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ROBUSTNESS OF A MULTIPLE-USE RESERVOIR TO SEASONAL RUNOFF SHIFTS ASSOCIATED WITH CLIMATE CHANGE

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ABSTRACT

Although much remains to be learned about long-term climate change associated with anthropogenic increases in concentrations of the so-called "greenhouse gases," such as carbon dioxide and methane, there is a general consensus that some global warming will result from past and present emissions. Climatologists' projections of global average temperature increases are on the order of several degrees centigrade over the next century. In the western United States, the dominant hydrologic effect of such warming, aside from any accompanying changes in precipitation, would be to reduce winter snow accumulations in mountainous headwaters regions. Insofar as more than 70 percent of the annual runoff in the western United States is presently derived from snowmelt, reduction of snow accumulation, with attendant increases in winter runoff and reduction in spring and summer runoff could have significant effects on water users.

To assess the robustness of reservoir operation to such shifts in seasonal runoff, simulations were developed of monthly runoff for the American River, Washington, using the National Weather Service River Forecast System. The American River is a tributary of the Yakima River, which drains the eastern slopes of the Cascade Mountains. The American River is presently unregulated; however, we tested the performance of hypothetical reservoirs with capacity of 0.25 and 0.50 of the mean annual flow for a range of annual temperature changes from 0.0 (present climate) to 4.0°C. Most of the reservoir storage in the Northwest, and the Columbia River Basin in particular, is within-year; therefore, the range of reservoir sizes tested should be regionally representative. We considered a multiple-purpose reservoir system operated for water supply and hydropower, with minimum releases required for fisheries enhancement. In addition to evaluating the sensitivity of water supply, low flow, and hydropower performance using a heuristic operating rule, the relative performance of the system under present and altered climates was evaluated using an optimization algorithm, extended linear quadratic Gaussian control. The results showed that water supply reliability would be significantly degraded by a shift in the seasonal runoff pattern that would accompany a general warming, but the hydroelectric revenues

might increase due to larger releases during the winter peak demand season. The optimization algorithm was able to increase hydropower revenues substantially relative to the heuristic rule under present climate, with the greatest improvement achieved for the larger reservoir size. Under the altered climate, the improvement was less, especially for the smaller reservoir. The degradation in water supply performance of the reservoirs is controlled more by reservoir storage capacity than by the operating policy.

INTRODUCTION

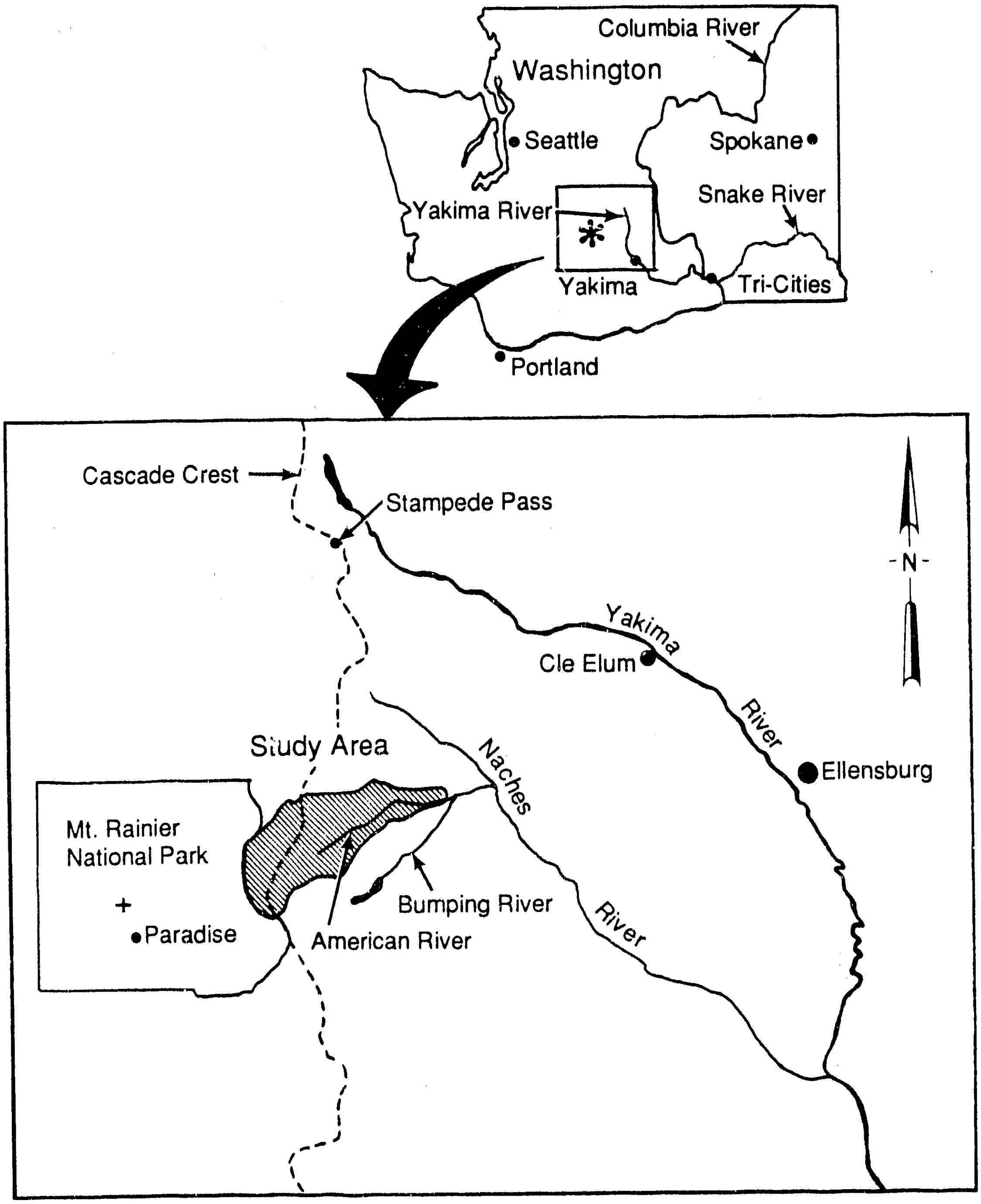
The goal of the water manager is maximization of the monetary and others societal benefits of such water uses as municipal, industrial, and agricultural water supply, recreation, navigation, and hydropower generation, while mitigating the effects of water shortages (droughts) and excesses (floods). To accomplish this goal, ways have been sought to regulate water supply and demand. Often, this has been achieved by constructing surface water reservoirs, which provide a means of buffering, or smoothing, variations in natural streamflows. Operating policies for multi-objective reservoir systems usually prioritize objectives implicitly or explicitly, often through rule curves that specify reservoir releases depending on the time of year, reservoir contents, and past and/or forecasted future inflows. Conceptually, multiple objectives may be treated in an operating policy either by reducing them to a common metric (e.g., monetary), or as constraints.

