ANALYSIS OF INFORMATION SYSTEMS FOR HYDROPOWER OPERATIONS

Jet Propulsion Laboratory

A REPORT TO
THE OFFICE OF
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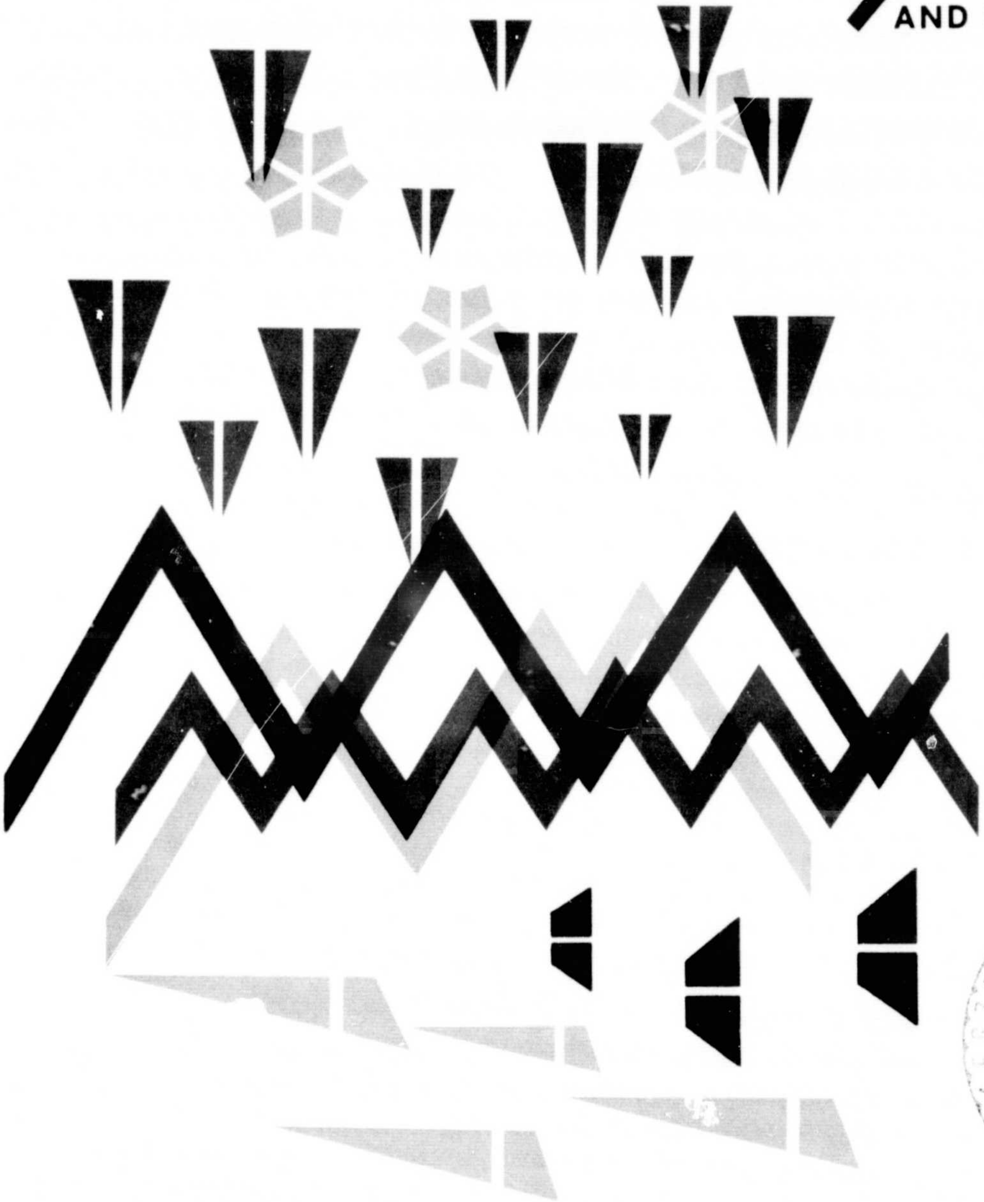
NATIONAL AERONAUTICS
AND SPACE ADMINISTRATION



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ANALYSIS OF INFORMATION SYSTEMS FOR HYDROPOWER OPERATIONS – EXECUTIVE SUMMARY

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ABSTRACT

An analysis has been performed of the operations of hydropower systems, with emphasis on water resource management, to determine how aerospace derived information system technologies can effectively increase energy output. Better utilization of water resources was sought through improved reservoir inflow forecasting based on use of hydrometeorologic information systems with new or improved sensors, satellite data relay systems, and use of advanced scheduling techniques for water release.

Specific mechanisms for increased energy output were determined, principally the use of more timely and accurate short term (0 - 7 days) inflow information to reduce spillage caused by unanticipated dynamic high inflow events. The hydrometeorologic models used in predicting inflows were examined in detail to determine the sensitivity of inflow prediction accuracy to the many variables employed in the models, and the results used to establish information system requirements. Sensor and data handling system capabilities were reviewed and compared to the requirements, and an improved information system concept outlined.

The results of the study are presented in the Executive Summary contained herein. The detailed results and methods of analysis are given in a companion volume, JPL 5040-44.

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CONTENTS

EXECUTIVE SUMMARY

The purpose of this document is to summarize and provide a framework that unifies the diverse segments of the analysis. As such, it serves as an Executive Summary with conclusions and recommendations, and as a guide to the study approach and methodology.

General Objectives and Scope

The general objective of this study was to analyze the operations of hydropower systems, with emphasis on water resource management, to determine how aerospace derived information system technologies can effectively increase energy output. Better utilization of water resources was sought through more accurate reservoir inflow forecasting based on use of hydrometeorologic information systems with new or improved sensors, satellite data relay systems, and use of optimal scheduling techniques for water release.

Study Approach

The principal guideline for the study approach was to develop a qualitative and quantitative understanding of the interrelations between hydropower operations and the supporting hydrometeorologic information systems. To accomplish this, specific mechanisms for improving energy output were determined, primarily the use of more timely and accurate inflow information to reduce spillage due to short term high inflow events. (This type of spillage is a dominant loss factor for a major class of hydropower installations.)

The present study differs significantly from the prior studies both in the methods for reducing spillage, and consequently, in the analysis approach. Prior studies have concentrated primarily on the seasonal aspects of spillage; percentage reductions in total seasonal spillage were assumed, and cost benefits derived on the basis of these reductions. Specific mechanisms by which improved information systems could bring about these reductions were not defined, however, improved predictions of long term, seasonal precipitation are implied. Improvements in such predictions are quite speculative at present, and detailed, quantitative analyses of advanced information systems for this purpose are somewhat premature. This in fact has been the dilemma encountered in prior studies.

The present study established at an early stage in the analysis that, for a large number of major reservoirs, spillage is a dynamic, short term phenomenon attributable to unanticipated high inflow events. This type of spillage can be reduced in direct proportion to the number of days of anticipation (0 to 20 days) and to the accuracy of the inflow forecast. By defining the problems in these terms, specific methods for reducing spillage could be identified and their potential assessed. Basically, two techniques are useful for short term inflow prediction: the first is weather forecasting, and the second, use of empirical modeling techniques to simulate runoff from the snowpack and ground hydrologic system. Both techniques provide estimates of the amount and time of arrival of inflow (in most watersheds, moisture input to the snowpack/ ground hydrologic system requires several days to reach the reservoir). Both processes can be modeled. Further, we can establish the sensitivities of the model outputs to errors in the measured variables. These sensitivities form the basis for sensor and overall information system requirements: which variables must be measured, with what accuracies and how frequently; what is the desired density of the sensor network; how quickly must the inflow predictions be disseminated to the hydropower operators; and, what modifications to the models would improve the predictions. Finally, having determined sensor requirements, sensor capabilities can be compared to requirements, and a sensor set selected that best meets these requirements.

This approach has been used in the present study to define in a quantitative manner the spillage loss mechanisms and the benefits that can reasonably be expected from improved information/sensor systems, and to provide guidance for sensor R&D programs and the supporting data acquisition, transmission, processing and dissemination subsystem developments. The analysis activities were supplemented by many contacts with industry and government hydropower operators, who provided much useful data as well as the basic computerized hydrometeorological models; the latter are particularly valuable because they are based on actual operational policies and constraints.

For convenience in presenting the results of the work, the analysis tasks are described below:

1) Characterize hydropower operations relating to energy production. (Hydropower generation is governed by a variety of water release constraints, and a high degree of variability in the water inflow to the reservoir.)

2) Identify mechanisms responsible for less-than-optimum production, principally spillage resulting from lack of timely and accurate inflow information. Estimate benefits derivable from the forecast of high inflow events, and resulting reduction in spillage. (The reduction in spillage for a major class of reservoirs is shown to be related to the number of days of anticipation of high inflow events, and to the accuracy of inflow forecasts.)

3) Identify the principal processes that contain information about the time of arrival and magnitude of high inflow events, primarily the meteorologic and watershed ground and snowmelt runoff processes. Acquire models of the hydrometeorologic processes (weather forecast and ground/snow hydrologic models) from industry and government sources.

4) Determine the sensitivities of the hydrometeorologic models to uncertainties or errors in the model variables, i.e., influence of sensor system accuracy on the accuracy of predicted inflow magnitude and arrival time.

5) Establish information/sensor system requirements to achieve a desired accuracy in inflow prediction.

