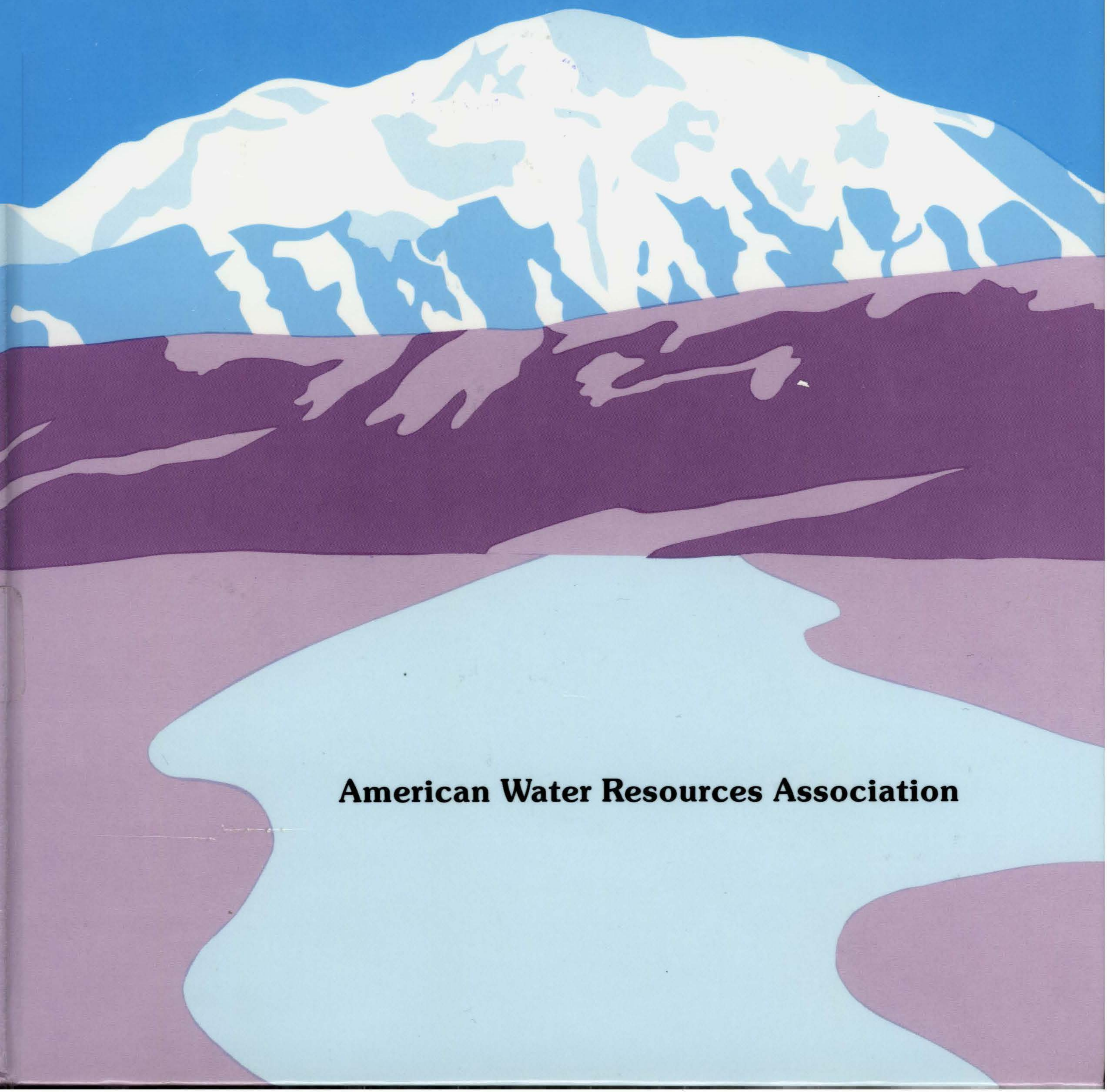
The Susitna Hydroelectric Project simulation of reservoir operations

by Yaohuang Wu, Joel I. Feinstein, and Eugene J. Gemperline .... pages 3-11

Proceedings: Cold Regions Hydrology



American Water Resources Association

PROCEEDINGS

of the

Symposium: Cold Regions Hydrology

UNIVERSITY OF ALASKA-FAIRBANKS, FAIRBANKS, ALASKA

Edited by

DOUGLAS L. KANE
Water Research Center
Institute of Northern Engineering
University of Alaska-Fairbanks
Fairbanks, Alaska

Co-Sponsored by

UNIVERSITY OF ALASKA-FAIRBANKS
FAIRBANKS, ALASKA

AMERICAN SOCIETY OF CIVIL ENGINEERS
TECHNICAL COUNCIL ON COLD REGIONS ENGINEERING

NATIONAL SCIENCE FOUNDATION

STATE OF ALASKA, ALASKA POWER AUTHORITY

STATE OF ALASKA, DEPARTMENT OF NATURAL RESOURCES

U.S. ARMY, COLD REGIONS RESEARCH
AND ENGINEERING LABORATORY

Host Section

ALASKA SECTION OF THE AMERICAN WATER RESOURCES ASSOCIATION

The American Water Resources Association wishes to express appreciation to the U.S. Army, Cold Regions Research and Engineering Laboratory, the Alaska Department of Natural Resources, and the Alaska Power Authority for their co-sponsorship of the publication of the proceedings.