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

Because the pattern of seasonal runoff in the West is closely linked to snowmelt, the western United States could be highly sensitive to global warming associated with the so-called greenhouse effect. Gleick (1987) and Lettenmaier (1990) have shown that, for the Sacramento River Basin of California, the warming predicted by global-scale general circulation models (GCM's) for a doubling of CO_2 and other so-called greenhouse gases would result in a major shift in the seasonal runoff pattern. For the four headwaters catchments investigated by Lettenmaier et al. (1988), which had mean elevations ranging from 4,100 to 8,200 feet, reductions in maximum seasonal snow accumulation ranged from 50 to 85 percent. Aside from any changes in precipitation, the hydrologic effects of such warming would be to reduce winter snow accumulations, increase winter runoff, and reduce spring and summer runoff. Simulation studies reported by Lettenmaier and Sheer (1990) showed that such changes in the seasonal pattern of runoff would have a significant impact on the performance of the California State Water Project.

In this paper, we report the results of hydrologic simulations for the American River, Washington (Figure 1). The American River is a tributary of the Yakima River, which in turn is a tributary of the Columbia River. The Yakima River is used to irrigate approximately 500,000 acres, and has been the subject of great concern because of the degradation of water quality and fisheries habitat brought about by irrigation. Prior to settlement of the basin in the 1800's and construction of dams on tributaries of the Yakima and the mainstem Columbia downstream, it is estimated that the Yakima River supported a population of anadromous fish of approximately 80,000 steelhead trout and a migratory fish population of about 700,000 salmon. The corresponding current estimates are about 2,500 trout and about 7,000 salmon. As a result of the Northwest Power Planning Act of 1980, a major fisheries enhancement project is based on improved agricultural practices and provision of additional reservoir storage to increase flows during the spawning season. On the mainstem of the Columbia, reservoir releases are now made using what is termed as the "water budget," which amounts to reserved storage for fisheries purposes, primarily reduction of the time of passage through the reservoir system, which significantly affects predatory and other losses as the probabilities of extreme flows, could significantly affect fisheries enhancement efforts, as well as hydropower production from the Columbia River system.

Some insight into the character of the hydrologic changes in the Columbia River drainage that might be associated with climate variations can be provided by paleo records. Paleohydrologic studies by Chatters (1986) have indicated that as recently as 6,000 years before present, there was a period during which the regional climate was significantly warmer than at present, and precipitation was much lower. Chatters' work has also indicated a



<u>FIGURE 1</u>. American River catchment location map

streamflow pattern during that period somewhat similar to that projected for California under the CO_2 doubling scenario, specifically, a shift in the runoff peak toward the winter months, and a reduction in spring and summer runoff relative to present. Preliminary investigations by Pacific Northwest Laboratory have indicated that under such a climate, there would be a significant negative impact on the proposed Yakima River fisheries enhancement program. There is concern about the possible effects on the mainstem Columbia water budget and hydropower generation as well. At present, about 80 percent of the electric energy consumption in the Northwest is derived from hydropower; any reduction in this amount would affect projected future needs for power production and, in the event the reduction in hydropower was made up by burning of fossil fuel, would increase regional emissions.

In this paper, we explore possible effects of regional warming on hydropower production, agricultural water deliveries, and fisheries releases through a sensitivity analysis of a single multiple-purpose reservoir. At present, there is no significant production of hydropower in the Yakima River Basin. Therefore, in order to consider both fisheries and power production issues that are relevant to the Columbia Basin as a whole, we evaluated the performance of a hypothetical reservoir, using real topographic, hydrologic, and meteorological data for the American River. Ultimately, a more detailed study of the Columbia Basin as a whole will be necessary to fully evaluate the water resources and related effects of regional warming. However, consideration of a hypothetical system with characteristics typical of the Columbia Basin as a whole offers an opportunity to explore the relationship of climate and water resource system performance without the logistical complications introduced by the complexity of the entire system.

In addition to the interaction of multiple operating objectives, we considered how possible improvements in reservoir operating policies might mitigate the effects of climate change by comparing two reservoir operating policies. The first is rule curve operation similar to that currently used in practice. The second is optimal operation, which treats hydropower production as a monetary objective and minimum flow (fisheries) and agricultural water supply releases as constraints.

SYSTEM DESCRIPTION

The American River drains 78.9 square miles of the eastern slopes of the Cascade Mountains of south-central Washington (Figure 1). The elevation of the American River Basin ranges from 3,200 feet at U.S. Geological Survey gauge 12-4885 to a maximum of 6,800 feet. With the exception of a small amount of alpine area above about 6,000 feet, the entire basin is mixed conifer forest, with lodgepole pine dominating. The average annual precipitation over the catchment is about 55 inches per year, with a large proportion of the precipitation falling as snow during the winter months. Average annual potential evapotranspiration is about 24 inches per year; actual evaporation, inferred from water balance considerations, averages about 19 inches per year.

As noted above, the American River is presently unregulated. We simulated the performance of hypothetical reservoirs with storage capacities of 0.25 and 0.50 of the mean annual flow (maf) of the river. This represents the approximate range of reservoir sizes within the Columbia River Basin; the total reservoir storage in the Columbia River Basin is slightly larger than 0.35 of the mean annual flow. To the extent possible, we made use of actual characteristics of the five existing Yakima River reservoirs. For instance, we assumed an annual water supply demand of 69 percent of the mean annual reservoir inflow, distributed as shown in Figure 2; these values are identical to the actual values for the Yakima River system as a whole, as provided by the U.S. Bureau of Reclamation.

Although none of the reservoirs on the Yakima is designed for hydropower production, we chose to include hydropower in our operation's objective function because of its importance to the rest of the Columbia River system. Based on the head-storage relationship corresponding to an assumed trapezoidal reservoir, and a constant assumed turbine efficiency of 0.80, a family of curves representing hydropower revenue as a function of reservoir monthly release and monthly average head was derived (Figure 3). Finally, a minimum streamflow release of 70 cfs, which corresponds approximately to the 7-day, 10-year low flow in the absence of the reservoir, was specified. Recreational benefits were not identified specifically, although variations in reservoir