6) Survey the capabilities of state of the art and advanced information/sensor system elements to determine feasible concepts for improved information systems.

7) Develop an improved information system concept.

This approach to the analysis of hydropower systems is reflected in the following discussion.

Characteristics of Hydropower Operations

Major hydropower storage reservoirs in the United States must operate efficiently with inflow rates that can vary greatly from month to month and season to season. In addition, releases from the reservoirs are governed by a number of constraints relating to the delivery of power, delivery of water for irrigation, navigation, water quality control, etc., and the observance of adequate flood reservations. A number of important aspects of hydropower operations are shown in Figure 1.

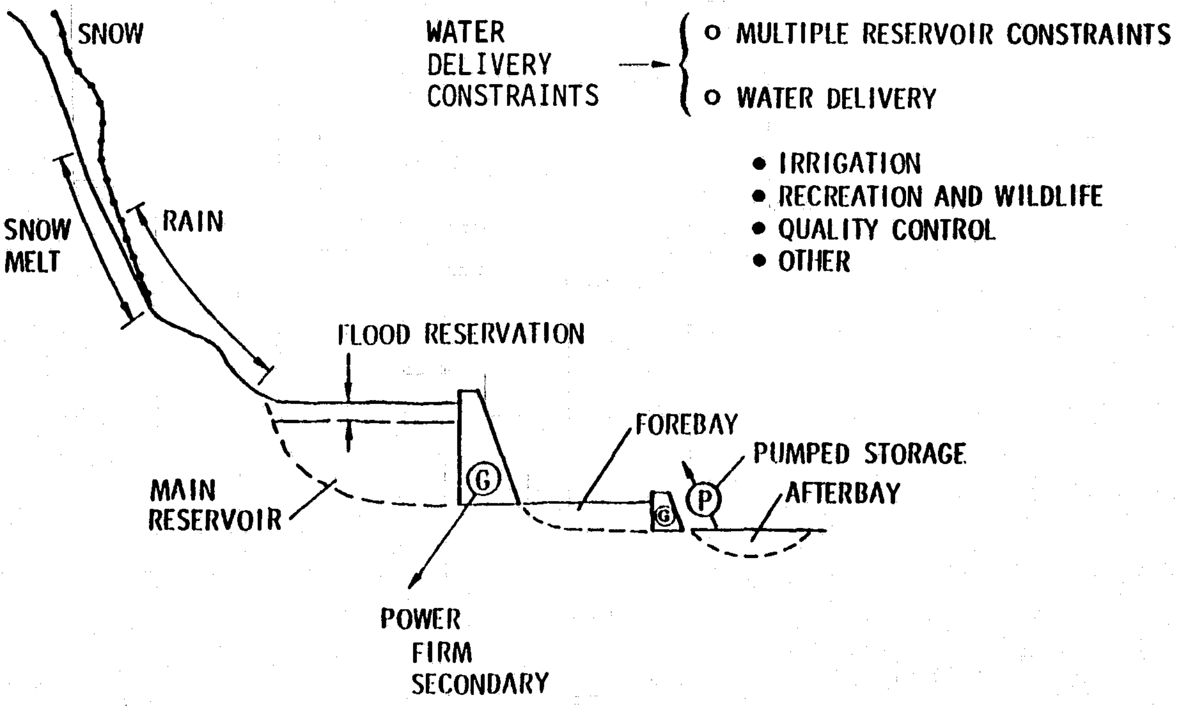

Figure 1. Hydroelectric Power System.

Sources of inflow to the hydropower system include melt from snowpacks, rain, and drainage from the ground hydrologic system. Each source of inflow has a characteristic lag time that is dependent on the physical characteristics of the basin and on the state of the snow and ground hydrologic systems; knowledge of these lag times can be of use in scheduling water releases for the reservoir, but they are difficult to measure because of the complex, non-uniform topography of the basin.

Of the numerous constraints, the flood reservation rules are vigorously enforced; federal laws govern the use of the reservoirs constructed with federal funds, and stipulate that a prime consideration in reservoir management is prevention of flooding, or minimization of damage due to flooding through use of flood plains in conjunction with the reservoirs. Flood rules are established for each reservoir on the basis of historical inflow records, and typically specify storage volumes that must be set aside to accommodate peak inflows, given the current storage levels, expected inflows, and surface moisture conditions. The set aside volumes can be a significant fraction of the active storage available in the reservoirs.

The reservoir operator usually is contractually obligated to produce specified amounts of power and energy during a season, based on historical records of water availability; this is known as firm power. Contracts are also taken for secondary power delivery, contingent upon water availability. Target deliveries are established for each month and each day; release schedules are made down to the hourly level.

The basic advantage of hydropower generation is the relative ease of varying the power output level, in contrast to large fossil-fueled nuclear generation systems that are operated at fixed output when possible. In mixed systems using both hydropower and fossil-fuel or nuclear generation units, the hydropower generators are used to provide peak loads, thus permitting the fossil/nuclear plants to run at constant output near peak efficiency. In fact, the economies of operation are such that many reservoirs have been equipped to operate in a pumped energy storage mode, in which water releases from the main reservoir to meet peak loads are retained in an afterbay and pumped back into the main reservoir during periods of lower power demand. Power can be purchased from the system at a relative low rate for this purpose.

Water delivery constraints and agreements are noted in Figure 1. Additional constraints can be imposed for multiple-reservoir systems such that releases from upstream reservoirs do not exceed inter-reservoir channel capacities, or impair downstream reservoir operations.

Figure 2 illustrates a major difficulty in scheduling water releases caused by the wide variation in inflow during the course of a season. Typically, inflow is at a minimum during the late summer and early fall months, when the snowpack is depleted and rainfall is at a seasonal low. The snowpack accumulates during the winter months, but may not contribute significantly to inflow because little if any melt occurs during this period. During the spring months, considerable rainfall may occur, and with the onset of warm weather and heavy snowmelt, inflows tend to peak sharply during a relatively short period

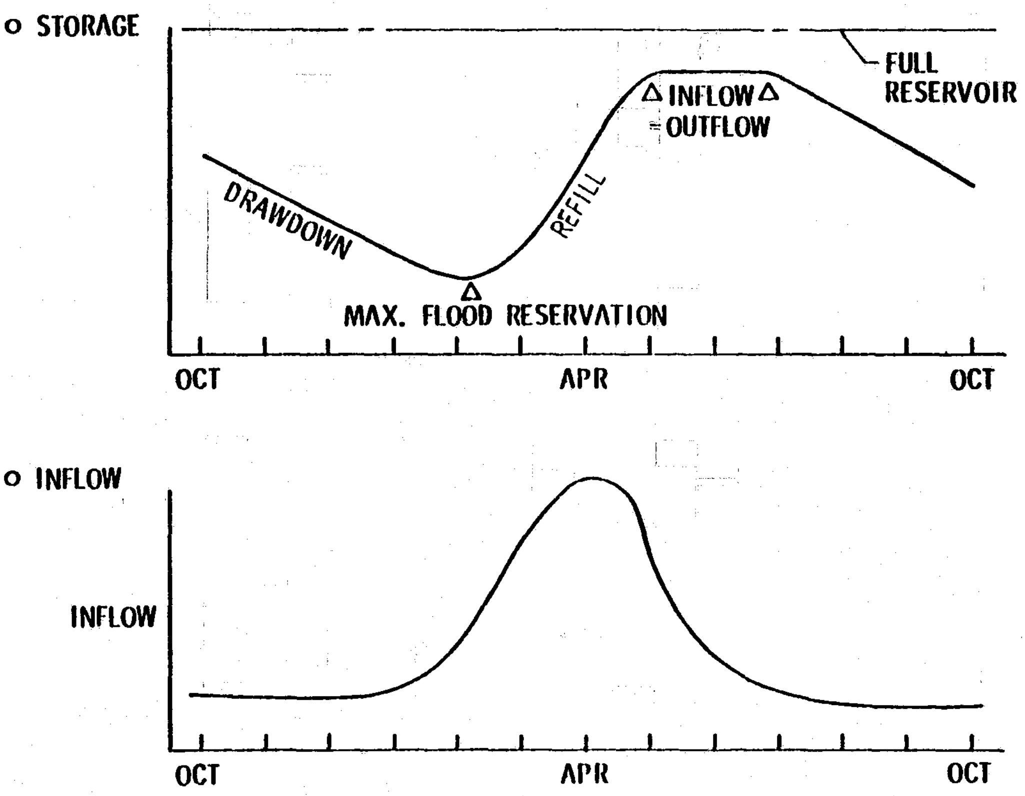

Figure 2. Reservoir Operations.

of several weeks. The actual levels of inflow can vary significantly from season to season. The storage level in the reservoir is managed in such a way as to enter the dry season with a nearly full reservoir so that power and water delivery commitments can be fulfilled during the dry season. A critical management period is encountered during refill since refill rates are heavily dependent upon forecasted inflows. If inflows are overestimated, adjustments late in the refill cycle may not be adequate to compensate for excessive early-season releases. Conversely, underestimates of inflow may lead to excessive spillage as the reservoir reaches maximum storage levels. The wide variations in inflows experienced at Shasta are shown in Figure 3, which compares monthly inflows for the 1973 and 1974 seasons. The monthly as well as seasonal variations in inflow emphasize the difficulties of water resource management for large, multi-purpose storage reservoirs. Daily and weekly variations within the monthly inflows contribute to the problem, particularly in controlling spillage.

