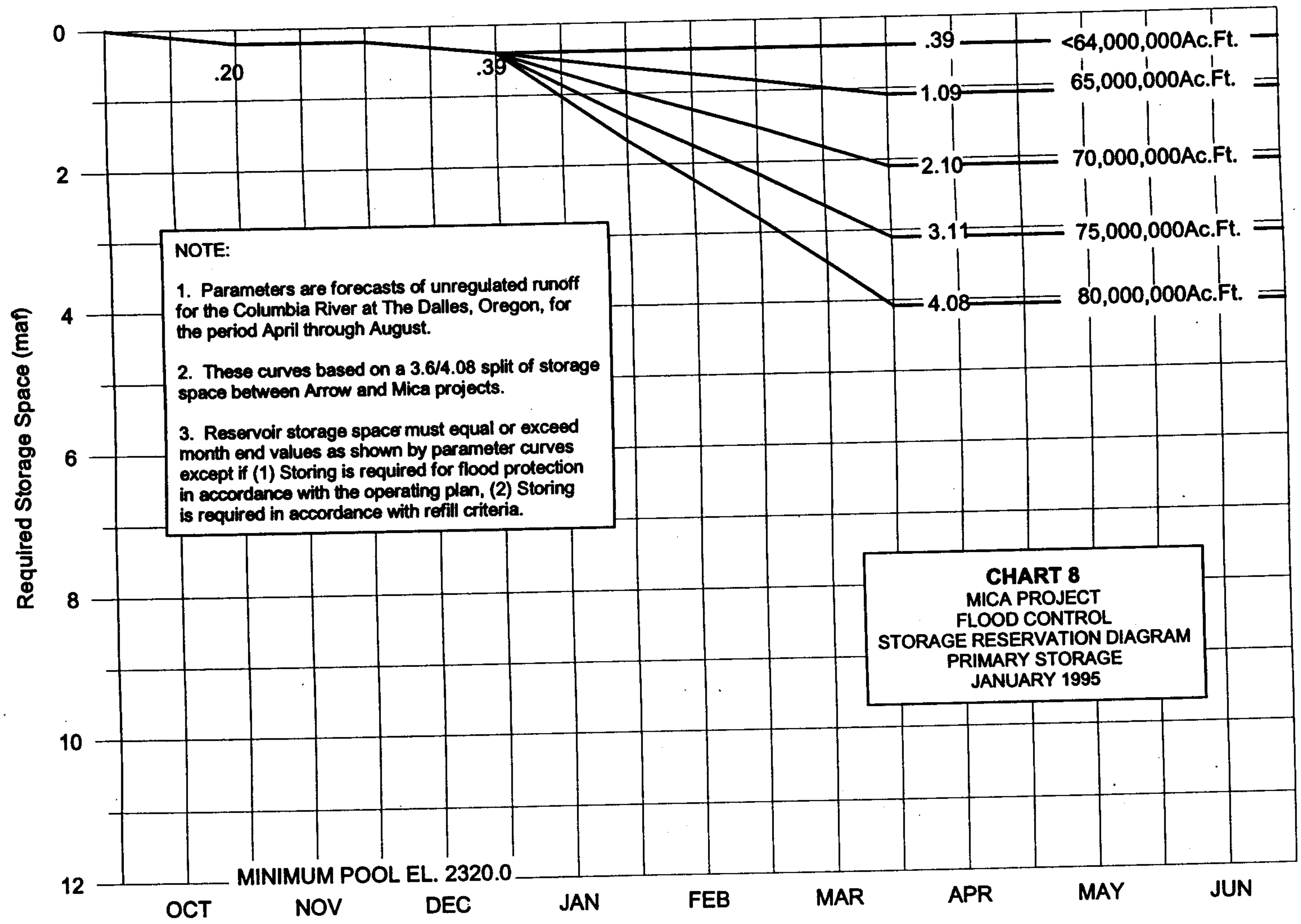


CHART 8
MICA PROJECT
FLOOD CONTROL
STORAGE RESERVATION DIAGRAM
PRIMARY STORAGE
JANUARY 1995
NOTE:
1. Parameters are forecasts of unregulated runoff for the Columbia River at The Dalles, Oregon, for the period April through August.
2. These curves based on a 3.6/4.08 split of storage space between Arrow and Mica projects.
3. Reservoir storage space must equal or exceed month end values as shown by parameter curves except if (1) Storing is required for flood protection in accordance with the operating plan, (2) Storing is required in accordance with refill criteria.
Required Storage Space (maf)
0
2
4
6
8
10
12
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
MINIMUM POOL EL. 2320.0
.20
.39
.39
1.09
2.10
3.11
4.08
<64,000,000Ac.Ft.
65,000,000Ac.Ft.
70,000,000Ac.Ft.
75,000,000Ac.Ft.
80,000,000Ac.Ft.