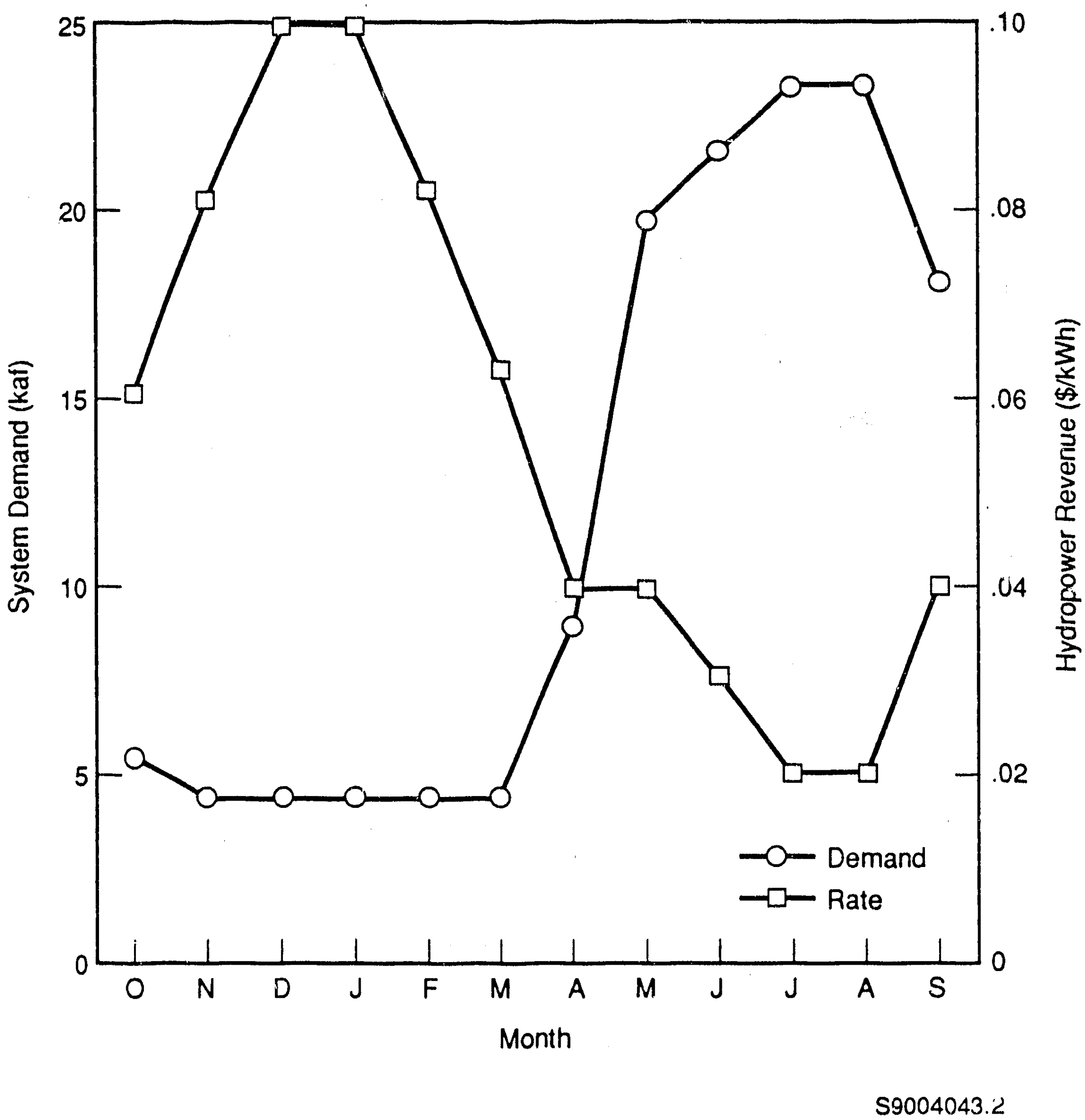


FIGURE 2. Assumed monthly water supply demand and unit hydropower revenue for hypothetical American River reservoir

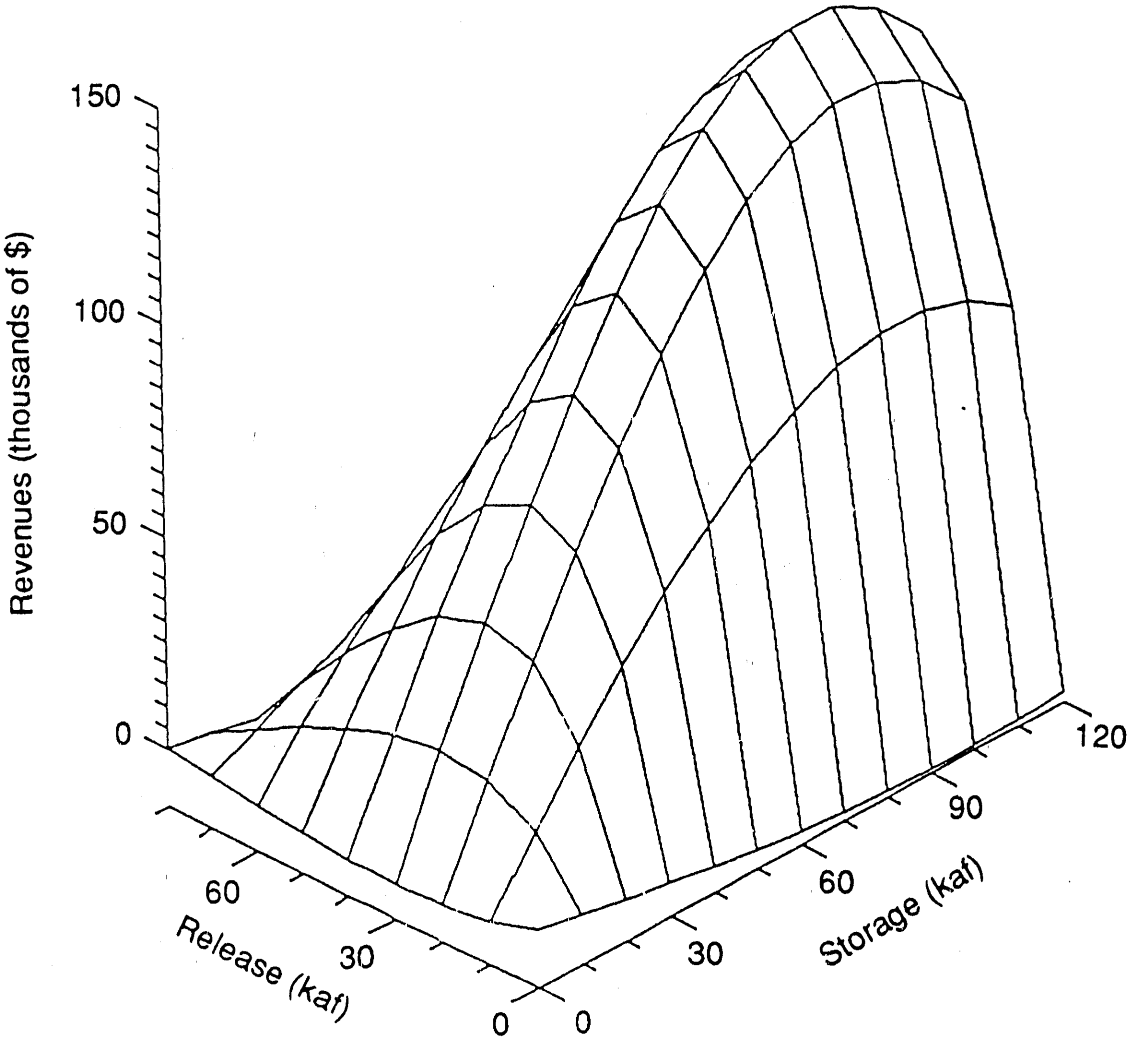


FIGURE 3. Hydroelectric power generation function for 0.50 maf reservoir at $0.10/kWh

stage were recorded in the simulation model as a surrogate for recreational use. The optimization model could be modified to treat variations in reservoir stage as a constraint, although such a formulation was not pursued here. As in the prototype system, no downstream navigation use was assumed.