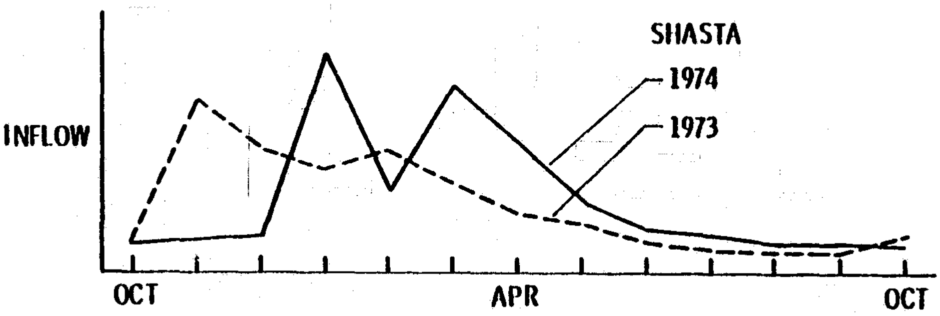

Figure 3. Inflow Variation

Prior Studies

Many studies over the past 8 - 9 years have addressed the potential for improving hydropower operations through the use of advanced information systems, based principally on the use of air/spaceborne sensors to improve the accuracy of predicting reservoir inflows. These studies generally were designed to provide guidance and support for remote sensor R&D programs by assessing the potential cost/benefits of applying these sensors to hydropower operations.

The principal loss in hydropower operations identified by the prior studies was spillage, i.e., release of water over spillways to avoid encroachment of flood reservations.[1] In a majority of studies historic reservoir release records were obtained on one or more major hydropower systems, and the total spillage summed for the season. The resulting loss of water was used as the basis for estimating the dollar benefits that could be realized if spillage were eliminated.

This general approach provides an upper bound estimate on potential benefits, assuming that mechanisms exist for reducing spillage. The usual mechanism put forth was an improvement in the accuracy of the prediction of total seasonal precipitation. Such improvements are quite speculative at present, and benefits derived on this basis tend to be over-estimated.

The results of six key cost/benefits studies are summarized in Table 1; these studies cover nearly a decade of activity in this area since the PRC effort was initiated in 1967. For each study the table give the estimated annual

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[1] That fraction of the reservoir storage volume that must be reserved for a flood event.

Table 1. Review of C/B Studies (Satellite Based Systems).

STUDY	ANNUAL BENEFITS (MILLION $)		BASIS	ANALYSIS TECHNIQUE	EXTENSION TO U.S.
PRC-1969 (GRAND COULEE)	HYDROPOWER FLOOD IRRIGATION (U.S.)	94 305 282 688	PERFECT SEASONAL INFO, NO HEDGE, OPTIMAL DRAWDOWN & REFILL, PERFECT KNOWLEDGE OF IRRIGATION DEMAND, RIVER LEVEL REDUCED TO MINIMIZE FLOODING.	UPPER BOUND ESTIMATES	TYPE AND SIZE OF RESERVOIR, IRRIGATION ACREAGE, FLOOD LOSSES IN U.S.
EARTH SAT CORP - 1974 (HUNGRY HORSE)	HYDROPOWER (WESTERN STATES)	10 - 28	PARAMETRIC VARIATION OF SEASONAL FORECAST ACCURACY	SIMPLIFIED SIMULATION OF DRAW & REFILL	RATIOED BY KWHRS
ECON - 1974 (OROVILLE)	HYDROPOWER IRRIGATION (WESTERN STATES)	42.0 8.6 50.6	ASSUMED A 20% REDUCTION IN FLOOD RESERVATION.	UPPER BOUND ESTIMATES	RATIOED BY KWHRS
MICH (1974) (PALISADES)	IRRIGATION (PALI)	.38-.76	PERFECT INFO FOR SHORT TERM (30 DAYS) AND LONG TERM.	SIMULATION MODEL (DAILY)	
*ECON (1975-1) (OROVILLE)	HYDROPOWER IRRIGATION	.6 2.2 2.8 (ORO) 19.2 (U.S.)	PARAMETRIC IMPROVEMENTS IN SHORT TERM (30 DAY) FORECAST.	SIMULATION MODEL (WEEKLY)	ALL WATERSHEDS WITH 811 KAF, 200 MW, 1000 GWHR, LARGE SNOW PACK.
ECON (1975-2) (SHASTA, GRAND COULEE, HOOVER, + 6 WESTERN RESERVOIRS)	HYDROPOWER IRRIGATION FLOOD	.65 .34 --- .99	FRACTION OF UPPER BOUND ESTIMATES.	UPPER BOUND ESTIMATES	(AS IN 1975-1). NOTE: SHASTA DOES NOT MEET CRITERIA, BUT CONTRIBUTES 33% OF BENEFITS.

*ALSO CONCLUDED THAT IMPROVED MEASUREMENT OF SNOW PACK DOES NOT IMPROVE FORECASTING SIGNIFICANTLY.

benefits for reducing or eliminating spillage; the basis for the estimate, the analysis technique; the extension of the case study results (Grand Coulee, Oroville, etc.), to the entire United States; and the extent to which forecasting techniques were analyzed, if at all.

As an example, the ECON 1974-75 studies were based on analyses of Oroville operations on the Feather River. The early study (1974) simply assumed that the flood reservation could be reduced 20% through improved forecasting. Since the total flood reservation can reach 750,000 AF (over one-third of the active storage volume of the reservoir), projected benefits due to a 20% reduction in the reservation are very substantial. No specific mechanisms were identified or hypothesized for achieving the improvement in forecasting. In actuality, the flood reservation at Oroville is based on accommodating a "maximum" storm event, 9 inches of rain in approximately 4 days. To reduce the flood reservation, it would be necessary to establish with a high degree of confidence, that a major storm could be forecasted both as to the time of occurrence and amount of precipitation. Weather forecasting techniques cannot achieve the necessary accuracies since forecast scores decrease rapidly beyond the first 24 to 36 hours, and decrease with increasing amounts of precipitation. Hence, the ECON-1974 benefits assumptions are optimistic. Extrapolating the benefits based on the Oroville case study to a large number of other hydropower systems is unrealistic.

The ECON 1975-1 study, also based on Oroville, is a significant improvement over prior analyses in that the benefits are related to forecast period, i.e., days of anticipation, and accuracy. These results provide a clue as to the role of short term inflow forecasting in hydropower operations. Unfortunately the investigators did not extend this analysis to examine short term inflow forecast techniques, which involve streamflow synthesis and weather forecasting, both of which can provide a limited number of days of anticipation. The ECON 1975-1 study went on to estimate benefits based on perfect information, and extrapolated the results to other hydropower plants meeting certain criteria related to storage and generating capacity, and fraction of inflow derived from snowmelt. The resulting total estimate of benefits for all watersheds is questionable.

The ECON 1975-1 report also concluded that more accurate measurements of snowpack water content would not increase hydropower output at

Oroville because such improvements would not lead to better estimates of total remaining inflow for the season, i.e., could not contribute to perfect long term inflow predictability, which they had previously identified as the only means for improving hydropower output. This conclusion is inappropriate for several reasons. First, hydropower output can be enhanced if short-term forecasting (2 - 20 days) can be improved, since, as will be shown, measurements of the snowpack are vital to short term, dynamic forecasting. Secondly, other investigators have shown some correlation between the areal extent of snowcover and percent of the remaining seasonal inflow; if these correlations can be established with reasonable confidence for given river basins, the information might be used to reduce flood reservations, although an adequate data base is not currently available. Finally, major hydropower systems in the Pacific Northwest have relatively heavier snowpacks, which places greater emphasis on accurate knowledge of the snowpack; the general applicability of the conclusion is therefore questionable.

The ECON 1975-2 study perpetuates the "upper bound" approach to benefits analysis used in prior studies with the same assumptions and conclusions. A more sophisticated attempt was made to extrapolate the benefits estimates to major reservoirs in the Western States, but the approach did not address the dynamic, short term nature of spillage, nor the capabilities and limitations of information systems that must be relied upon for high inflow anticipation.

In summary, prior studies have consistently based benefits estimates on an assumed percent reduction in total spillage over a season; the levels of reductions were arbitrarily chosen, and not related to an assessment or analysis of information system capabilities or constraints. The dynamic, short term nature of spillage, which is usually caused by unanticipated high inflow events, was not fully represented in the analyses, although the ECON 1975-1 study developed a relation between benefits due to spillage reduction and days of forecast with various degrees of forecast accuracy. As a result of the over emphasis on seasonal forecasting, information systems techniques providing short term inflow forecasts were not identified, and hence, not properly evaluated; further, the ground and snow hydrologic system models.

and weather forecast techniques upon which such information systems must be based, were not identified nor analyzed except by PRC, however, PRC did not relate inflow lag times and weather forecastability to spillage reduction potential. Admittedly, information systems cannot hope to achieve perfect forecastability in the foreseeable future, but with improved hydrometeorologic models, better anticipation of high inflow events is achievable; benefits due to spillage reduction through short term forecasting will not be large compared to the upper bound seasonal limits, but the potential gains are not insignificant.

An outcome of prior studies has been the failure to provide proper guidance to information systems R&D programs, particularly those dealing with air/spaceborne sensors. Too few analytical studies of remote sensor applications to hydrometeorological information systems are available, particularly those that address the difficulties of measuring and interpreting key variables for complex snow and ground hydrologic systems in non-uniform mountainous terrain. Results obtained over level, uniform topography have been too easily extrapolated to the far more difficult hydrologic systems associated with hydropower operations. Future studies must be oriented to address these factors.