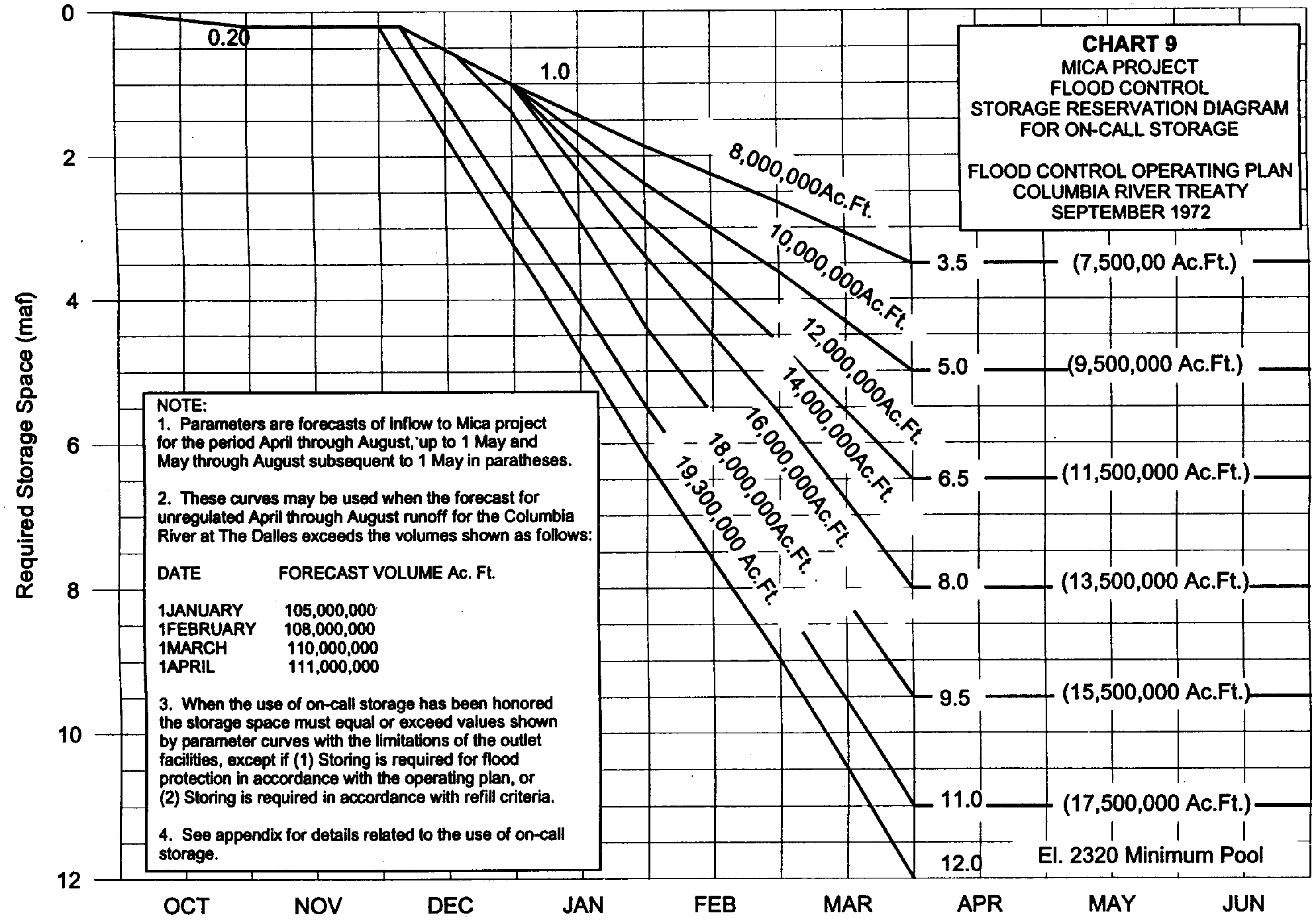


CHART 9
MICA PROJECT
FLOOD CONTROL
STORAGE RESERVATION DIAGRAM
FOR ON-CALL STORAGE
FLOOD CONTROL OPERATING PLAN
COLUMBIA RIVER TREATY
SEPTEMBER 1972
Required Storage Space (maf)
0
2
4
6
8
10
12
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
0.20
1.0
8,000,000Ac.Ft.
10,000,000Ac.Ft.
12,000,000Ac.Ft.
14,000,000Ac.Ft.
16,000,000Ac.Ft.
18,000,000Ac.Ft.
19,300,000 Ac.Ft.
3.5
(7,500,00 Ac.Ft.)
5.0
(9,500,000 Ac.Ft.)
6.5
(11,500,000 Ac.Ft.)
8.0
(13,500,000 Ac.Ft.)
9.5
(15,500,000 Ac.Ft.)
11.0
(17,500,000 Ac.Ft.)
12.0
El. 2320 Minimum Pool
NOTE:
1. Parameters are forecasts of inflow to Mica project for the period April through August, up to 1 May and May through August subsequent to 1 May in paratheses.
2. These curves may be used when the forecast for unregulated April through August runoff for the Columbia River at The Dalles exceeds the volumes shown as follows:
DATE FORECAST VOLUME Ac. Ft.
1JANUARY 105,000,000
1FEBRUARY 108,000,000
1MARCH 110,000,000
1APRIL 111,000,000
3. When the use of on-call storage has been honored the storage space must equal or exceed values shown by parameter curves with the limitations of the outlet facilities, except if (1) Storing is required for flood protection in accordance with the operating plan, or (2) Storing is required in accordance with refill criteria.
4. See appendix for details related to the use of on-call storage.