American Water Resources Association

5410 Grosvenor Lane, Suite 220
Bethesda, Maryland 20814

COLD REGIONS HYDROLOGY SYMPOSIUM
JULY AMERICAN WATER RESOURCES ASSOCIATION 1986

THE SUSITNA HYDROELECTRIC PROJECT SIMULATION OF RESERVOIR OPERATION

Yaohuang Wu, Joel I. Feinstein, and Eugene J. Gemperline[1]

ABSTRACT: This paper presents the general concept and methodology used in the simulation of reservoir operation, which played an important role in the study of the Susitna Hydroelectric Project. The objective of the simulation was to find optimum operation rules which would meet projected energy requirements of the Alaska Railbelt, while at the same time satisfying flow regimes which would maintain habitat for resident and anadromous fish. Computer models were used for the simulation of reservoir operation on a monthly, weekly, and hourly basis, using streamflow records of 34 years. The results of the simulation allowed the selection of a preferred flow regime which could meet the projected energy requirements and also provide no net loss of habitat for the fish.
(KEY TERMS: reservoir operation modeling; rule curve; operating guide.)

INTRODUCTION

The proposed Susitna Project consists of two tandem reservoirs on the Susitna River. The two proposed dam sites are the Watana site, a rockfill dam to be located at river mile 184 of the Susitna River, and the Devil Canyon site, a concrete arch dam 32 miles downstream from the Watana site as shown in Figure 1. The project would operate by storing the high natural flows in the summer for release during low flow periods in the winter when the energy demand is high. This alteration of the natural flow pattern would affect the quantity and availability of spawning, incubating, and rearing habitat for fish,

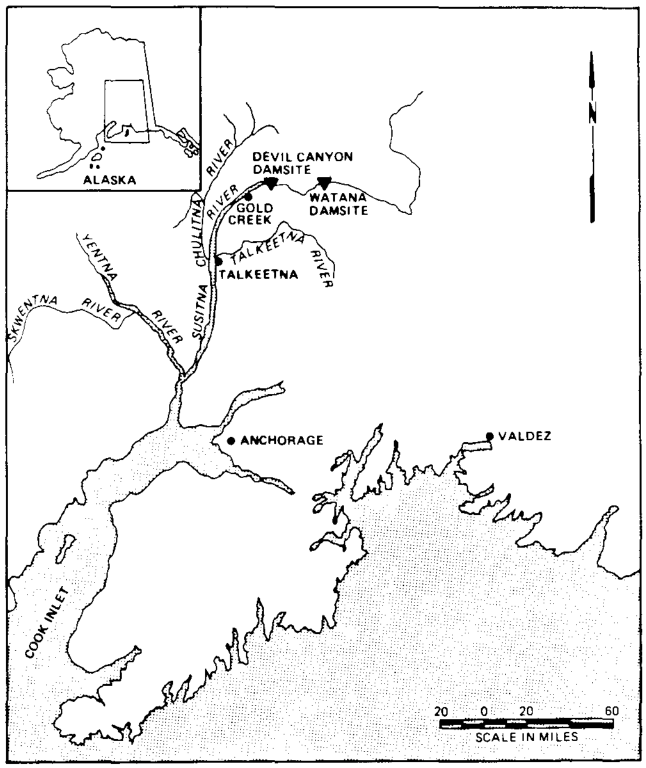


Figure 1. Susitna Project Location Map

[1] Respectively, Principal Engineer, DeLeuw, Cather and Company, 525 Monroe Street, IL 60606 (formerly Senior Power Planning Engineer of Harza Engineering Company); Power Planning Engineer, Harza Engineering Company, 150 South Wacker Drive, Chicago, IL 60606; and Manager of Hydrologic and Hydraulic Studies, Harza-Ebasco Susitna Joint Venture, 711 H. Street, Anchorage, AK 99501

primarily in the middle reach of the river. The impounding of water in the reservoirs and the alteration in flow patterns would also change water quality parameters associated with mainstem flow such as water temperature, turbidity, and suspended sediment. The simulation of water temperature, ice formation, and suspended sediment were conducted in a series of separate studies using the reservoir water levels and discharges from the reservoir operation study.

To mitigate the impacts on chum salmon spawning and incubation in side sloughs and chinook salmon rearing in side channels, eight different flow regimes were developed for evaluation (Alaska Power Authority, 1985). Each of the flow regimes was designed to provide a given amount of habitat for the fish species. Each flow regime consists of a series of weekly maximum and minimum flows through a year keyed to chum and chinook salmon life cycles. The maximum or minimum flows were specified at the Gold Creek station, which is located 15 miles downstream of the Devil Canyon site. Figure 2 shows the E-VI flow regime which was selected as the preferred alternative. Minimum summer flow requirements would provide flow stability and would maintain a minimum watered area for salmon habitat. Maximum winter requirements would provide flow stability and would minimize the potential for winter water levels to overtop side slough habitats affecting incubating and rearing chum salmon.