CLIMATE SCENARIOS AND HYDROLOGIC MODELING

The alternative climate scenarios used in this study are based on a fixed increase in temperature applied to all the historical records for the 35-year simulation period 1948-82. Alternative climates corresponding to +2°C and +4°C warming, in addition to the base case (present climate), were considered. The alternative climate scenarios, as represented by 35-year records of daily precipitation and daily temperature maxima-minima were used as input to deterministic snowmelt and soil moisture accounting models, the application of which are described in this section. Simulated streamflows were aggregated to a monthly time interval, and formed the input to reservoir simulation and optimization models described in the next section. The study approach is similar to that taken by Lettenmaier et al. (1988) for the Sacramento-San Joaquin rivers of California, with the exception that the present study examines the performance of a single reservoir rather than a reservoir system, and the alternative climate scenarios represent fixed temperature increments with historical precipitation, rather than precipitation and temperature taken from GCM output under alternative atmospheric CO_2 scenarios.

To obtain reservoir inflow sequences, two hydrologic models were used to simulate runoff given precipitation, temperature, and potential evapotranspiration (PET). The snowmelt model developed by Eric Anderson of the U.S. National Weather Service Hydrologic Research Laboratory (Anderson 1973) was used to produce daily rain-plus-melt sequences given daily precipitation and temperature maxima-minima, which were disaggregated to a 6-hourly time step. Anderson's model, which deterministically describes the change in storage of water and heat in the snowpack, has been tested in a number of mountainous basins in the western United States and elsewhere. It was used by Lettenmaier et al. (1988) in the Sacramento-San Joaquin study. The model was applied to the American River Basin in an elevation band mode, with the catchment divided into four bands of equal area. Within each band, precipitation was implicitly assumed to fall entirely as rain or as snow during any 6-hour time interval, depending on the temperature within the band. Because there are no long-term climatological stations in the catchment, temperature data were interpolated by elevation from stations at Cle Elum (elevation 1,930 ft), Stampede Pass (elevation 3,960 ft), and Paradise (elevation 5,430 ft). Precipitation data for the lowest zone were taken from the Cle Elum record, while precipitation data for the upper three zones were taken from the Stampede Pass record. The actual station data were adjusted using (time-constant) factors specific to each elevation band to preserve the long-term mean annual water balance, and the seasonal distribution of basin-average snowmelt. The model was calibrated coincidentally with the soil moisture accounting model (see below) using the historical precipitation and temperature data. The output rain-plus-melt sequences for each elevation band were aggregated to a daily time step, and subsequently, over the four elevation bands to produce a long-term daily sequence of mean areal precipitation, which was used as input to the soil moisture accounting model.

The soil moisture accounting model was developed by Burnash et al. (1973), originally for forecasting runoff in the Sacramento River Basin. It is a deterministic, spatially lumped, conceptual model that describes the flux of soil moisture between conceptual storage zones. Input to the model was the rain-plus-melt output of the snowmelt model and potential evapotranspiration. Precipitation (interpreted as rain-plus-melt) is considered to be incident on one of two types of basin covers: (1) a permeable soil mantle, or (2) lakes, channel networks, and impervious areas. Rain falling on impervious areas always becomes direct runoff, whereas that which falls on the permeable soil mantle undergoes a complicated sequence, which represents the infiltration process.

Potential evapotranspiration (PET), which is input to the soil moisture accounting model, was calculated using the Penman equation, adjusted via a calibration process to the basin using the method described by Lettenmaier et al. (1988). For the alternative climate scenarios, the incremental change in Penman PET resulting from the changed temperature was calculated, with the other independent variables (average wind speed, humidity, mean solar radiation, and the ratio of bright sunshine to the maximum possible duration of bright sunshine) held constant. Penman's PET was computed on a monthly basis, using average values of the input variables. For calibration to historical conditions, some of the variables (wind speed, humidity) were not well known, so these were estimated using data from a weather almanac and data obtained from the Natches Ranger District of the Wenatchee National Forest.

The soil moisture accounting model was calibrated to historical data using the parameter search procedure described by Gan (1988). The model was then run for the base case and the alternative climates, and for each case, a 35-year record of monthly simulated streamflows was generated. The base case corresponded to the simulated monthly discharges for the historical climate, rather than observed historical monthly flows. This choice was intended to reduce the effect of data, parameter estimation, and model errors on the subsequent sensitivity assessments.

As expected, simulated streamflows for the alternative climates were higher in the winter and lower in the summer when compared with the base case streamflows (Figure 4). Annual streamflow was little changed, both because the historical precipitation was unchanged in the alternative climate simulations, and because higher PET was compensated by a reduction in "actual" soil moisture, hence reducing actual evapotranspiration (ET) relative to PET in the warmest months, such that the inferred annual ET under present and alternative climates was nearly the same.