Analysis of Hydropower Operations

The first, and critical task in the present study was to develop a more detailed understanding of real time reservoir operations to serve as a basis for establishing information system requirements, and to determine under what conditions and to what extent better inflow information can improve hydropower production.

The American River basin in the Sierra Nevada range was selected for analysis because the reservoir at Folsom was representative of major multi-purpose reservoirs operating under highly variable inflow conditions described previously. Folsom is a moderately large installation of 200 mw installed capacity with 1,010,000 acre feet of storage. Spillage is an important loss factor, but moderate production gains are possible through spill reduction. Inflow release records are available for Folsom for a representative number of years.

An immediate question arises as to optimum release strategies given a forecast of inflows for a particular planning period, say, one month. With no forecast capability, the operator must rely on historical records to formulate daily release schedules for the month. The release schedule is subsequently adjusted to account for differences between the expected and actual inflows. Simulations are frequently used to assist the operator in maximizing the hydropower output within the constraints related to flood reservations, contractual water and power delivery, etc. Improved information forecasting enables the operator to develop better release schedules, such that less variation between expected and actual inflow is experienced, and fewer adjustments required. The operator has available to him weather forecasts, estimates of water content and condition of the snowpack, soil moisture condition, and some forewarning of storms. Perfect information about future inflows tends to maximize the system output, provided a methodology is available to the reservoir manager to make best use of the information.

Researchers at UCLA (Drs. Yeh and Becker) recently developed a dynamic programming technique under the Bureau of Reclamation sponsorship to optimize releases for real time reservoir operations, given water and energy release targets for the month and day. This program has been computerized for application to operations at Folsom, and provides an accurate and consistent tool for evaluating the benefits of improved information systems.

This dynamic programming methodology was used to analyze the potential benefits to hydropower operations at Folsom for improved inflow information over a range of forecast periods, including the upper bound case of perfect accuracy over a given period. The program maximizes the benefits of improved inflow information, since it provides the optimal strategy for releases under specified constraints.

The results are shown in Figure 4 in terms of benefits in GWHRS as a function of days of anticipation with perfect information. For example,

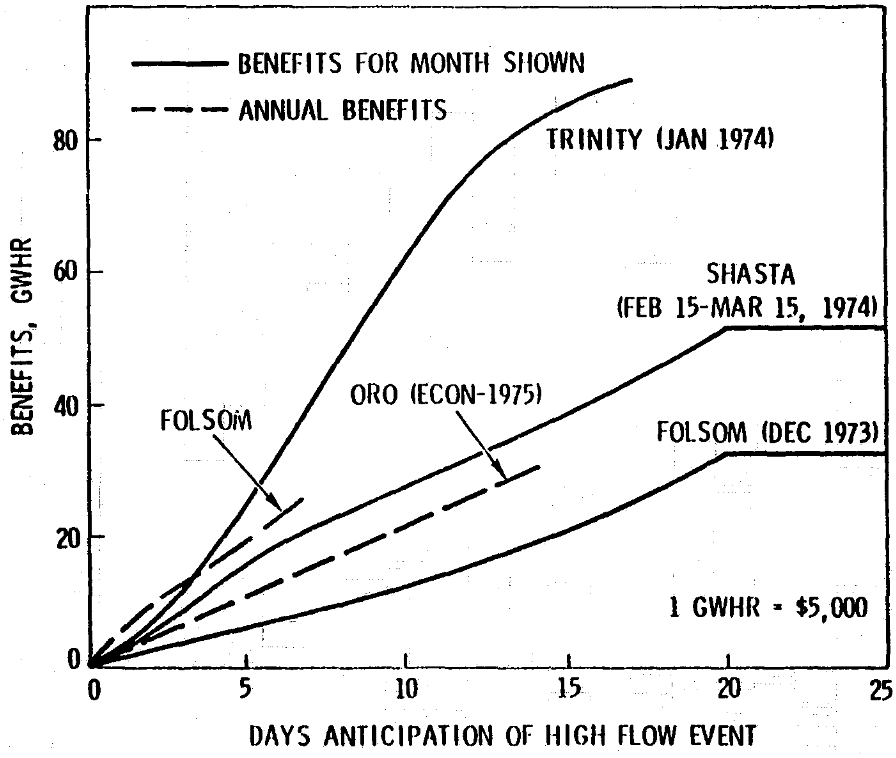

Figure 4. Hydropower Benefits Central Valley Project.

prediction of inflow with 100 percent accuracy for a period of 7 days at Folsom would yield a benefit of 7.6 GWHRS for a month over actual energy generation. Folsom currently sells energy to the net at $5,000 per GWHR, hence the benefit for the month is $38,000. If the anticipation time is extended to 20 days with 100 percent accuracy, benefits increase linearly to 33 GWHRS over actual production. Extension of anticipation time beyond 20 days results in little further improvement in energy production.

Annual benefits at Folsom were estimated, based on 10 years of operational data. For an anticipation time of 7 days, annual benefits are approximately 28 GWHRS or a net annual increase in energy production of 2.7 percent; the annual value of the increase is $140,000.

The benefits analysis was extended to two other storage reservoirs in the California Central Valley, Shasta and Trinity. The approximately linear relationships between the benefits and days of anticipation for these reservoirs are very similar to that derived from Folsom. Also, nearly all the potential benefits are achieved with 20 days of anticipation. An approximate extrapolation to all Northern California units on the basis of installed capacity gives a total potential benefit of 600 - 800 GWHRS for 7 days of anticipation.

An analysis was also made of major hydropower plants on the main stem of the Columbia River, which have about half the total capacity in the Pacific Northwest system, and about 25 percent of the nation's total hydropower capacity. Seven years of detailed historical records were obtained for these plants. An analysis of the data brought out several distinct patterns. Spring and summer runoff from snowmelt is dominant; rainfall runoff also contributes to the high spring inflows. The second characteristic is the continued heavy spilling during the high inflow season arising from the disparities between maximum hydropower releases and the very heavy spring inflows. Frequent below-maximum power releases were also noted while simultaneously spilling water, due primarily to insufficient load demand by the present power markets. It was estimated that the following average annual benefits could be obtained from anticipation of high inflows, provided that maximum power releases could be made:

Chief Joseph to Priest Rapids	
1 day anticipation	49.0 GWHR
2 days anticipation	92.9
McNary to Bonneville	
1 day anticipation	23.4 GWHR
2 days anticipation	59.6
Grand Coulee	
1 month anticipation	250.0 GWHR

In summary, spillage is attributable primarily to random, high inflow events that cannot be accommodated entirely within the reservoir, and which exceed the capacities of the power turbines. If accurate advance warning of high inflow events is available, storage levels within the reservoir can be reduced in advance of the events, approximately in proportion to the number of days of anticipation.

The forecast must be of relatively high accuracy to be of benefit to the hydropower operator, since releases on the basis of low probability forecasts are generally considered too risky.

Since reduction of spillage is dependent upon inflow forecasting accuracy, i.e., days of anticipation, a knowledge of lag times for ground and snow hydrologics systems is required. Parameters and variables affecting the lag times must be identified, and ranked in terms of their relative importance. An assessment must be made of the capabilities of instrument systems to measure the many variables affecting lag times. Similarly, assessments must be made for weather forecasting techniques, since these also provide for a limited number of days of anticipation. The results can then be compared to benefits versus anticipation time as shown in Figure 4 to establish a realistic although approximate estimate of potential benefits.

Inflow Forecasting

Inflow forecasting relies upon three basic models, including the ground hydrologic system, the snowpack hydrologic system, and weather forecast. Each has been analyzed to determine the characteristic lag times, accuracy, and suitability for real time estimation using ground based and/or remote sensors.

A schematic of a typical ground hydrologic systems is presented in Figure 5. The system is comprised of various elements of a complex hydrologic cycle involving percolation, soil mositure storage, drainage and evaportranspiration. The hydrologic system model calculates each component of run-off (surface run-off, interflow and baseflow), using a concept of moisture accounting for upper zone tension and free water, and lower zone tension and free water.