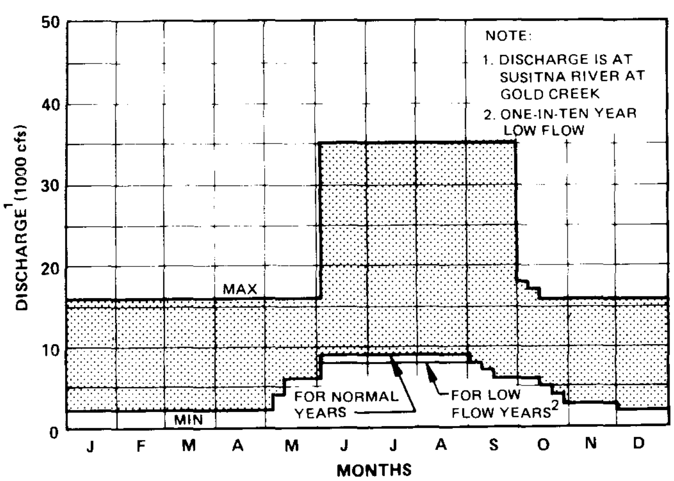


Figure 2. Environmental Flow Requirement, Flow Regime E-VI

The evaluation of the flow regimes was carried out by estimating the total cost to meet the projected Railbelt energy demand. These include capital and operating costs of the Susitna Hydroelectric Project, other generating facilities, and any mitigation measures required to meet the objective of no net loss of habitat value. Among the mitigation measures included in the evaluation of the alternative project flow regime were hatcheries and multi-level intakes for temperature and sediment control. Since the maximum and minimum flow constraints of the alternative flow regimes would restrict the seasonal distribution of Susitna energy production, the construction and operation of additional power plants to meet the system demand were also considered.

RESERVOIR OPERATION SIMULATION

Reservoir operation models simulate the reservoir storage, power generation, turbine discharge, valve release, and flood release as a function of time based on reservoir and power plant characteristics, power demand distribution, and environmental constraints. Cone valves may operate at each dam to satisfy an instream flow requirement or to keep the water surface elevation at the normal maximum level without having to use the spillway. These simulations are normally undertaken in two parts; long-term simulation and short-term simulation (Dondi and Schaffe, 1983). The long-term simulation for the Susitna Project uses a monthly program and a weekly program for simulating the operation for 34 years of streamflow record. The monthly program was used to determine the overall trend, while the weekly program was used for refinement of operation rules and to understand the behavior of the reservoirs and flows during critical periods. The short-term simulation used an hourly program to simulate the operation over a week, using the output from the weekly simulations as input data. The hourly program was designed for simulation of hourly generation to meet the daily peak and off-peak loads.

The monthly operation used a single rule curve as an operation guide to estimate the annual energy production and to satisfy the monthly instream flow requirements. A rule curve indicates the desired reservoir water level in different months. The weekly operation program used an operation guide for seasonal adjustment of flows which produce a series of reservoir outflows with gradual changes. Operation guides consist of a series of rule curves to control the reservoir outflow. The hourly operation program used an hourly load curve as the upper limit of possible generation. The load curve was based on actual hourly load data and a load forecast. This program tested how well the energy obtained from the long term analyses could fit the hourly load curve, subject to environmental restrictions on the daily and hourly flow changes.

Power and energy production from the monthly simulation of the Susitna Project was used in the Railbelt expansion planning studies, which in turn was used in both the economic and financial analyses. Although monthly simulations were sufficient for these studies, they were not adequate to estimate environmental effects. Therefore, a simulation with a weekly time step was needed to generate input data for subsequent computer models used in the environmental impact studies. Other environmental studies required hourly discharge to estimate river stage fluctuations.

The monthly program was originally developed by Acres American for the Susitna feasibility study (Alaska Power Authority, 1982) and later improved by Harza-Ebasco Susitna Joint Venture. The weekly program was developed by Harza-Ebasco by using parts of the monthly program. The hourly operation program was developed by Harza-Ebasco. All of the programs were written in Fortran IV.

The Susitna project was scheduled to be built in three stages. First an initial Watana Project would be developed, followed by construction of Devil Canyon downstream. Finally, Watana would be raised to its ultimate height. The full reservoir areas for the low and high dams at Watana would be 19,900 and 38,000 acres respectively, and 7,800 acres at Devil Canyon. Because of the large reservoir surface area at Watana, release of a large quantity of water would cause a relatively small change in the project head. In contrast, Devil Canyon would have a small surface area, and would hence lose considerably more head for the same volume of release. Consequently, the reservoir operation methodology attempted to keep the Devil Canyon reservoir close to its normal maximum operating level while using Watana's storage to provide the necessary seasonal regulation. Therefore, the modeling effort in both the single and double reservoir operation in monthly and weekly simulation was focused on the Watana operation. The operation levels of the reservoirs for the various stages are shown on Table 1.