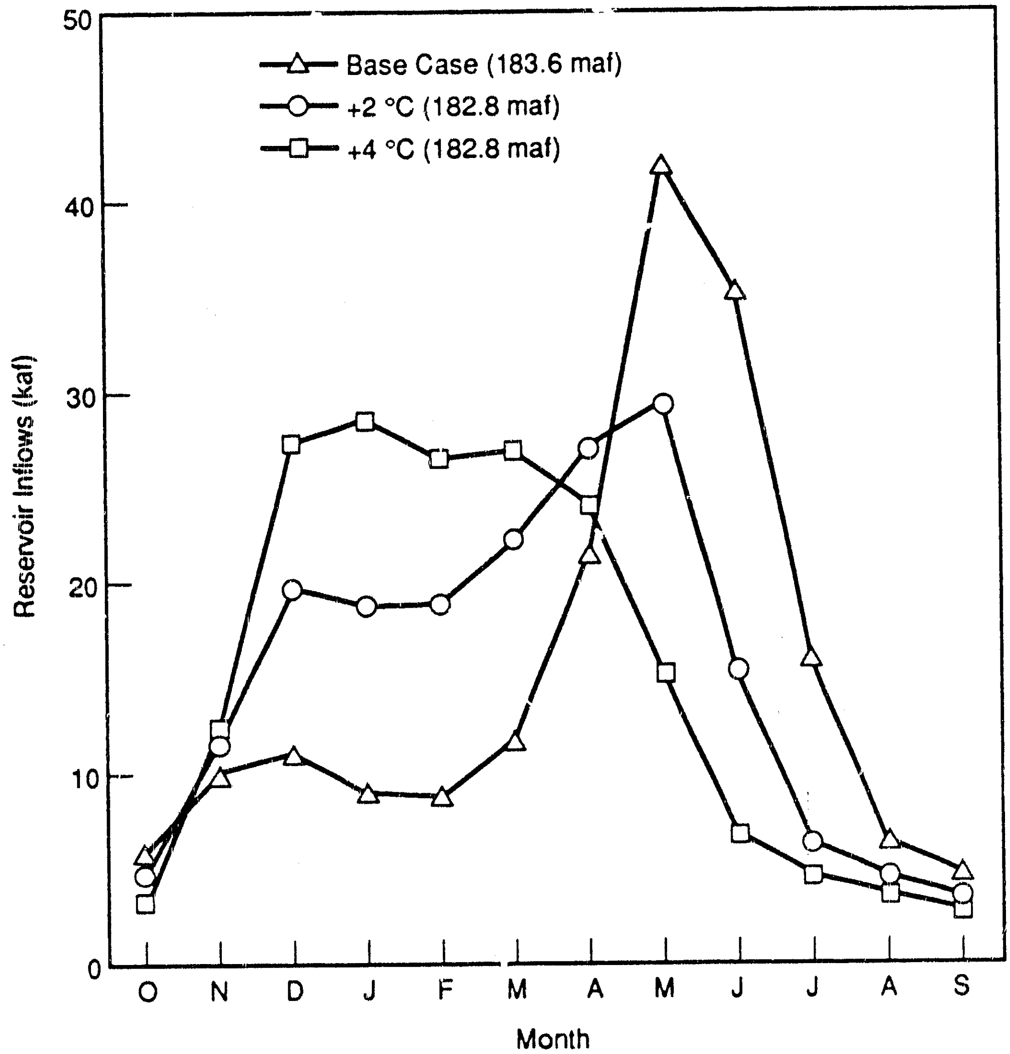


FIGURE 4. Simulated American River mean monthly flows for base case (nominally present conditions), +2°C and +4°C climate alternatives; mean annual flow (maf) in parenthesis.

RESERVOIR OPERATION MODELS

Performance of the hypothetical reservoirs was evaluated using a heuristic, simple "fill-and-spill" model and optimal operation as determined using extended linear quadratic Gaussian control (ELQGC) as described by Georgakakos and Marks (1985). Performance of the reservoirs was based on their ability to meet minimum release and water supply requirements, and to generate hydroelectric power. Hydroelectric power revenues were computed as a rate that varied from 2 cents per kilowatt-hour (July and August) to 10 cents per kilowatt-hour (December and January). Since the highest revenues for hydropower generation in the Northwest occur during the winter months when a seasonal demand peak occurs from space heating (Figure 2), it is beneficial to make large releases during these months, while storing enough water to meet the high irrigation demand during the summer months. The heuristic model simply prioritizes the water uses, with the minimum flow release (a surrogate for fisheries protection and enhancement) given highest priority, followed by water supply requirements (primarily agricultural). Hydropower is not given a specific priority, but all releases up to turbine capacity are assumed to pass through the turbines. In the optimization model, the objective function is maximization of hydropower revenues subject to constraints on minimum flow and water supply releases.

The heuristic model simulated operation of the reservoir as follows. Initial storage was computed by adding the current monthly inflow to the previous month-end storage (at the beginning of the sequence, reservoir storage was taken as 70 percent of capacity). If enough water was available in the reservoir, the minimum flow release was first made, followed by the water supply release. If, after the initial release, as excess of water remained (overflow conditions), water was spilled from the reservoir, and the end-of-month storage was taken as full. If sufficient water was not available in the reservoir to meet system demands, all available storage was released from the system and the end-of-month storage was zero. All releases up to the turbine capacity were assumed to be used for hydropower generation. Both storage failures (zero end-of-month storage) and release failure (release insufficient to meet either minimum flow release or water supply demand) were recorded, as were spills (end-of-month storage full).

Performance of the system was also evaluated using an optimization algorithm, ELQGC. ELQGC is a non-linear, stochastic control method, the application of which to reservoir operation was first proposed by Wasimi and Kitanidis (1983) and extended by Georgakakos and Marks (1985). We posed the optimization problem as the maximization of hydropower revenue subject to constraints in a manner similar to that used by Hooper et al. (1990). The constraints included both physical constraints (maximum and minimum storage) and water supply and minimum streamflow release objectives, which are incorporated in the objective function as penalty terms. Although the algorithm is designed to maximize hydropower revenues, the penalty coefficients were made large enough that the primary target was meeting the minimum flow and water supply demands.

ELQGC is an open-loop approach, (since release is not explicitly a function of storage), and is implemented via a trajectory-iteration algorithm. A control sequence of reservoir releases for 12 consecutive months is assumed, and then propagated forward in time to obtain the corresponding values of storage and the associated system performance indices for the 12-month sequence. Then, feasible control (release) sequences are searched to find the optimal sequence of system releases. Since releases are determined independently of storage, minimum and maximum release constraints can be applied directly during the optimization procedure. This ensures that the 70 cfs minimum flow requirement will be met each month, assuming enough water is present in the reservoir. However, since the control variable (release) is not a function of storage, storage constraints cannot be applied directly. Storage constraints are therefore incorporated in the objective function as quadratic penalty terms, which penalize deviations from the target storage value. Due to the quadratic form of the penalty function, and the relatively large weighting coefficients placed on storage constraints, storage trajectories are driven toward the feasible range.

Because storage constraint violations are not prohibited by the model (even though the penalty function should make them infrequent), storage and release values for the first month of the control horizor were post-processed to determine if any storage violations occurred. If the algorithm generated an optimal storage greater than the reservoir capacity, the excess storage was spilled (added to the existing release value) until the reservoir was at maximum capacity. A similar correction was made if the algorithm attempted to release too much water; in such cases, the release was reduced to prevent a negative storage. Once post-processing was completed, hydroelectric power revenues were recalculated based on the corrected values of storage and release. The control horizon was then advanced by one month. An optimal release trajectory for the new control horizon was determined using an initial trajectories the optimal release and storage trajectories from the previous control horizon. The algorithm proceeded in this manner for 35 years (420 months). In order to maintain comparability with the heuristic model, perfect forecasts of the flow in the control horizon were assumed, although this is not a requirement of the algorithm.

The determination of a monthly release value in the ELQGC algorithm depends on successful convergence of the algorithm at each time step. In past applications, (e.g., Georgakakos and Marks 1987; Hooper and Lettenmaier 1989) ELQGC has been used to operate multiple reservoir systems with relatively large storage capacities (larger than the mean annual flow) for which storage failures tend to occur infrequently. When applied to smaller reservoirs such as the hypothetical ones on the American River, the algorithm was not always able to satisfactorily converge on a solution in situations of impending storage failure. In such cases, we determined the monthly release from the heuristic model. Essentially, the "optimal" releases were resumed when the storage failure had passed. As the potential for storage failures increased (warmer alternative climates and smaller reservoir sizes), an increasing number of the monthly release decisions were made using the heuristic approach. This was especially true when the 0.25 mean annual flow (maf) reservoir was tested using the +2°C and +4°C climate alternatives. For these two cases in particular, reservoir operation using ELQGC became a "pseudo-optimization" process in which a significant number of the release decisions were determined using the heuristic approach.

RESERVOIR SIMULATION RESULTS

Results of the reservoir simulations from both operating policies are shown in Figures 5-8. Figure 5 shows the increased hydropower revenue that resulted from optimal operation, primarily due to larger releases during the winter months, when unit hydropower revenues were greatest. For the larger reservoir under optimal (ELQGC) operation, there was a slight reduction in hydropower revenues for the warmer climates, apparently due to an attempt to store more water to displace the reduction in natural spring and summer runoff so that water supply demands could be met. For the smaller reservoir, and the larger reservoir under heuristic operation, hydropower revenues increased for the warmer climates. The apparent reason for this, especially for the smaller reservoir, was that the system operation became storage bound as the seasonal runoff pattern shifted, forcing spills during the winter and early spring, which coincided more closely with the peak in the unit hydropower revenue. For the smaller reservoir, the difference between optimal and heuristic operating policies was modest, especially for the warmest climate alternative, for the reasons noted in the previous section. However, for the larger reservoir, comparison of the annual average hydropower generation attributable to climate change was considerably less than the difference attributable to altered operating policies.