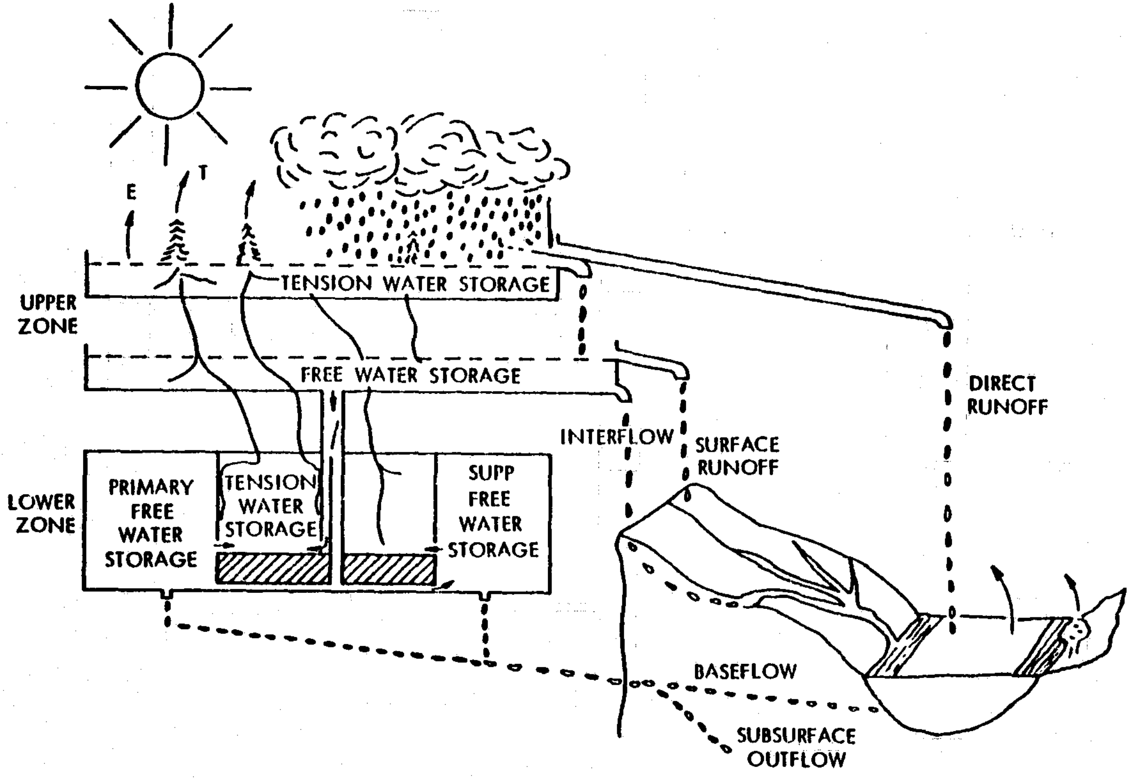

Figure 5. A Generalized Hydrologic Model (GSSS).

The basic parameters and variables used in the hydrologic model, include:

- Initial conditions

  Upper zone tension and free water content
  Lower zone tension, primary free and secondary free water content

- Precipitation (rainfall and snowmelt)
- Evaportranspiration demand
- Watershed parameters

  Impervious area
  Drainage and percolation rates
  Lower zone tension and primary and supplemental free water storage capacities

and several parameters related to the various processes simulated by the model such as surface runoff, interflow, base flow and channel storage.

Snowmelt runoff poses complex problems for inflow predictions. It is not adequately handled in any of the several available inflow models, which generally assume that snowmelt enters directly into the ground hydrologic system, and is therefore equivalent to rainfall in terms of moisture input. In actual fact, snowmelt may not enter the ground hydrologic system as the melt occurs, but can be retained in the snowpack for days and weeks before entering the ground system. This is a serious shortcoming in the existing inflow prediction methods that should be emphasized in snow hydrology research programs.

Unlike rainfall, snowmelt is not generally measured quantitatively, but must be estimated indirectly from observation of the snowpack. The Streamflow Synthesis And Reservoir Regulation (SSARR) model developed for the Columbia River basin, uses a snowmelt predictor based on several melt components including those related to short wave and long wave radiation, convection and condensation, rain, and ground state. The observables include: air temperature, dew point temperature, wind, solar radiation and albedo. An inventory of snowmelt accumulation and melt can be computed for the basin, sub-basin, or for snow bands, which are zones of relatively equal altitude. The approach is designed for mountainous watersheds that pose particular difficulties in inflow prediction.

The sensitivity analysis was performed for the American River watershed in the Central Sierra Nevada's, using the General Streamflow Synthesis System (GSSS) inflow model for the ground hydrologic system processes and the SSARR model for the snowmelt functions (the former model does not include a detailed snowmelt component). Based on the sensitivity analysis, the relative importance of the several parameters and observables was determined for a representative period of operations in the basin (March 1957) at Folsom. The results are given in Table 2 for three sets of variables, those related to the watershed, input and initial conditions, and snowmelt parameters.

The most important watershed parameters were found to be the lower zone water storage capacity, amount of water required to fill non-impervious areas, and percolation rates. None of these parameters are amenable to direct measurement by remote sensors, and for the most part, must be determined indirectly by variance minimization techniques.

Table 2. Sensitivity Analysis.

a. Sensitivity Analysis ($\Delta V/V$).

Ranking	Watershed Parameters (GSSS)	$\frac{\text{\% Change in Streamflow}}{\text{\% Change in Parameters}}$
1	P_5, Lower Zone Free Water Storage Capacity	-3.8
2	P_3, Lower Zone Tension Water Storage Capacity	-3.5
3	P_1, Depth of Water to Fill the Non-Impervious Area	-1.3
4	P_9, Percolation	-1.2
5	P_4, Lower Zone Supplemental Free Water Capacity	-1.2
6	P_6, Upper Zone Lateral Drainage Rate	1.2
7	P_{10}, Shape Factor for Percolation	1.2
8	P_{12}, Upper Zone Free Water	1.1

b. Sensitivity Analysis ($\Delta V/V$).

Ranking	Input Parameters and Initial Conditions	$\frac{\text{\% Change in Streamflow}}{\text{\% Change in Parameters}}$
1	MI, Moisture Input (Precip + Snowmelt), MI	4.0
2	I.C.3, Lower Zone Tension Water Contents	3.8
3	I.C.5, Lower Zone Primary Free Water Contents	2.9
4	I.C.1, Upper Zone Tension Water	1.3
5	I.C.4, Lower Zone Supplementary Free Water	0.60
6	Evapotranspiration	-0.10

c. Sensitivity Analysis ($\Delta MI/MI$).

Ranking	Snowmelt Parameters	$\frac{\text{\% Change in Melt Rate}}{\text{\% Change in Parameters}}$
1	P_1, Snow Covered Area	-0.5
2	P_{14}, Air Temperature	-0.2
3	P_{17}, Insolation	-0.1
4	P_{13}, Precipitation	-0.1
5	P_{16}, Albedo	0.05

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The most important input parameters are: moisture input (rainfall and snowmelt), and lower and upper zone water content. The latter parameter is amenable to remote sensing, and has an impact on the accuracy of inflow prediction. Snowmelt is an important function and its measurement is one of the few to which remote sensing can contribute. Of the several snowmelt variables, areal extent is one of the most important; remote sensing has been employed for measuring snowpack areal extent with good success when not limited by cloud cover. The other high ranking variables generally are not amenable to remote sensing.

In summary, watershed hydrologic models are highly empirical in nature, and utilize a large number of variables in estimating stream flow. Many of these are determined indirectly by variance minimization techniques; few are amenable to direct measurement by remote sensing. It can also be observed that a highly accurate measurement of a single variable will have little effect on overall inflow prediction because of the large variances associated with the remaining variables; it probably will not be cost effective to pursue costly remote sensing developments that improve the measurement accuracy of only one or two variables. Sensor requirements must be established on the basis of overall system accuracy improvement, and used as the basis for sensor R&D programs. The extremely complex non-uniform nature of mountainous watershed hydrologic systems imposes severe constraints upon the effectiveness of remote sensing for inflow prediction.

Initial conditions and watershed variables are expressed as single lumped parameters; this contributes sources of errors in prediction since in nature the parameters are distributed. The errors can be minimized by dividing the watershed into sub-basins, each with its own set of parameters. This approach requires considerably more information, but improvements in accuracy may demand models that better represent the spatial variations in hydrologic systems characteristics.

The hydrologic system modeling techniques provide little information on a critical factor in hydropower operations, viz., the prediction of inflow lag. The GSSS model estimates the lag in the American River basin to be 4 days. The model does not distinguish the differences in lag between direct and base flows, or differences that obviously depend on the state vector of the hydrologic system, which varies greatly over the runoff season. It also does not differentiate between the lags of the different sub-basins; a single lumped value is calculated. The possible inaccuracies associated with this highly empirical approach to lag time estimation are evident.

Synoptic Inflow Models

The LANDSAT Multi-Spectral Scanner (MSS) imagery program has led a number of investigators to test various synoptic inflow models which relate seasonal runoff to the areal extent of the snowpack. Using MSS data in the visible and IR bands, the fraction of the basin covered by snow is measured during the late winter and spring runoff seasons, and related to the accumulated runoffs at start of heavy snow melt. Good correlation has been found for the few cases tested, and appears to warrant further study. The technique unfortunately has not proved successful in the Columbia River basin because of extended periods of cloud cover, which prevent the accumulation of sufficient data.

The synoptic model relating accumulated seasonal runoff to snow covered areas does not by itself provide dynamic inflow data, i.e., it cannot be used to predict inflow and thus help avoid spillage. Snowmelt models based on energy balance techniques as described earlier are required for this purpose. However, flood reservations for some reservoirs are based in part on expected total seasonal runoff; if the synoptic models can provide such information with a high confidence level, flood reservations could be reduced, with significant increases in hydropower production. For this reason, some research efforts should continue in this area.

Weather Prediction

Weather prediction provides the second primary method for anticipating high inflow events. Several meteorological variables are important in predicting inflow, including precipitation (type, amount, and spatial distribution), and those related to snowmelt: air temperature, insolation, wind, humidity, etc. Key questions pertain to how accurately these variables can be predicted, what advances can be expected in prediction accuracy, and which variables are amenable to remote sensing.

Two basic approaches are taken to prediction of meteorological variables, statistical and physical modeling. The statistical model ignores physical dynamics and uses historical measurements of dependent variables and several independent variables. Such a model in general cannot predict time variations, and is used more frequently for seasonal estimating.

The physical modeling approach utilizes the physical laws that govern the complex dynamics of the atmosphere, and include thermodynamic equations, the equations of motion, equations of state, and continuity of mass. Solutions to these resulting complex nonlinear equations can be obtained by large-scale computer program. Such models are suitable for short-range forecasts, but are questionable for prediction periods of more than a few days.