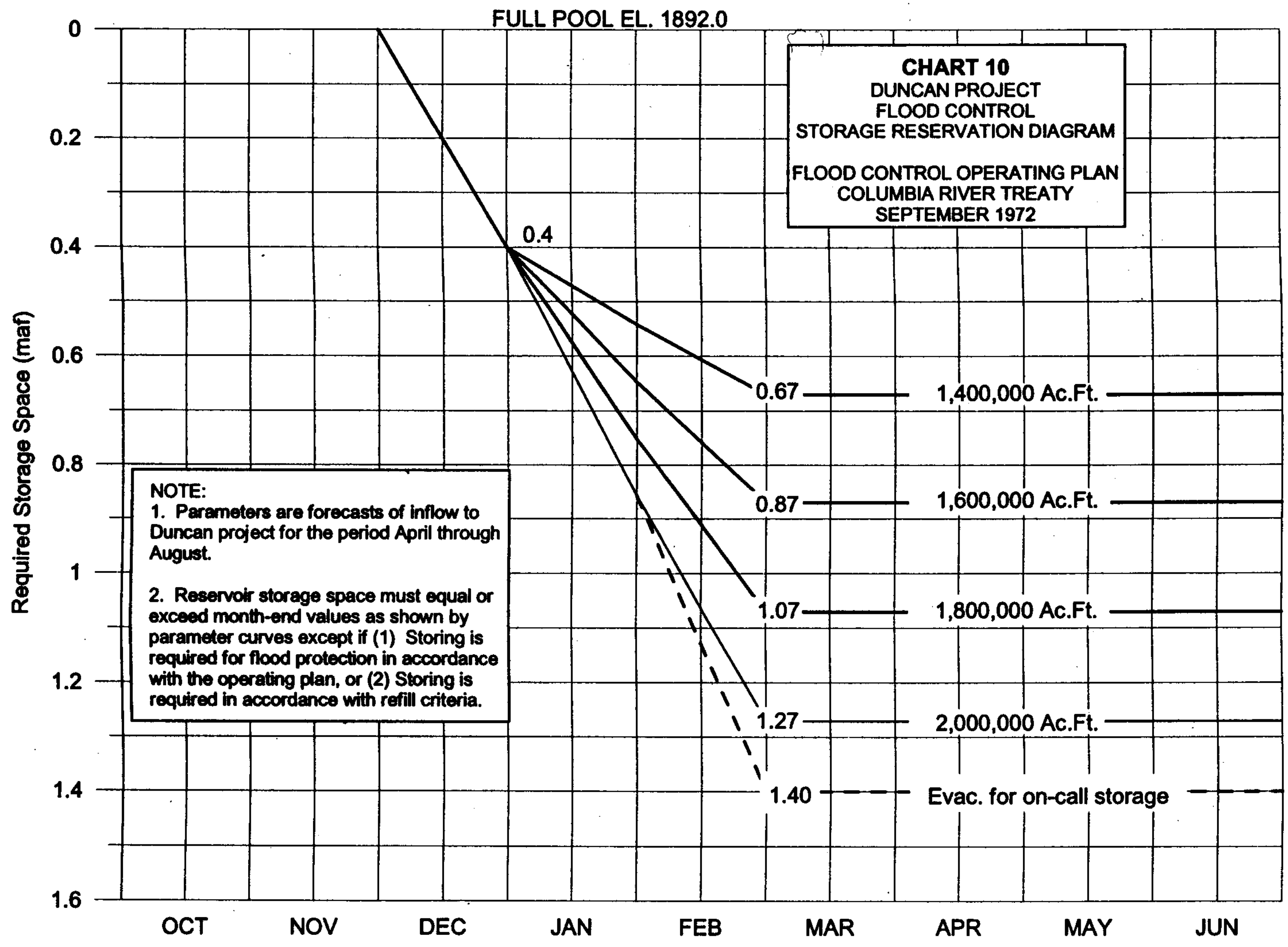


CHART 10
DUNCAN PROJECT
FLOOD CONTROL
STORAGE RESERVATION DIAGRAM
FLOOD CONTROL OPERATING PLAN
COLUMBIA RIVER TREATY
SEPTEMBER 1972
FULL POOL EL. 1892.0
Required Storage Space (maf)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
0.4
0.67
1,400,000 Ac.Ft.
0.87
1,600,000 Ac.Ft.
1.07
1,800,000 Ac.Ft.
1.27
2,000,000 Ac.Ft.
1.40
Evac. for on-call storage
NOTE:
1. Parameters are forecasts of inflow to Duncan project for the period April through August.
2. Reservoir storage space must equal or exceed month-end values as shown by parameter curves except if (1) Storing is required for flood protection in accordance with the operating plan, or (2) Storing is required in accordance with refill criteria.