Table 1

OPERATION LEVELS

	Minimum Level (ft)	Normal Maximum Level (ft)	Environmental Surcharge Level (ft)	Nominal Plant Capacity (MW)	On-line Date
Watana Low Dam	1850	2000	2014	440	1999
Watana High Dam	2065	2185	2193	1110	2005
Devil Canyon	1405	1455	1455	680	2012

MONTHLY OPERATION MODEL

Monthly reservoir simulations were carried out to optimize project energy production subject to environmental flow requirements. The rule curve which would optimize energy production was determined by trial and error. The optimal energy production is a function both of the firm energy and total energy. Figure 3 shows a sample rule curve of the Watana reservoir.

During the simulation in each time step, the reservoir release has to satisfy the firm energy and environmental minimum flow requirement. If the end-of-month water surface elevation is lower than the corresponding rule curve elevation, only firm energy is produced and no additional water is released. If the end-of-month water surface elevation is higher than the rule curve elevation, the water stored between these two elevations is released to generate secondary energy up to the system energy requirement.

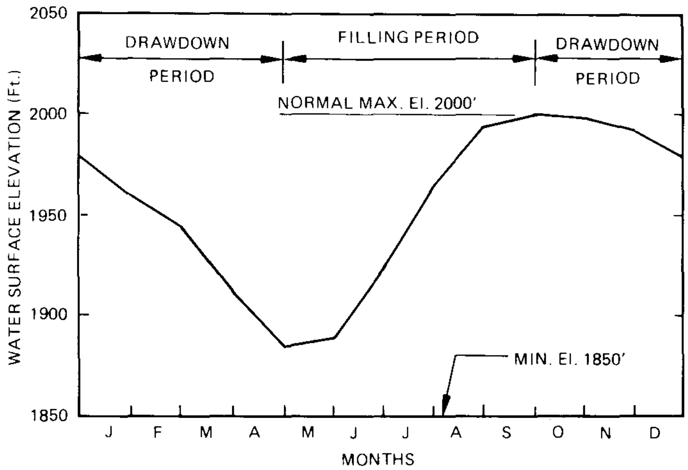


Figure 3. Example Rule Curve For Watana Operation, Year 2004

The dry season is from October to April and the wet season from May to September, as shown in Figure 4. The rule curve elevation at the end of September is at the normal maximum pool elevation because the reservoir is expected to be full at

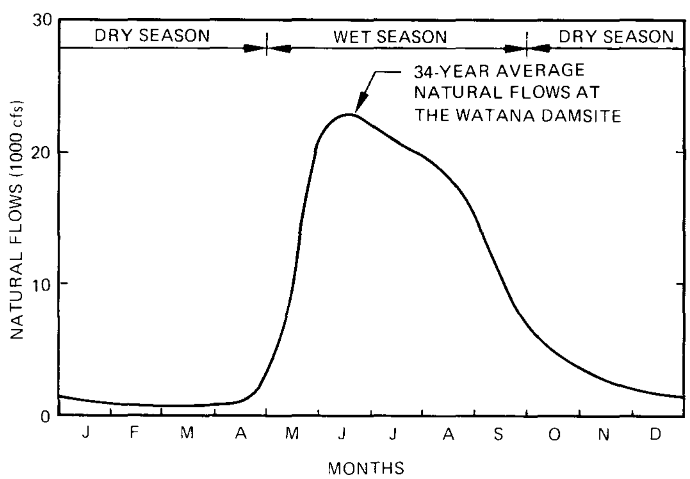


Figure 4. Natural Flows at Watana

the end of the wet season. In contrast, the rule curve elevation at the end of April is at its minimum because the drawdown is required for firm energy production in the dry season. The higher the minimum rule curve elevation (at the end of April), the greater the firm energy production. This is because the reservoir levels would be kept relatively higher and the storage available for firm energy would be more in the drought period. Alternatively, the lower the rule curve, the greater the total energy production. This is because there would be more active storage for flow regulation and less amount of spills on a long term basis. Various sets of rule curve elevations with various minimum elevations will give different values of firm energy and total energy. The acceptable minimum rule curve elevation for the Susitna Project was selected based on an operation in which the increase of total energy is about one percent when lowering the minimum elevation by five feet.

Once the maximum and minimum rule curve elevations were determined, the rest of the rule curve elevations were determined by a trial and error procedure to obtain an acceptable distribution of energy through the year. The operational strategy was to capture additional economic benefits through adjustments of the Susitna generation by leaving the residual thermal generation during each of two periods, the summer filling period and the winter drawdown period. As stated above, the reservoir would be almost full at the end of September and would be at the lowest levels at the end of April. Therefore, Susitna energy distribution during the filling period, May to September, and during the drawdown period, October to April, could be varied as a function of reservoir water surface variation without reducing total project energy production. It was assumed that it would be more economical to provide thermal energy by running the least-cost thermal units throughout a whole period rather than running them for part of the period along with other less efficient units. Also the system was assumed to be more reliable if the thermal requirement would be about the same from month to month. This would mean that investment in additional thermal capacity could be delayed as long as possible. Therefore, the energy distribution was adjusted so that the Susitna energy production would maintain constant thermal generation in both the filling period and the drawdown period as much as possible.