Recently, some researchers have combined the physical and statistical approaches. The Model Output Statistics (MOS) technique developed by the National Weather Service is an example. This technique consists of determining a statistical relationship between a predictand and variables forecast by a numerical (physical) model over some time period. It is particularly useful in matching observations of local weather with outputs of numerical models. The biases in numerical models as well as local climatology can be accounted for in the forecast.

The National Weather Service is applying an MOS model to the Columbia River basin. The representative equations have been developed for forecasting warm season precipitation and temperature, both of which can contribute to impoved forecast accuracy.

The general levels of accuracy attainable with MOS techniques are shown in Table 3. Table 3a shows the forecast accuracy for precipitation amounts for various forecast periods and amounts of precipitation. The accuracies tend to drop off significantly beyond the first 24 to 36 hours. A more discouraging aspect from the standpoint of predicting high inflow events is the sharp reduction in accuracy for heavy precipitation, i.e., rain of one inch or more. This characteristic also precludes the possibility of reducing flood reservations, which are dictated by worst case inflow events; to reduce flood reservations, it would be necessary to demonstrate a capability to predict worst case high inflow events with high confidence. This clearly is not possible in the foreseeable future.

Table 3a. MOS — Prediction of Precip Amount.

STATIONS

$$\text{ACCURACY} = \frac{H}{F + O - H}$$

(PERFECT SCORE = 1.0)

THREAT SCORE (NOV 75)					
	0.5"	1"	2"	3"	4"
12-36 HRS	.33	.17	.01	0	0
24-48	.26	.13	.02	0	0
36-60	.23	.11			

Table 3b shows the accuracy of max-min temperature predictions compared to past methods. Although not analyzed in the present report, it would be appropriate to relate the accuracy of max-min temperature forecast to the sensitivity of SSARR type inflow models to air temperature accuracy.

It is possible that the MOS technique is sufficiently accurate to serve as a source of information for several important snowmelt variables, including humidity, wind and insolation. Although the precipitation amount cannot be predicted with a high degree of accuracy, inflow is more dependent on snowmelt in the Pacific Northwest region, which is a major producer of hydropower. Further research along these lines is appropriate.

Recent analysis of numerical weather forecasting models at JPL indicates some of the difficulties of improving multi-variant predictor techniques. Using a numerical (physical model), the variance of one input variable, surface wind, was reduced, with the expectation that the accuracy of the overall model would be improved. To the contrary, the model tended to damp out the variances in the input values of surface wind, such that no improvement in forecast accuracy was achieved. Reduction in bias errors in input values might yield better results. These studies are continuing.

Information Systems Requirements

Based on the knowledge of spill mechanisms, and the relationship between spillage reduction and the inflow anticipation time and accuracy, quantitative requirements were developed for information systems designed to support hydropower operations. These requirements were stated in terms of the accuracies of key variables used in the ground hydrologic and snowmelt models that are employed to predict the amounts and rate of inflow into the reservoirs. Because many key variables contribute to the variance in inflow prediction, all such key variables must be measured with a relatively high degree of accuracy to achieve overall gains.

General and specific requirements have been devloped for sensors. The general requirements include:

- High confidence predictions of imminent rainstorms or rapid snowmelt events within a time frame that permits effective control action is desirable. Once a day sensing is necessary.

Table 3b. Verification of Objective Maximum/Minimum Temperature Forecasts, Averaged at 126 Cities, made twice a day, from Operational Prognostic Data by MOS and Perfect Prog (PP) Systems. Winter Season (Oct. 1973 – Mar. 1974).

Projection	Type	Mean Absolute Error (°F)		Correlation of Forecast with Observed Temperature	
		MOS	PP	MOS	PP
24 h	Max	3.6	4.5	0.87	0.81
36 h	Max	4.4	4.8	0.82	0.78
48 h	Max	4.9	5.4	0.79	0.76
60 h	Max	5.3	5.7	0.74	0.72
24 h	Min	4.3	4.7	0.80	0.77
36 h	Min	5.1	5.1	0.76	0.71
48 h	Min	5.2	5.2	0.73	0.73
60 h	Min	5.8	5.7	0.67	0.67

- Accurate spatial sampling of precipitation and climatic variables is necessary to reduce sampling errors.

- An accurate assessment of soil moisture content is desirable. Weekly sampling is necessary.

- Knowledge of snowpack ripeness or maturity is of great importance where snowmelt is a significant contributor to runoff. This would indicate the imminence of substantial snowmelt runoff. A measurement frequency of several days during peak melt season is satisfactory. Resolutions of 1 km or less are necessary for non-uniform mountainous watersheds.

- Snowpack areal extent is a key variable in most snowmelt models, and should be included in information system implementations. An accuracy of 100 m is desirable.

- Data acquisition, transmission, processing, and dissemination on a timely basis is mandatory for prompt control action; slow turnaround time greatly reduces the value of the data. Data should be available to the operator in no more than 24 hours.

In deriving a quantitative error budget for measuring key variables, we note that errors can be allocated in any number of ways to produce an improvement in hydropower operations. An optimum error budget would take into account the total cost effectiveness of sensor and information system R&D program; since this data was not available, accuracy requirements have been parameterized for a representative basin, the American River in the Central Sierra Nevadas. The results are shown in Table 4 for 3 and 7 days of anticipation, and 2 levels of hydropower output improvements, 10 and 20 percent, respectively. Generally, instrumentation errors must be reduced by 5 to 15 percent to achieve the desired increases in hydropower output.

Sensor Capabilities

The preceding discussion has established requirements for sensor systems for inflow forecasting, and has articulated the mechanisms through which the sensors can contribute to improved hydropower operations. Based

Table 4. Allowable Parameter Estimation Errors.

Parameter	If 7 Days High Inflow Anticipation Possible[3]				If 3 Days High Inflow Anticipation Possible[3]			
	10% Benefit Decrease		20% Benefit Decrease		10% Benefit Decrease		20% Benefit Decrease	
	Prorated[1] Benefit Decrease %	Maximum Error %	Prorated[2] Benefit Decrease %	Maximum Error %	Prorated[1] Benefit Decrease %	Maximum Error %	Prorated[2] Benefit Decrease %	Maximum Error %
Precipitation (Water on Soil)	4.1	2.0	11.4	4.0	4.1	2.0	10.8	7.0
Upper Zone Soil Moisture	4.1	2.7	11.4	6.2	4.1	2.0	10.8	9.0
Snow Covered Fraction of Basin	4.1	3.4	11.4	7.8	4.1	3.0	10.8	13.0
Basin Insolation	4.1	11.0	2.0	5.0	4.1	8.0	4.0	8.0
Wind Speed	4.1	12.0	2.0	7.0	4.1	9.0	4.0	10.0
Albedo of Snow Pack	4.1	18.0	2.0	9.0	4.1	9.0	4.0	15.0

[1] Equally distributed benefit change budget, errors assumed to RMS to total benefit decrease.

[2] As above, but with second set of 3 parameters restricted to smaller budget to limit maximum errors.

[3] Reference benefit values = 27.5 GWH and 12.5 GWH, respectively.

on these stated requirements, a review of sensor capabilities was performed to determine the adequacy of present sensors (primarily in situ instruments), and the potential for application of air/spaceborne sensors to hydrometeorological information systems.

The results of the survey are summarized in Table 5, which lists those parameters that can be measured directly or remotely, and those that must be determined indirectly by variance minimization techniques. For the measurable parameters, the types of in situ sensors currently in use or under development are indicated; the feasibility of measuring the parameters by remote sensors (air/spaceborne instruments) is also noted. The relative ranking of the parameters in terms of their effect on inflow prediction is included in the table.

Of the key variables, all but snowpack areal extent can be measured by ground based sensors; photo imaging is well suited to measuring snowpack area, provided adequate cloud-free viewing time is available. These sensors can also measure the relatively stable physiographic parameters of the basin, such as forest cover areas, impervious areas, and surface drainage characteristics. Ground sensors must be used for other measurable parameters.

Ground Sensors. Treating the ground sensors first, the standard precipitation gages suffer the perennial problems of catch deficiency due to wind, improper shielding, and inability to account for the rain to snow ratio.

Snowpack depth, density and water equivalent are usually obtained manually with cutting tubes at specific sites along a snow course. The accuracies of such measurements are generally adequate. Snowpack structure cannot be determined, however. Pressure pillows are now used in many locations to measure water equivalence and (if depth is known) average density. A 12-ft rubberized pillow, filled with an anti-freeze solution, suitably installed, is the minimum size that will produce adequate weighings of the snow without experiencing considerable ice bridging of the pillow. Accuracies without ice bridging are within ±10 percent. Development work is continuing in this area.

Measurement of snow depth with the use of unattended sensors has not been satisfactorily resolved. Pole markers are usually distributed throughout the basin and observed from low-flying aircraft, however, the operation may be too risky to undertake with any reasonable frequency.

Table 5a. Field Measurable Parameters.