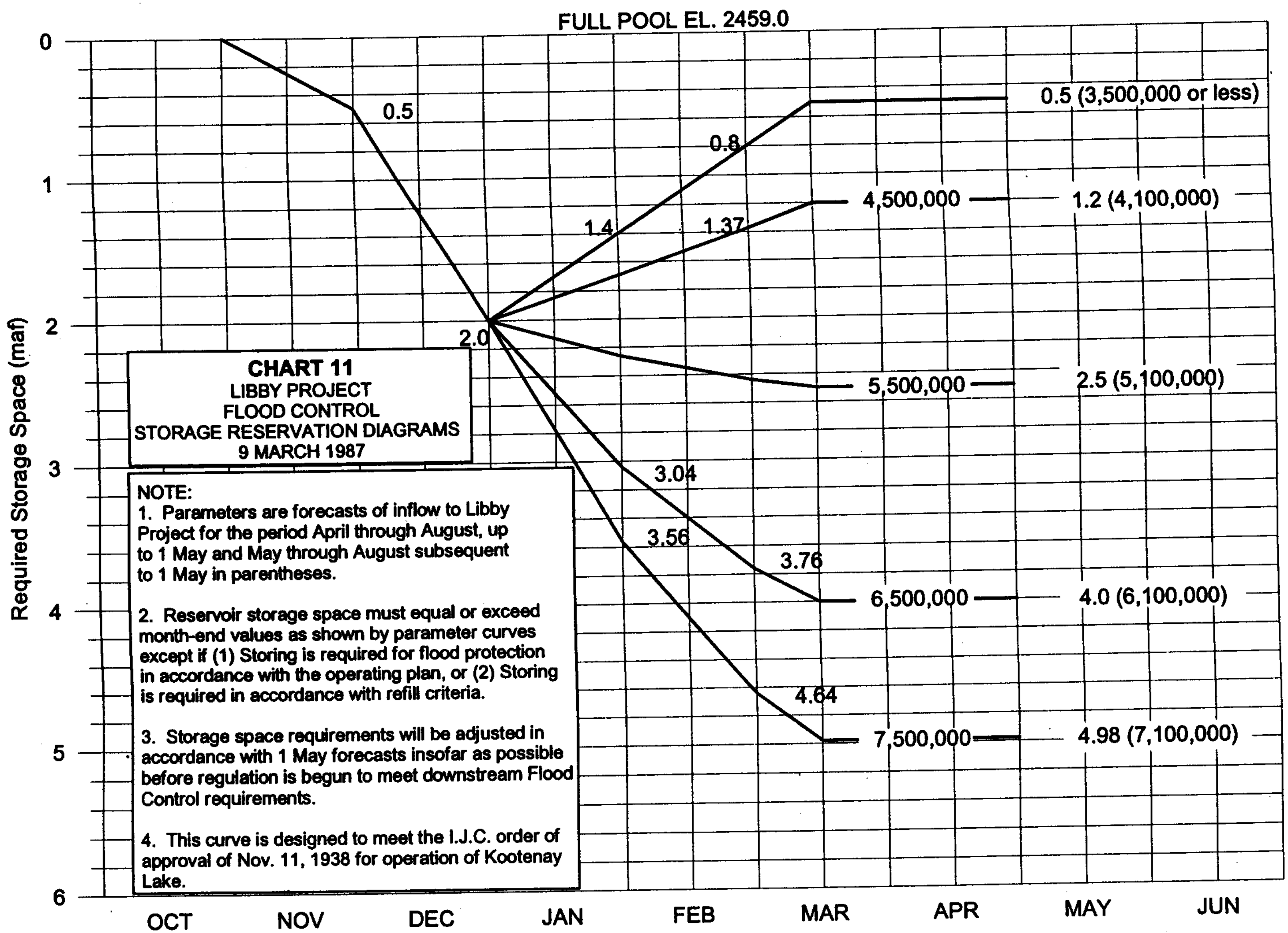


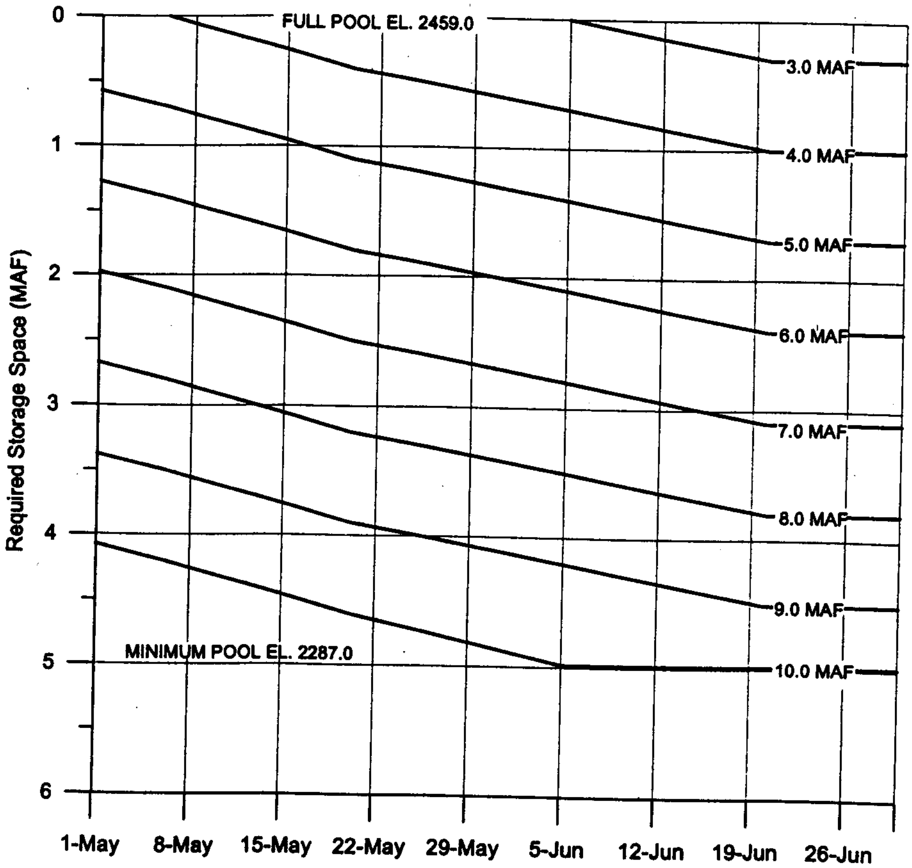
CHART 11
LIBBY PROJECT
FLOOD CONTROL
STORAGE RESERVATION DIAGRAMS
9 MARCH 1987

NOTE:
1. Parameters are forecasts of inflow to Libby Project for the period April through August, up to 1 May and May through August subsequent to 1 May in parentheses.

2. Reservoir storage space must equal or exceed month-end values as shown by parameter curves except if (1) Storing is required for flood protection in accordance with the operating plan, or (2) Storing is required in accordance with refill criteria.

3. Storage space requirements will be adjusted in accordance with 1 May forecasts insofar as possible before regulation is begun to meet downstream Flood Control requirements.