Figures 6-8 show that, especially for the smaller reservoir size, deterioration of the system's ability to meet water supply targets could not be avoided under either operating policy. Storage failures and release failures both increased for the warmer climates, most markedly for the smaller reservoir. Generally, the performance under both operating policies was quite similar with respect to water supply deliveries. Both the frequency and severity of release failures increased for the warmer climates, with an accompanying increase in storage failures. The observed decreases in system reliability under the alternative climates were attributable to the shift in the seasonality of reservoir inflows. Although there was little difference in yearly runoff between the base and alternative cases, (see Figure 4) increased winter runoff in the alternative climates occurred at the expense of a reduction of natural storage in the snowpack, which resulted in lower

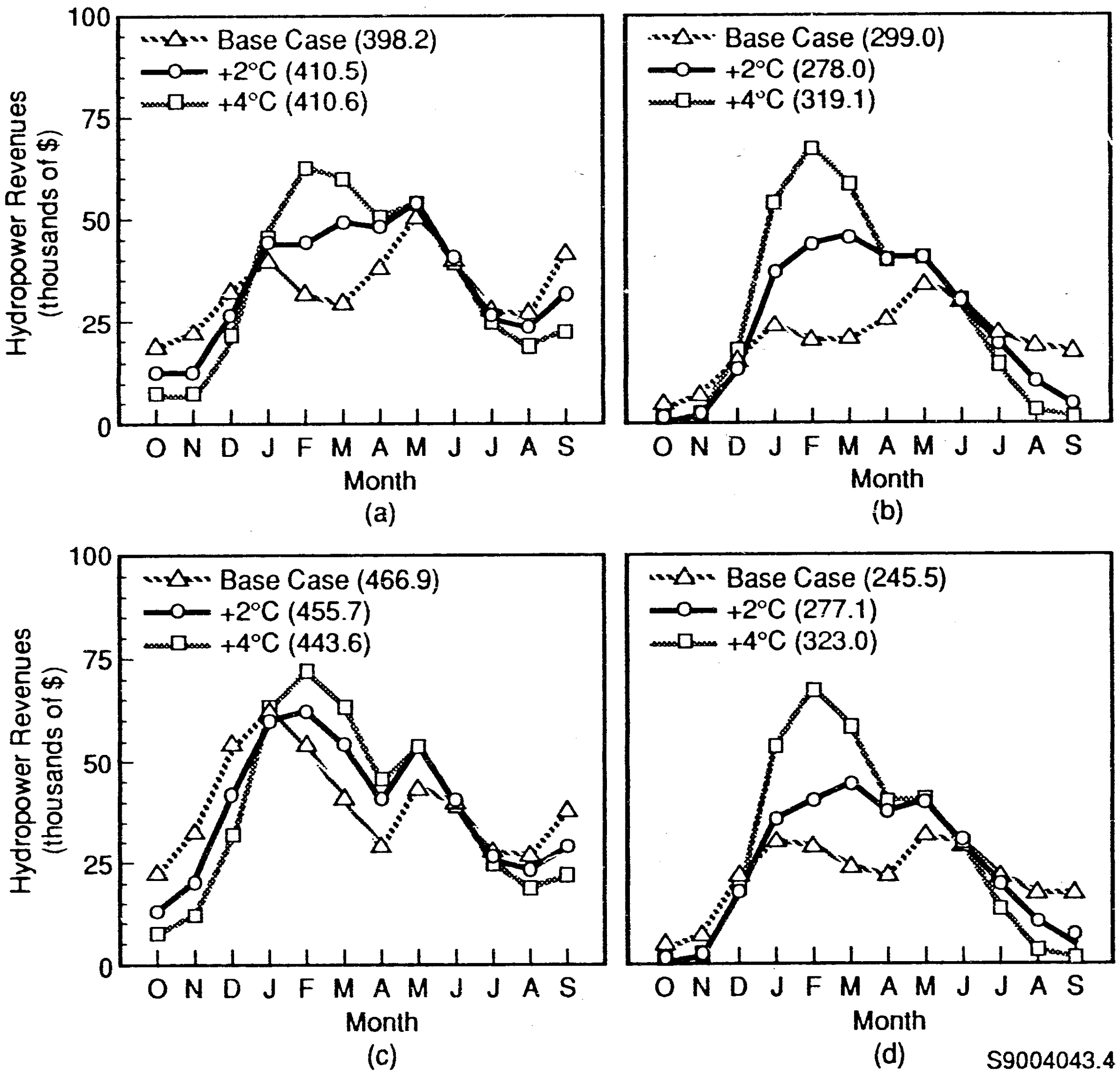


FIGURE 5. Simulated mean monthly hydropower revenues.
a) heuristic operating policy with 0.50 maf reservoir
b) heuristic operating policy with 0.25 maf reservoir
c) ELQGC operating policy with 0.50 maf reservoir
d) ELQGC operating policy with 0.25 maf reservoir