Variable	Runoff Sensitivity Ranking[3]	Instrumentation	Comments	Currently Amenable to Remote Sensing	Potential for Remote Sensing
Precipitation	High	Standard rain and snow gages	Location and sampling problems	No	Storm anticipation, areal distribution possible, microwave.
Snowpack Areal Extent	High	Photo-imaging	Satellite sensing although limited by cloud cover.	Yes	
Upper Zone Tension Water	High	Electrical resistance meters	Calibration problems	No	L-band or lower frequency microwave, upper 10 cm possible.
Impervious Fraction Basin	Low	Photo-imaging	Frozen soil under snow not sensed	Sometime – see comments	
Water Surface Fraction	Low	Photo-imaging	Static parameter	Yes	
Forest Cover Fraction	Low	Photo-imaging	Static parameter	Yes	
Mean Overland Surface Length	Low	Photo-imaging	Static parameter	Yes	
Streamflow	High	Standard streamgage		No	
Insolation[1]	Low	Pyrheliometer	Field problems	No	
Air Temperature	Medium	Thermograph		No	
Humidity[1]	Low	Hygrothermograph or psychrometer	Field problems	No	
Albedo of Pack[1]	Low	Back to back pyrheliometers	Impractical for field	No	Possible correlation with active microwave reflected signals.
Wind Speed[1]	Low	Anemometer		No	
Snow Depth[2]	Parameters not in model	Snow survey/pole markers/ radioisotope profiler	Sampling problems	No	Depth averaged snowpack characteristics sensing by active or passive microwave requires further theoretical and sensor development and test. Good potential.
Snow Water Equivalence[2]		Snow survey/pressure pillow/radioisotope profiler	New developments	No	
Snow Liquid Water Content[2]		Microwave profiler	New development	No	
Snow Density[2]		Snow survey/radioisotope profiler	New development	No	

1. Parameter not generally used for day to day operation because of data inadequacy.
2. Parameter not generally used in current watershed models.
3. High sensitivity corresponds to absolute value ≥ 1.
   Medium sensitivity corresponds to absolute value < 1. and ≥ 0.5.
   Low sensitivity corresponds to absolute value < 0.5.
   (See Tables 5-7 to 5-9.)

Table 5b. Non-Measurable, High Sensitivity Model Parameters.
(listed in order of sensitivity ranking)

Relative Rank	Variable
1	Lower Zone Free Water Storage Capacity
2	Lower Zone Tension Water Contents
3	Lower Zone Tension Water Storage Capacity
4	Lower Zone Primary Free Water Contents
5	Depth of Water to Fill Non-Impervious Area
6	Percolation
7	Lower Zone Supplemental Free Water Capacity
8	Upper Zone Lateral Drainage Rate
9	Percolation Shape Factor
10	Upper Zone Free Water

In addition to depth and water equivalence, some knowledge of snowpack structure is highly desirable, but remains one of the most difficult phenomena to measure. As noted previously, snowpack structure can change markedly as it matures during the season; the snowpack can absorb large quantities of water, either rainfall or snowmelt, without releasing the water to the ground hydrologic system and hence to the reservoir. Conversely, a minor rainfall or snowmelt event can trigger a large water release from a ripe snowpack. Hence, the "state" of the snowpack is of vital concern to the reservoir operator.

A profiling snow gage is being developed to obtain better estimates of rain and meltwater runoff. The gage consists of a gamma radiation source and scintillation detector that traverse in two parallel vertical tubes through the snowpack. The gage detects snowpack density over the height of the pack. Liquid water content is also of interest, however, calorimetric sensing methods are difficult to automate. In a development similar to the radioactive isotope density profiler, a microwave source and detector are capable of accurately measuring liquid water content. The two profilers operating together can give data as to pack structure, which when combined with climatic information, will enable accurate short term predictions of snowmelt runoff. While these profilers are not prohibitively expensive, simpler, less costly implementations would permit more extensive sampling, as well as application to more watersheds.

The other variables listed in Table 5 can be measured with state of art ground sensors, although adequate spatial sampling frequency is often limited by sensor and site implementation costs, ease of access for servicing, and data transmission facilities. The synoptic measurement potential of air/spaceborn sensors is clearly desirable if it can be exploited.

Visible and IR Sensors. Candidate remote, i.e., air/spaceborne sensors include visible and IR sensors, and passive and active microwave sensors. The application of visible/IR sensors for measurement of snowpack area has been discussed. Achievable accuracies of 100 m or better with LANDSAT MSS type instruments are quite satisfactory, but these sensors suffer from some basic operational limitations, principally the inability to penetrate heavy cloud cover, forest cover, and fog. Also, if the satellite vehicle is at low enough altitude for good imaging, the frequency of coverage may be low, and this characteristic exacerbates the problem with cloud and fog. Partial compensation is obtained with the use of multiple satellites and more than one type of sensor. A further difficulty is encountered in the transmission, reduction and dissemination of the large volume of image data. In addition, relatively low altitude satellite vehicles limit the basin size that can be observed per pass. Melting snow can be detected by observing the reflectance of snow in various IR bands, however, no quantitative data has been made available.

Passive Microwave. Snow emits small amounts of radiation at microwave wavelengths. Despite the low power, low resolution and complex patterns of the emissions, there is some indication that snow areal extent can be determined by current passive microwave radiometers without the operational problems of shorter wavelength radiometers. Microwave brightness temperatures of dry snow, wet snow, and snow-free terrain are sufficient that snow extent can be calculated either by snow-line mapping or by intergrating the brightness temperature values within a resolution element (requiring a number of frequency, polarization, and/or viewing angle considerations, depending on the number of different types of snow within the element). However, the latter method has not been demonstrated adequately; thin dry packs will allow radiation from the soil, degrading the measurement accuracy. It also appears that wet snow might be difficult to distinguish from snow-free ground or from dry snow.

Researches suggest that snow water content and water equivalence might be determined for dry snowpacks up to about 2 meters by judiciously varying frequency, polarization, viewing angle, etc., and noting changes in brightness temperature. These suggestions are speculative at the present time. The results of field and laboratory investigations and theoretical studies indicate that snowpack emissions vary with snow water equivalence but that moist snow may present problems in separating the effects of liquid water from those associated with water equivalence. In general, the useful application of microwave radiometry will depend on a better understanding of the bulk snow properties (volume scattering phenomena) and, possibly the properties of the soil layers.

L-band may be used to minimize the influence of vegetation and surface roughness on soil mositure measurements by passive microwave, but antenna size would be a distinct problem. The S194 L-band radiometer on Skylab appeared to correlate satisfactorily antenna temperatures with a 30-day antecedent precipitation index. This would relate to the top layers of soil; longer wavelengths would be required for deeper penetration.

At the wavelengths sensitive to subsurface moisture the resolution at orbit (460 km) is 30-150 km, not adequate for use in most watershed models. (Aircraft overflights are a possibility.) The corresponding resolution for sensing surface moisture is from 3-30 km. There is no available accuracy data although aircraft radiometric measurements over bare flat fields have yielded about 5 percent error for moisture contents of 10 - 40 percent.

The shorter wavelengths for surface moisture measurements are sensitive only to very thin surface layers, which can undergo wide diurnal fluctuations in near-surface moisture content.

In summary, it is difficult to reconcile the low resolution capabilities of passive microwave sensors with resolutions required to measure ground and snowpack parameters in mountainous watersheds with complex, nonuniform hydrologic systems. Sensors of this type are much more amenable to application to broad planar areas of uniform hydrologic makeup.

Active Microwave. Radars possess advantages over passive microwave in that they offer high spatial resolution through the use of synthetic apertures. However, these advantages are compensated by high complexity and cost. Active microwave sensors suitable for measurement of hydrologic parameters are presently being developed.

In principle some important physical properties of the snowpack can be obtained with multi-frequency radars (lossless and homogeneous layered media and normal incidence assumed). As frequency is varied, the reflection amplitude will go through cycles of minima and maxima. Noting these values and taking measurements before and after the first appreciable snowfall, snow and earth dielectric constants can be calculated from theoretical relationships. Snow depth can be determined from the snow dielectric constant and from values of the frequency at which the first minimum is encountered. The approximate average density of the dry pack also can be determined, but the density distribution of the pack cannot be determined. It is claimed that the wetness (liquid water content) of a wet snowpack can be determined by the behavior of the reflection coefficient vs frequency, provided volume wetness is greater than 1 percent.

It is estimated that the snowpack depth and density can be obtained within a ±15 percent tolerance, however, this has not been demonstrated even under carefully controlled laboratory conditions with simple snowpack structures. It is not clear how the technique could hope to succeed when applied to mountainous watersheds with widely variable non-uniform snowpack structures. It is not clear how well wetness can be measured in lossy media although ripening of the pack might be noted adequately by time observations of approximately wetness measurements.

The microwave radiometric investigation of snowpacks by Aerojet-General Corporation is of particular significance in this connection, and indicates the complexities of snowpack microwave radiation and the consequent difficulties in interpreting radiometric measurements. The results of this investigation indicate that although empirical relationships between pack water equivalence and microwave emission were demonstrated, theoretical models which approximated subsurface snow structure could provide only rough qualitative explanations of measured results but no quantitative agreement. Such phenomena as ice and snow layers of varying densities and thicknesses, variable liquid water content, surface roughness, and the granular structure of the snow, and ground-pack interface were inadequately treated by the most sophisticated current snowpack models. These phenomena require a treatment of radiation scattering and emission by random media. In particular, emissions from wet snow varies with water equivalence in a complex fashion, and it was not possible to separate effects due to water equivalence from those due to liquid water. Further, soil emissions can penetrate substantial depths of snow so that information as to the nature of these emissions is important to the accuracy of snowpack measurements. Freezing and thawing of the soil and its moisture content produce significant effects. On the other hand, the study indicates that it may be possible to measure the water equivalence of dry snowpacks over a broad class of terrains by radiometric means. Also, there appears to be little polarization and radiation dependence on incidence angle over the angular range of interest and the terrain slopes common in mountain snowpack regions.