The analysis of the project's benefits was based on its ability to meet energy requirements. These requirements were the total projected Railbelt system energy demand minus the energy production of existing hydroelectric facilities. Figure 5 shows the monthly distribution of energy requirements, and also indicates how the Susitna energy would be distributed throughout the year.

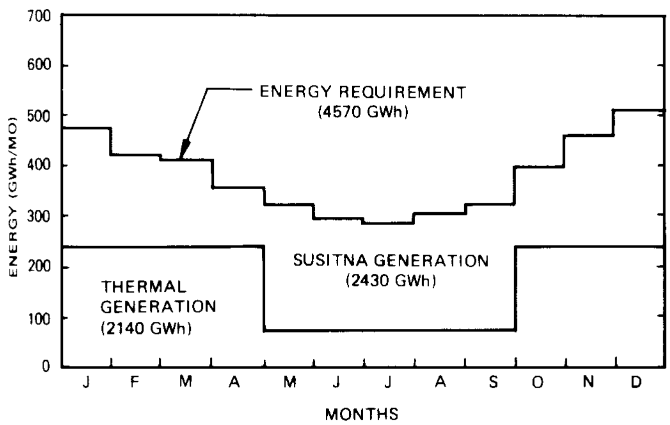


Figure 5. Monthly Energy Distribution, Watana, Year 2004

The rule curve approach is predictive because it attempts to achieve an end-of-month elevation which presumes some knowledge of the expected reservoir inflow during that period. The operation guide approach, which will be discussed below in conjunction with the weekly program, is non-predictive because it specifies a discharge rate through the powerhouse based on the reservoir elevation at the beginning of the period. The rule curve approach is easy to apply for simulation but can be operationally difficult to achieve, because reservoir inflows are difficult to accurately forecast. The operation guide approach is more difficult to model, but more closely approximates how the project would actually operate. The two approaches yielded similar power and energy results in many trial runs, so the monthly model (rule curve approach) was used for the economic and financial analyses in selection of the best scheme. The rule curve approach could not be used in the weekly simulations for the environmental studies because the release of the storage above the rule curve elevation for the secondary energy could cause an unrealistic change of discharge between two consecutive weeks. The operation guide in the weekly simulation was designed to prevent these large changes.

WEEKLY OPERATION MODEL

The weekly operation model was primarily designed for simulation based on the operation guide. An operation guide is composed of a series of rule curves which are used as a guide for determining the turbine discharge in each week during the simulation. An example operation guide is shown on Figure 6. Each guide has two families of rule curves; increasing curves and decreasing curves. Each curve defines the reservoir level at which the powerhouse discharge should increase or decrease to a specified percentage rate of the expected powerhouse discharge. These specified percentage rates are in 20% intervals. The expected powerhouse discharges are a set of weekly discharges which would produce an expected distribution of energy production over a year. The single rule curve operation is based on the target firm energy; however, the operation guide uses 60% of the expected powerhouse discharge as the minimum discharge and 140% as the maximum normal discharge.

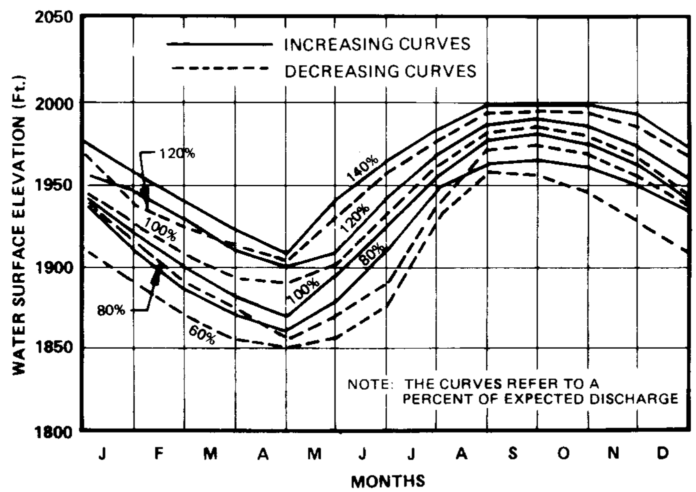


Figure 6. Operation Guide For Watana Operation, Year 2004

At the beginning of each simulation week, these curves are used to determine whether the current discharge rate is kept the same, increased to the next higher rate, or decreased to the next lower rate. The water surface elevation at the beginning of the week is put on the operation guide and compared with the elevations of increasing and decreasing curves. If the water surface elevation is higher than the elevation of the increasing curve of the next higher rate, the discharge is increased to that rate. If the water surface elevation is lower than the elevation of the decreasing curve of the next lower rate, the discharge is decreased to that rate. Otherwise, the discharge is kept the same. The change of rates in two consecutive weeks is limited to 20%. For example, if the discharge rate is at 100% of the expected powerhouse discharge in the preceding week, the rate may be changed to either 80% or 120% or stay at 100%. Because of the difference in elevation between the increasing curve of the next higher rate and the decreasing curve of the next lower rate, the rate will generally be kept the same for a few weeks. In contrast with the simulation using a single rule curve, an operation guide will give an outflow hydrograph with relatively gradual changes in the discharges.