4. This curve is designed to meet the I.J.C. order of approval of Nov. 11, 1938 for operation of Kootenay Lake.



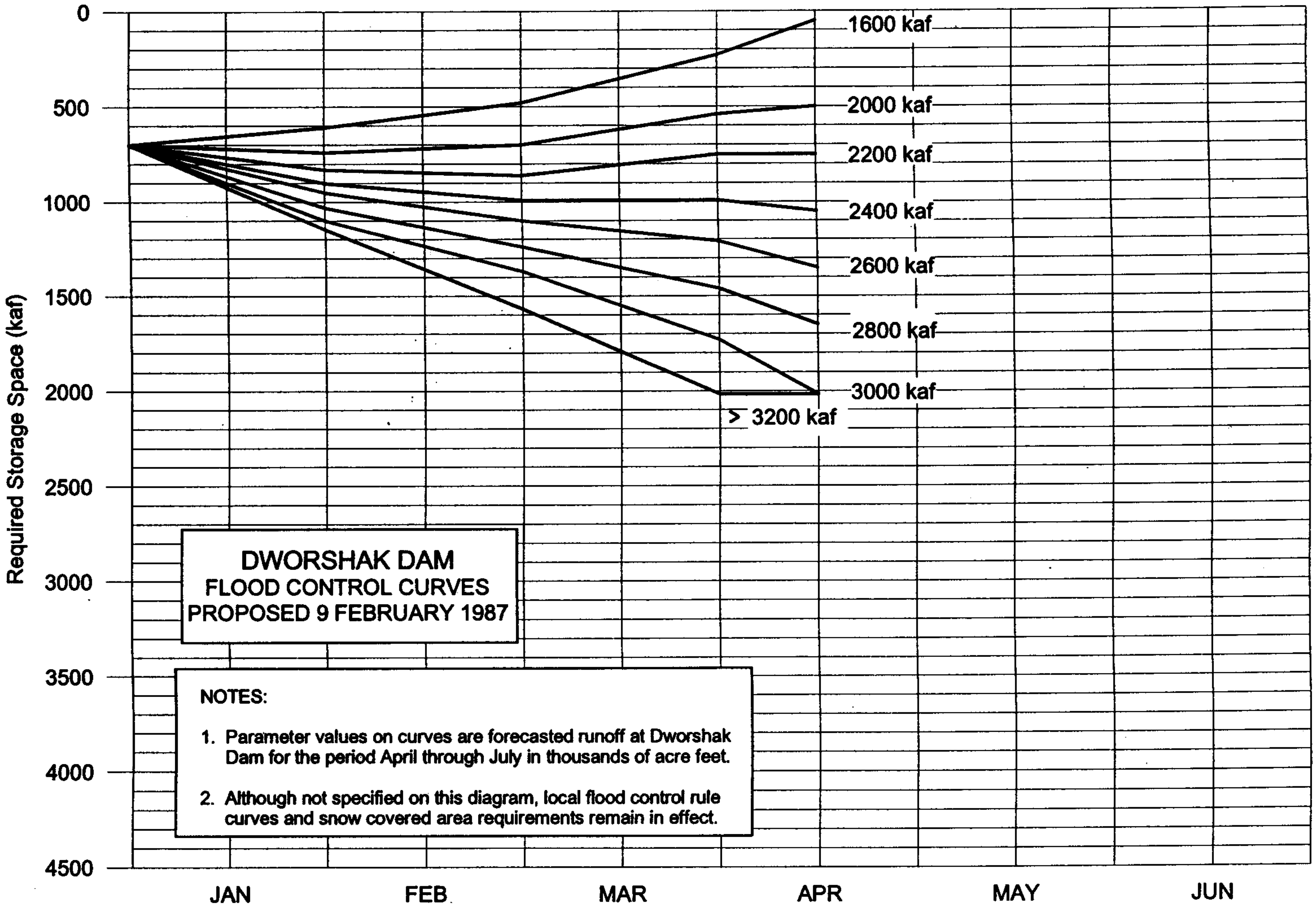
NOTE:
1. PARAMETERS ARE FORECASTS OF INFLOW TO LIBBY PROJECT FROM DATE THROUGH AUGUST.

2. RESERVOIR STORAGE SPACE MUST EQUAL OR EXCEED VALUES AS SHOWN BY PARAMETER CURVES EXCEPT IF (1) STORING IS REQUIRED FOR FLOOD PROTECTION FOR KOOTENAI BASIN, OR (2) STORING IS REQUIRED IN ACCORDANCE WITH REFILL CRITERIA.