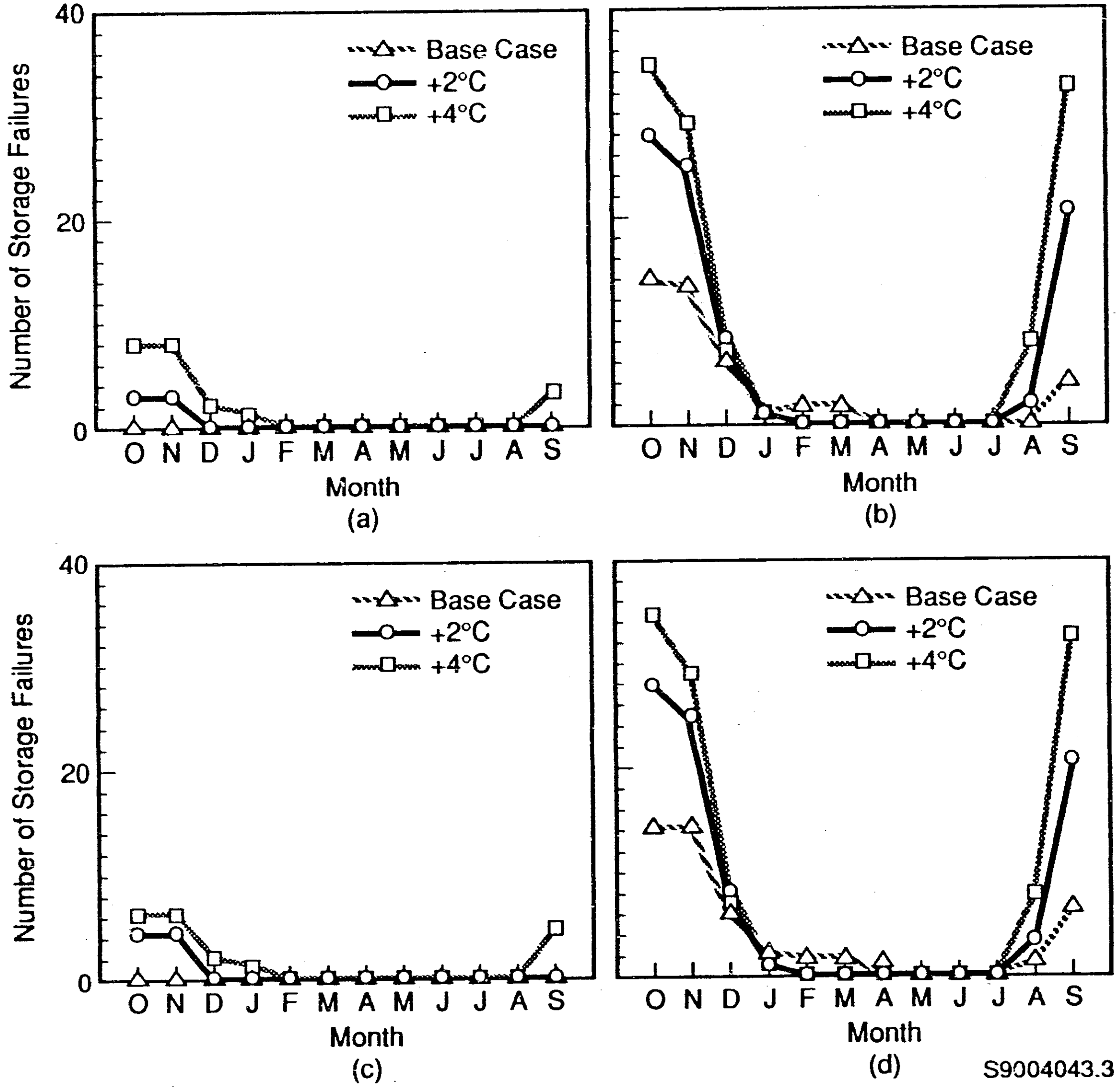


FIGURE 6. Simulated number of storage failures per month over the 35-year simulation period.
a) heuristic operating policy with 0.50 maf reservoir
b) heuristic operating policy with 0.25 maf reservoir
c) ELQGC operating policy with 0.50 maf reservoir
d) ELQGC operating policy with 0.25 maf reservoir

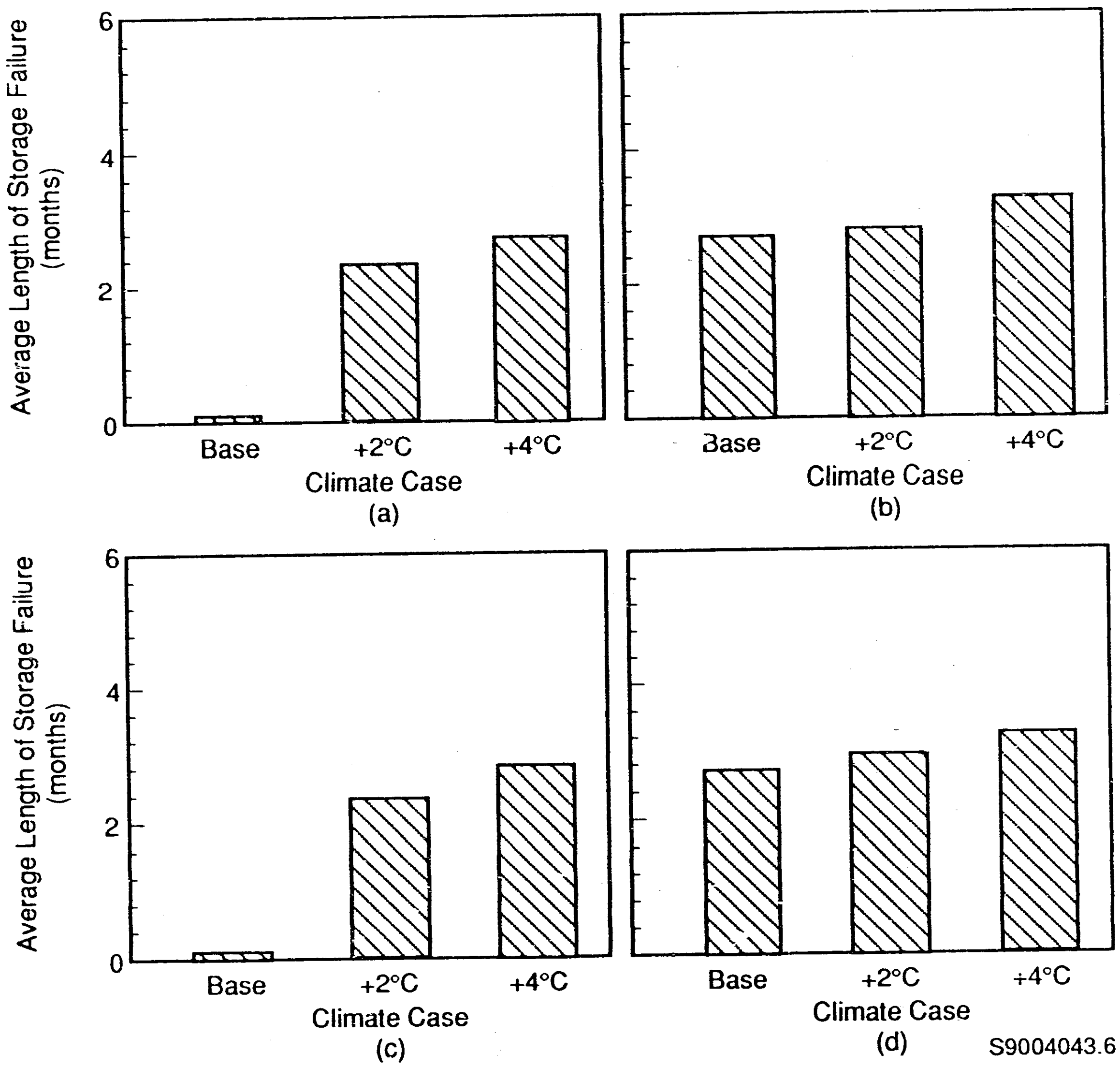


FIGURE 7. Simulated average length of a storage failure.
a) heuristic operating policy with 0.50 maf reservoir
b) heuristic operating policy with 0.25 maf reservoir
c) ELQGC operating policy with 0.50 maf reservoir
d) ELQGC operating policy with 0.25 maf reservoir