A smooth curve giving the energy requirements throughout the year is shown on Figure 7. The average energy production of the Susitna Project in the drawdown and filling periods was determined from the monthly simulation. Similar to the monthly modeling, efforts were made to capture the additional economic benefits by leaving the thermal generation constant in both the drawdown period (October to middle May) and the filling period (middle May to September). In weekly runs the reservoir level is the lowest in the middle of May and full in most years at the end of September. The energy production in these two periods are inexchangeable, but redistributing energy production within either period does not cause additional valve and spillway releases or flow deficits. Adjustments of energy production within either period by leaving thermal requirements constant was assumed to increase the economic value of the project. Gradual changes of thermal energy requirements at the boundaries of the filling and drawdown periods were considered for a smooth transition of the operation. The resulting weekly distribution of energy production over a year was used for computation of the weekly expected powerhouse discharge.

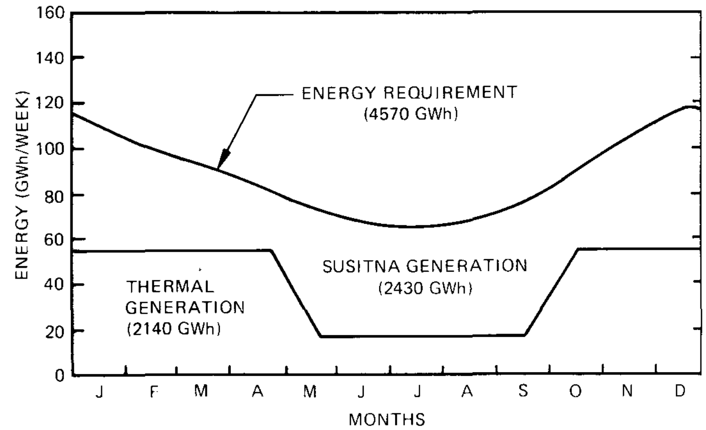


Figure 7. Weekly Energy Distribution, Watana, Year 2004

Development of an operation guide is an iterative process. An assumed set of rule curves for the operation guide were put into simulation initially to find flow deficits resulting from not satisfying the minimum flow constraints or from discharging less than the minimum powerhouse discharge (60% of expected discharge in the example). The curves were then gradually improved by satisfying these two requirements through the whole simulation period. The curves were again adjusted to maximize the average energy production and improve the energy distribution through the year. A good operation guide should provide: 1) turbine discharges close to the expected powerhouse discharge, 2) discharge rates generally constant for a period of at least several weeks, and 3) average energy production maximized.

Figure 8 shows the historical inflow hydrograph at Watana. Figure 9 shows the simulated outflow hydrograph of Watana operation for the load year 2004. The comparison of duration curves between the pre-project and post-project flows at Gold Creek Station is shown on Figure 10. Note that, through flow regulation by Watana, the high flows in summer would be substantially reduced and the low flows in the winter would be increased for power generation. The simulated outflows from Watana were, in general, consistent with the expected discharges and there were no rapid changes of discharge except those during floods.