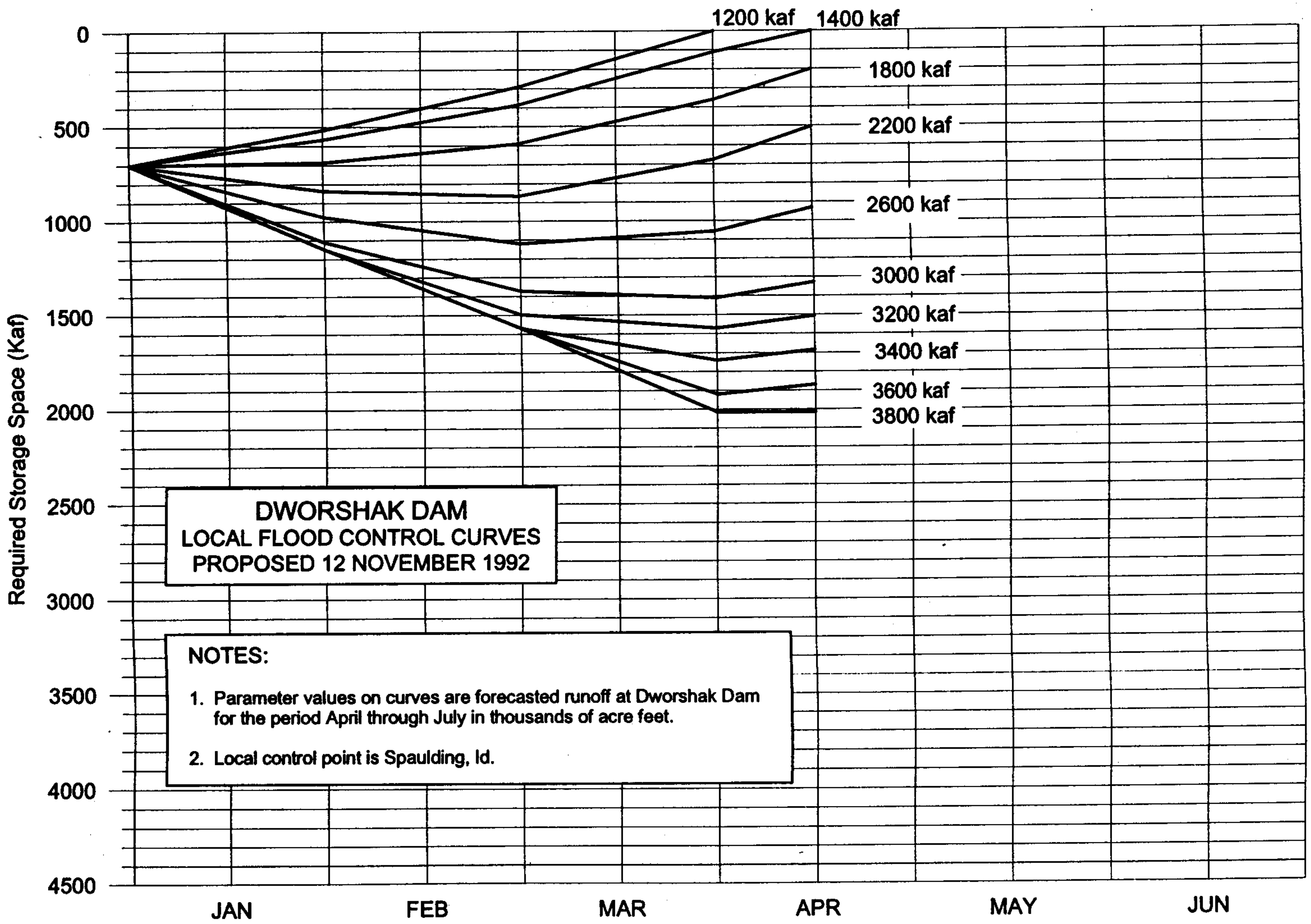
CHART 12

LIBBY PROJECT
LOCAL FLOOD CONTROL
STORAGE RESERVATION DIAGRAM
FLOOD CONTROL ON KOOTENAI RIVER

FLOOD CONTROL OPERATING PLAN
COLUMBIA RIVER TREATY
SEPTEMBER 1972



DWORSHAK DAM
FLOOD CONTROL CURVES
PROPOSED 9 FEBRUARY 1987
Required Storage Space (kaf)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
JAN
FEB
MAR
APR
MAY
JUN
1600 kaf
2000 kaf
2200 kaf
2400 kaf
2600 kaf
2800 kaf
3000 kaf
> 3200 kaf
NOTES:
1. Parameter values on curves are forecasted runoff at Dworshak Dam for the period April through July in thousands of acre feet.
2. Although not specified on this diagram, local flood control rule curves and snow covered area requirements remain in effect.