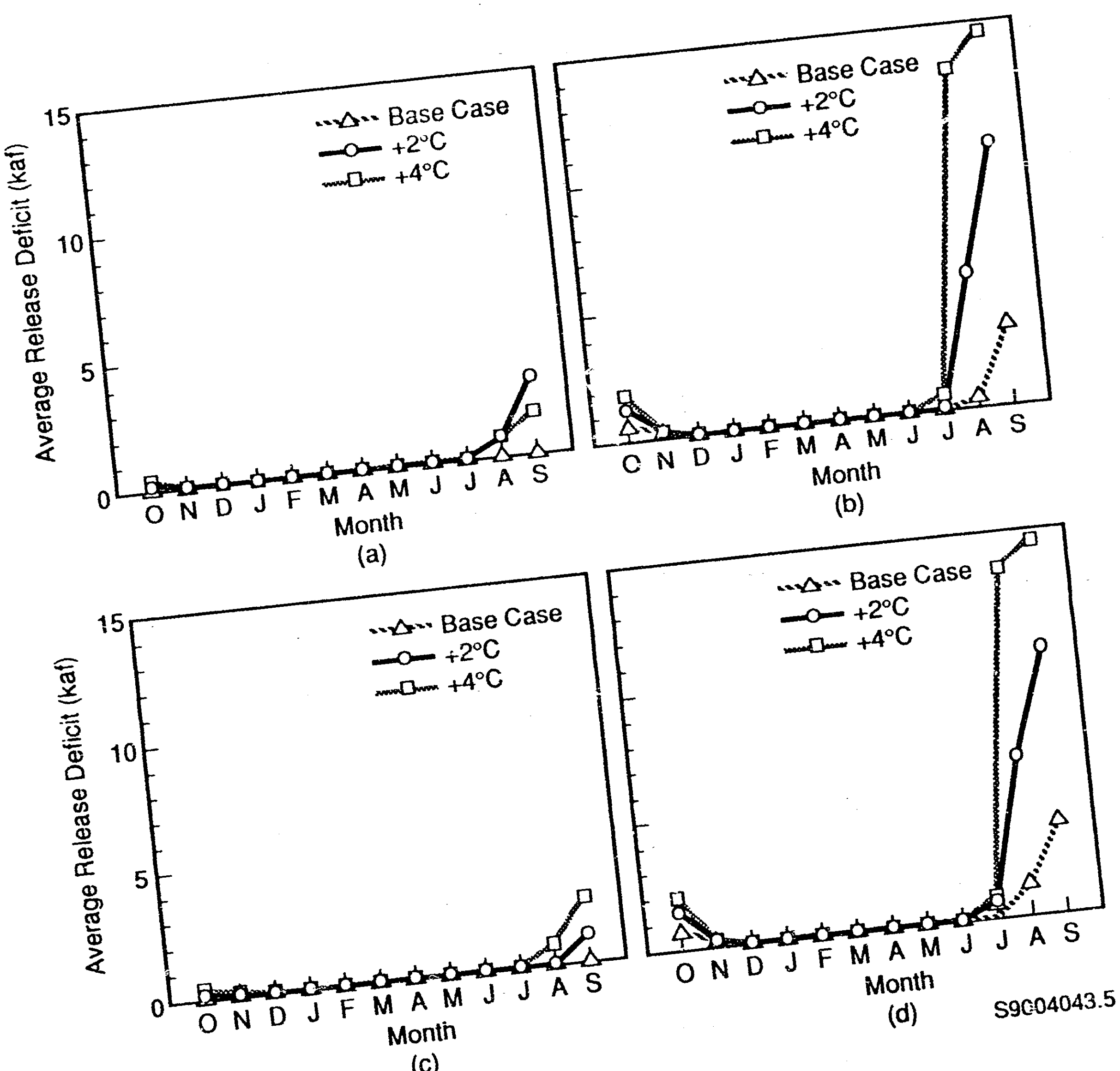


FIGURE 8. Simulated mean monthly release deficits.
a) heuristic operating policy with 0.50 maf reservoir
b) heuristic operating policy with 0.25 maf reservoir
c) ELQGC operating policy with 0.50 maf reservoir
d) ELQGC operating policy with 0.25 maf reservoir

reservoir inflows in late spring and summer. Reservoir storages were lower during the summer under the alternative climates, which led to an increased probability of storage and release failures.

For the 0.50 maf capacity reservoir, both ELQGC and the heuristic operating policy resulted in roughly the same number of storage failures (Figure 6), which had roughly the same average length (Figure 7). Although ELQGC is designed to optimize hydropower revenues while keeping system failures to a minimum, the performance of the algorithm with respect to release failures indicated that it was essentially bound by the storage constraints of the reservoir, and so was about as susceptible to system failure as the heuristic model. The major difference between ELQGC and heuristic operation was that ELQGC had higher monthly releases from October through March, thereby taking advantage of the higher unit hydroelectric revenues during these months. Since the heuristic model releases water based solely on system demand and reservoir inflows, it made its largest releases from May through July, which corresponds to a period of relatively low hydroelectric rates.

For progressively warmer climates, the number of release and storage failures increased for both the 0.50 maf and 0.25 maf capacity reservoirs for both operating policies. Storage and release failures usually occurred in the same month, and were most frequent during late summer and early fall periods of low flow. The majority of all storage and release failures occurred in September and October. For the +2°C climate case for the 0.50 maf reservoir, eight storage failures occurred over the 35-year simulation period for ELQGC operation, and six for the heuristic operation, which represent failure rates of 1.9 and 1.4 percent, respectively. For the 4+°C climate were 20.9 and 20.2 percent, and for the +4°C climate 26.7 and 26.7 percent. Comparison of the specific failures resulting from reservoir operation using the two operating policies showed that not only did the operating policies produce the same number of failures, but the failures almost always occurred during the same years and months. This appears to confirm that both of the operating policies were essentially bound by storage capacity as the warmer climates drove the seasonal runoff distribution toward a strong winter peak.

CONCLUSIONS

Long-term sequences of daily runoff were simulated using deterministic conceptual simulation models for snow accumulation and ablation and runoff for the American River, Washington, an east slope Cascade Mountain drainage. Daily runoff was aggregated to a monthly time step, and was used as input to hypothetical reservoirs of size 0.25 and 0.50 of the maf. The reservoirs were operated for minimum instream flow release (a surrogate for fisheries protection and enhancement), agricultural water supply (summer demand peak), and hydroelectric power generation. Both a heuristic or rule-curve operation and optimal (ELQGC) operation of the system were tested.

The results showed that water supply reliability would be significantly degraded by a shift in the seasonal runoff pattern that would accompany warmer climates, given present precipitation. However, assuming the present winter space heating-dominated peak that is now typical of electric power demand in the Northwest, hydroelectric revenues might increase due to larger releases during the winter peak demand season. The optimization algorithm was able to increase hydropower revenues substantially relative to the heuristic rule under present climate, with the greatest improvement achieved for the larger reservoir size. Under the altered climate, the improvement was less, especially for the smaller reservoir. However, the system's water supply reliability was substantially degraded for the warmer climates, and the degradation was about the same under both operating policies, suggesting that the water supply performance of the reservoirs is controlled more by reservoir storage capacity than the operating policy.

Although not explicitly considered in this study, there was some indication that the optimal operating policy would result in better flood mitigation under warmer climates than would the heuristic policy. ELQGC operation resulted in higher system releases during the winter and early spring, and hence, lower reservoir levels throughout these months. Previous studies have shown that one result of warmer climates on mountainous catchments with presently snow-dominated hydrology might be increased flood hazard. Although the effect of climatic warming on flood operation was not considered here, it will likely be the subject of future study.

ACKNOWLEDGMENTS

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