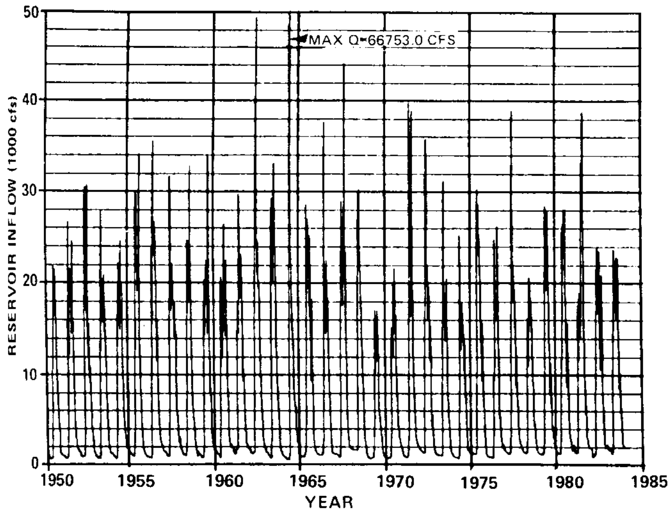


Figure 8. Watana Inflows

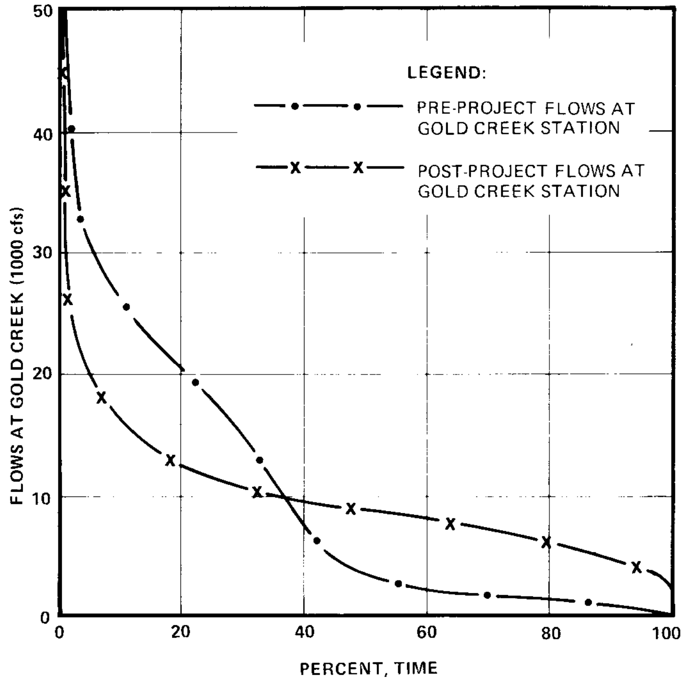


Figure 10. Duration Curves of Flows at Gold Creek

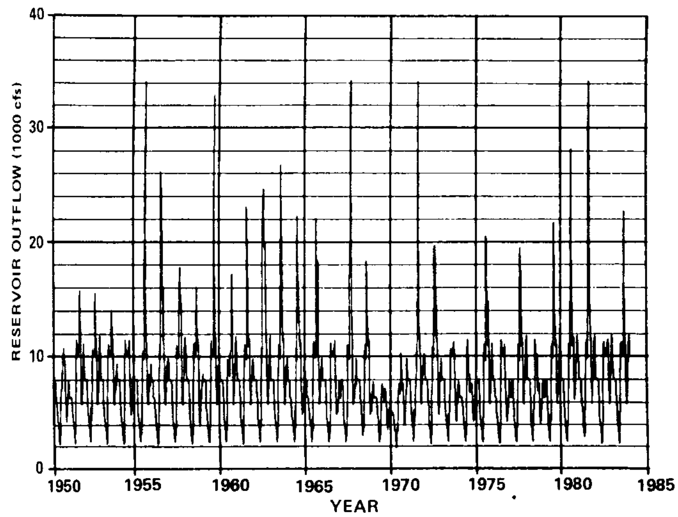


Figure 9. Watana Outflows, Stage I, Load Year 2004

HOURLY OPERATION MODEL

The hourly program modeled a reservoir operation over a week, using an hourly load curve (for the demand distribution within a week) as the upper limit of possible generation and discharges from the results of weekly simulation as input data. Outflow fluctuations were restricted by maximum hourly and daily variation constraints. The model tests how energy obtained from the long term analyses can fit the hourly variation of demand with environmental constraints. The output was used in river stage fluctuation studies. An example of the output is plotted as shown in Figures 11 and 12 to aid in understanding the results. Figure 11 contains a plot of generation showing the system demand, the existing hydro generation, and Susitna Project generation. Figure 12 shows the reservoir discharge through the powerhouse and the valves, and the minimum flow required to meet the environmental requirements at Gold Creek.

The reservoir outflow constraints limit how the plant can operate in the system. For example, if the daily variation constraint is very small, then the plant is essentially base loaded, but if both hourly and daily variation constraints are large, the hydro plant can load follow. Load following operation means that the plant can increase or decrease its generation by following the hourly fluctuation of the system demand, and will leave the