DWORSHAK DAM
LOCAL FLOOD CONTROL CURVES
PROPOSED 12 NOVEMBER 1992
Required Storage Space (Kaf)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
JAN
FEB
MAR
APR
MAY
JUN
1200 kaf
1400 kaf
1800 kaf
2200 kaf
2600 kaf
3000 kaf
3200 kaf
3400 kaf
3600 kaf
3800 kaf
NOTES:
1. Parameter values on curves are forecasted runoff at Dworshak Dam for the period April through July in thousands of acre feet.
2. Local control point is Spaulding, Id.

Procedure for Determining Flood Control Draft at Brownlee Reservoir, November 1998

Tabular Format

	Volume Forecast (MAF)			
	TDA ≤ 75			
Space Required (KAF)	Brn ≤ 3	Brn = 4	Brn = 5	Brn ≥ 6
28 Feb	0	200	300	400
31 Mar	0	100	200	350
15 Apr	0	50	150	250
30 Apr	0	0	50	150
	TDA = 85			
Space Required (KAF)	Brn ≤ 3	Brn = 4	Brn = 5	Brn ≥ 6
28 Feb	150	300	350	400
31 Mar	100	300	400	450
15 Apr	50	250	400	500
30 Apr	0	250	400	500
	TDA = 95			
Space Required (KAF)	Brn ≤ 3	Brn = 4	Brn = 5	Brn ≥ 6
28 Feb	200	300	350	400
31 Mar	150	300	400	500
15 Apr	100	300	425	550
30 Apr	50	300	450	600
	TDA = 105			
Space Required (KAF)	Brn ≤ 3	Brn = 4	Brn = 5	Brn ≥ 6
28 Feb	300	400	400	400
31 Mar	200	425	475	500
15 Apr	150	450	525	600
30 Apr	100	450	550	700
	TDA ≥ 115			
Space Required (KAF)	Brn ≤ 3	Brn = 4	Brn = 5	Brn ≥ 6
28 Feb	300	400	500	500
31 Mar	250	450	600	750
15 Apr	200	500	650	850
30 Apr	150	550	750	980

Notes. The procedure for determining flood control draft at Brownlee is applicable from January 31 – April 30 to facilitate regulation of the spring flood season on the lower Snake and lower Columbia Rivers. Forecasts from both The Dalles and Brownlee are used to specify draft volumes at designated time periods throughout the spring runoff season. Interpolation may be necessary at both The Dalles and Brownlee with respect to their forecasts. If a forecast at The Dalles is less than 75 MAF, equal to 85, 95 or 105 MAF, or greater than 115 MAF, then interpolation is necessary only at Brownlee. If Brownlee's forecast is less than 3 MAF, equal to 4 or 5 MAF, or greater than 6 MAF, then interpolation is necessary only at The Dalles. If the forecast does not lie at either of the volumes specified above, then interpolation is necessary at both projects. The following is an example of the interpolation process when necessary at both projects:

1. Determine the 4 lines of interpolation from the forecasts of The Dalles and Brownlee at a specified date. For example, a 30 April forecast of 88 MAF at The Dalles and 4.2 MAF at Brownlee would produce the 4 following interpolation lines:
   a. TDA=85, BRN=4, FC=250
   b. TDA=85, BRN=5, FC=400
   c. TDA=95, BRN=4, FC=300
   d. TDA=95, BRN=5, FC=450

2. Interpolate between the two different The Dalles runoff volumes for the same Brownlee runoff volume. For example, interpolate between TDA=85, BRN=4 and TDA=95, BRN=4:

   (88-85/95-85)*(300-250)+250=265kaf

3. Interpolate between the same two runoff volume values at The Dalles in step 2, but use the higher Brownlee runoff volume than in step 2. For example, interpolate between TDA=85, BRN=5 and TDA=95, BRN=5:

   (88-85)/(95-85)*(450-400)+400=415kaf

4. Interpolate between the values obtained from step 2 and step 3 to determine the space required at Brownlee. For example:

   (4.2-4.0)/(5.0-4.0)*(415-265)+265=295kaf