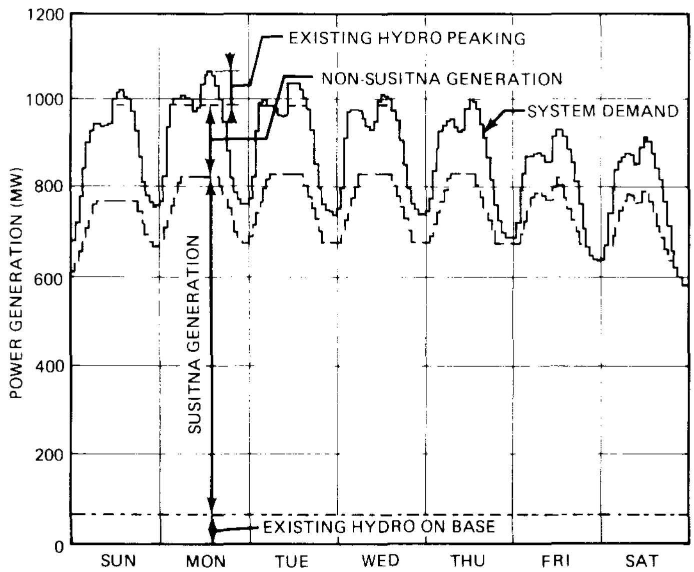


Figure 11. Hourly Power Generation

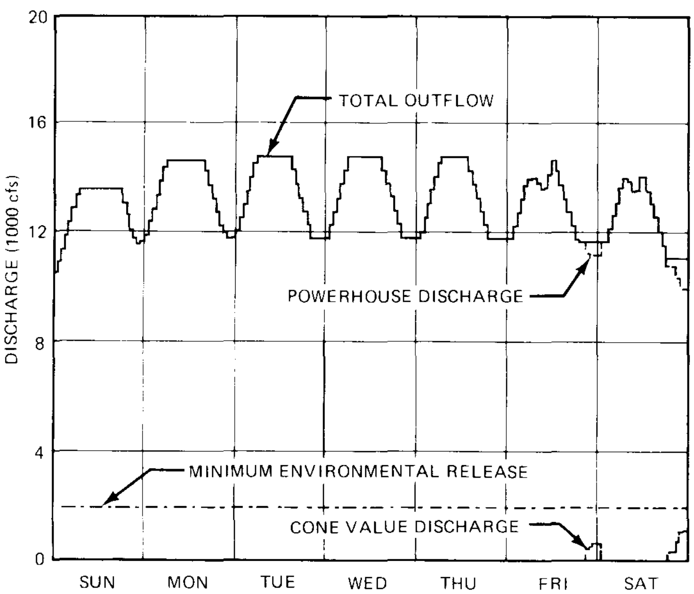


Figure 12. Hourly Reservoir Discharge

energy from other sources at constant capacity. Base loaded operation means that the plant generation is constant in principle, but a certain percentage fluctuation may be allowed. Load following operation would provide more capacity value for the project than base loaded operation. Base loaded operation would provide stable flows in the downstream channel. Project operation is currently constrained to be base loaded with allowable variations of 20% in total project discharge within a week, therefore, providing stable flows and minimizing impacts to salmon.

Chum and sockeye salmon spawn in sloughs along the river. These sloughs collect sediment and organic matter throughout the normal course of the year, which make it difficult for the fish to spawn and may reduce egg survival. Naturally occurring floods clean out the sloughs and thus provide better habitat. The dams would tend to reduce these naturally occurring floods which may decrease the natural fish habitat. Some of the flow regimes incorporate spikes of flow to create artificial floods to clean the sloughs. The hourly program can also model these spikes as instream flow requirements at Gold Creek.

Input to the hourly model consists of the initial storage at the beginning of the week and the amount of water to be released during the week (obtained from the results of the weekly simulation). The program generates a curve called a template for use as a guide in simulation of hourly power generation. The first template is equivalent to the hourly system load minus the existing hydro production. Turbine release in each time step is determined from the energy requirement of the template. The turbine release is then checked with the flow constraints and the total release is adjusted to satisfy the constraints if there is any violation. After the first iteration with the template, the template is adjusted according to the ratio of the amount of water to be released and the total outflow in the previous iteration. The simulation is iterated with new templates until the outflow for the week is equal to the amount of water to be released for the week.

The hourly program modeled a single reservoir. When the Devil Canyon reservoir is in operation, the Watana plant will load-follow and the Devil Canyon plant will be base loaded. Therefore, the release from Devil Canyon would be stable and the variation of discharge on the downstream channel could be easily controlled. Because of low flow from Watana in off-peak hours and high flow in peak hours, Devil Canyon will draw down in off-peak hours and fill in peak hours. The maximum drawdown for daily fluctuation at Devil Canyon was estimated at one-half foot.

The hourly program as well as the weekly program have provisions for flood operation. During a large flood when the reservoir is full, the reservoir inflow could be greater than the sum of turbine and valve capacities. If the spillway is used, nitrogen would be entrained in the water and there would be the potential for nitrogen concentration to exceed tolerable levels. In order to minimize use of the spillway, the reservoir is allowed to surcharge above the normal maximum level up to an environmental surcharge level. The environmental surcharge for Watana low dam would be 14 ft and that for Watana high dam would be 8 ft. These levels were determined on the basis of avoiding the use of the spillway in a flood of less than a 50-year return period. The spillway would not be open unless the water surface elevation reaches the environmental surcharge level.

In non-flood operation the valves would not release water unless it is necessary for the instream flow requirements. When the water surface elevation is at or above the normal maximum level, the excess water would be released from the valves. As the water starts to surcharge above the normal maximum level in a flood, the total outflow could be increased hourly at a special flood rate, designed to minimize impacts on the fishery from changes in flow and temperature, until the valves are fully open. However, the outflow would never be allowed to be greater than the peak discharge of inflow. As stated previously, if the water surface elevation reaches the environmental surcharge level, the spillway would be opened for release so that the outflow would be equal to inflow. The falling limb of the outflow hydrograph would also be constrained by an hourly decreasing rate for flood operation.

CONCLUSION

The monthly simulation with rule curve operation is simpler and less expensive than the others. It was effectively used in the economic analysis of the project.

The weekly simulation with the operation guide more closely simulates the discharge variations for the studies of environmental impacts. The operation guide restricts the discharge variation in a specified limit to secure the protection of fishery habitat. The simulation with the weekly model was successfully used for the evaluation of the flow regimes.

The hourly simulation was used to test how the energy obtained from the weekly analysis could fit the hourly load curve. It was also used for the study of peaking capacity with respect to the allowable fluctuation of discharge in the downstream channel.

Monthly, weekly, and hourly operation models are all indispensable in the study of the Susitna Hydroelectric Project.

REFERENCES

Alaska Power Authority, 1985. Case E-VI Alternative Flow Regime, Susitna Hydroelectric Project, Volume 1 - Main Report, Document No. 2600.

P.H. Dondi and G. Schaffe, 1983. Simulation and Optimization of a Series of Hydro Stations, Water Power and Dam Construction, Nov. 1983.

Alaska Power Authority, 1982. Feasibility Report, Susitna Hydroelectric Project, Volume 1, Engineering and Economic Aspects.