Soil moisture may also be sensed by multiple polarization radar. No accuracy assessment that would apply operationally is available. Difficulties may be encountered with surface roughness effects unless long wavelengths are used.

Conflicting results with side looking radar (SLAR) images of snowpack have been experienced. New snow and recrystallized old snow may not be seen.

In summary, it is not clear how microwave techniques can hope to succeed when applied to mountainous watersheds with widely variable non-uniform snowpack structures. A great deal of additional theoretical and experimental studies must be performed to justify the use of these sensors for present applications.

An Information System Concept

The preceeding discussion has indicated a number of deficiencies in current watershed runoff forecasting techniques, particularly forecasts intended for hydropower operations. Major inaccuracies result from rain-storm prediction and watershed and climatic parameter sampling errors, and from a failure to consider snowpack melt, maturation, and discharge phenomena in sufficient detail and with adequate instrumentation.

A runoff information system concept is outlined which will alleviate some of these deficiencies and improve hydropower day to day operations. It is clear that, for at least the 1970s, the bulk of the instrumentation must be ground based. However, since rapid data collection and dissemination is a necessity, automation and reliable hardline or telemetry (including satellite relay) of the data to a central operator are very desirable.

Watershed runoff and streamflow parameter sensing requirements are summarized in Table 6. The values given in Table 6 are primarily for the Sierra Nevada, in accordance with information obtained from Dr. James L. Smith, U.S. Forest Service at Berkeley. Climatic and topographical features are sufficiently regular and uniform throughout the area to permit a relatively sparse network. Regions such as the Pacific Northwest will require parameter sensing with approximately 2-4 times the density of

Table 6. Sensing Requirements.

Parameter	Measurement Frequency	Measurement Sampling Density	Comments
Precipitation	Daily	3-10 per Basin	
Soil Moisture	1 per wk	1-2 per Basin	
Relative Humidity	Daily	1 per Basin	
Wind Speed	Daily	1 per Basin	
Air Temp	Daily	1 per Basin	
Snowpack Albedo	1 per 3 days	1 per Region	A "Region" will include several Basins.
Insolation	Daily	1 per Region	
Snowpack Area	1 per wk in winter 1 per 3 days during snowmelt season	Each Basin	
Snowpack Water Equivalence	Same as Area	3-10 per Basin	
Snowpack Depth	Same as Area	3-10 per Basin	
Snowpack Density	1 per wk in winter; daily during snowmelt season	1+ per Basin	Density profile with depth required
Snowpack Liquid Water Content	Same as Density	1+ per Basin	Profile required
Snow Temp	1 per 3 days	1 per Region	Profile desirable
Soil Temp	1 per wk	1 per Region	Will detect frozen ground surface.
Streamflow	Daily	1 per Stream	

Note: Density and liquid water depth profiles probably not required for cold and dry snowpacks such as in Rocky Mountains.

those given in Table 2-6. Accuracies of currently available instrumentation are considered generally adequate.

The number of hydrologic and climatic sensors can be minimized through use of a hierarchy of data collection stations, and the correlation of appropriate data elements between them. Table 7 shows the necessary sensors, stations, and costs for a wet snow regions typified by the Sierra Nevada. The first order stations serve as primary reference (base monitor) stations for a geographical area with similar climatic regimes, and containing a number of watersheds. The first order stations generally would be manned or periodically attended, and would be instrumented to gather all relevant watershed and climatic data. The second order stations collect all data required for normal operational use. First and second order data can be correlated, particularly with regard to snowpack melt phenomena to produce an accurate estimate of day to day snowmelt runoff. In turn, second and third order data correlations can reduce measurement errors arising from complex snowmelt phenomena. These phenomena are sensed by the third order station sensors, snow pillows, only in the aggregate. The manually obtained fourth order data serve as checks on the automatic instrumentation.

The preferred mode of data transmittal to the central facility is by satellite relay, although a detailed trade-off with conventional ground relay techniques is required to justify the use of satellite relay for specific watersheds. Data Collection Platforms (DCP) have been designed to operate with LANDSAT or GOES satellites in a data relay mode to transmit hydrometeorological information to designated ground receiving stations. The reliability of this mode has been demonstrated by LANDSAT to be comparable or better than ground based microwave relay systems. Furthermore, there can be significant cost savings; it has been estimated that a $3 million telemetry cost for the Pacific Northwest HYDROMET installation in the Willamette Valley could be reduced to $1 million by using the GOES data relay system.

The total cost of data collection platform, power supply, and instrumentation (exclusive of multispectral scanner and manual surveys) for the range of stations given in Table 7 (and assuming 10 basins per region) is estimated to be $600, 000 - $2, 500, 000 if DCPs are used for the third order stations. However, the higher cost value may be an overestimate since

Table 7. Sensor and Station System Concept (Sierra Nevada).

Parameter	Sensor	Order of Station				Estimated Cost per Unit $1,000
		1st 3 per Region	2nd 1 per Basin	3rd 3-10 per Basin	4th 15-20 per Basin	
Precipitation	Heated Precip Sensor	X	X	X		1.2
Soil Moisture	Electrical Resistance	X	X			0.5
Rel. Humidity	Hygrometer	X	X			0.6
Wind Speed	Anemometer	X	X			0.7
Air Temp	Thermocouple	X	X			0.7
Albedo Insolation	Pyroheliometer — Two Req'd	X				1.2 for 2 units
Snow Area	Satellite-borne Multispectral Scanner					
Snow Water Equivalence	Pressure Pillow	X	X	X		0.7
Snow Density and Depth	Radioisotope Profiler*	X	X	(Portable)		10.0 (4.0)
Snow Liquid Water	Microwave Profiler	X	X			2.0
Insolation	Sunshine Duration		X			0.5
Snowpack Characteristics	Monthly Snow and Air Surveys				X	
Snow Temp	Thermocouple	X				0.7
Soil Temp	Thermocouple	X				0.7
Selected MOS† Predictors		X				
Streamflow	Calibrated Stage Gages	X	X	Δ		0.5

*Wilderness Act will not exclude use.

ΔGages at all tributaries.

†Weather prediction technique: Model Output Statistics (see Chapter 6).

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cheaper platforms or the use of one platform to serve several third order stations with ground to ground data transmittal between them might be preferable.

With regard to the Wilderness Act, efforts are currently underway (Sisk bill) to legitimatize reasonable data collection. In any event, at present, sensors such as the density profiler may be used at existing snow survey sites and correlations made with other stations.

Conclusions

The following are drawn from the results derived from this study.

1. Energy Loss Mechanisms

The major energy loss mechanism is the spillage of water — a forced release of water when the power pool is full and inflows are greater than turbine capacity.

A major cause of spillage is the inability to predict short term, high inflow events with sufficient accuracy, such that storage space can be made available in anticipation of the event. If high inflow events can be predicted, spill reduction and the consequent benefits increase in a roughly linear fashion with anticipation time and with forecast accuracy (up to three to four weeks).

Benefit functions have been derived for Folsom, Shasta and Trinity Reservoirs of the Central Valley Project; for the main stem of the Columbia River and the lower Snake River; and for the large hydropower plants in the upper Missouri River Basin. Improved short term streamflow predictions can produce benefits of about one-half percent to one percent of annual generation for each day of high inflow anticipation. Three days of anticipation at Folsom with 80 percent accuracy will yield an additional 10.5 GWH of energy per year, an equivalent benefit of $52,500 at $5,000 per GWH. A rough extrapolation to all of Northern California (based on analyses of Shasta, Trinity, Folsom and Oroville) gives an annual benefit of 200 - 300 GWH.

Additional large benefits are possible if inflow forecasts are sufficiently accurate to permit reductions in the size of flood control reservations; this could be done for high confidence forcasts only. For Folsom an increase of approximately two percent of annual energy generation can be achieved per day of anticipation.

A second major cause of spillage is due to under-estimates of seasonal run-off, such that less than allowable releases are made early in the season. This type of loss mechanism can occur with very large reservoirs (power pool approximately equal to total seasonal run-off). The large reservoirs on the Missouri are in this category, but analyses indicate little likelihood of beneficially altering the release schedules of these reservoirs because of downstream flow constraints.

Better seasonal estimates can also serve to reduce flood reservations when these are determined (in part) by expected run-off for the remainder of the season.

2. Role of Improved Information Systems

Hydropower output can be increased through use of information systems that provide increased anticipation times and accuracies for high inflow events. There are two basic anticipation mechanisms. The first is weather and climatic forecasting; current forecast methods limit the anticipation time for reasonably accurate forecasts to less than three days.

The second mechanism is hydrologic system lag time, i.e., the time between rainfall or snowmelt and inflow to the reservoir; this lag time is a function of the system topography and geometry, the value of the snowpack and ground hydrologic system state variables, and the locations of the reservoirs with respect to the watersheds. This lag is normally in the range of 0 - 5 days.

3. Hydrologic System Modeling

A hydrologic model is required for the short term inflow forecasting process. The accuracies of existing models are reduced because they do not represent the snowpack as a complex, time-varying hydrologic system which interfaces with a ground hydrologic system. Snowpack parameters such as density and liquid water content profiles, which determine drainage rates during the all-important melt season, are not utilized. In addition, although the better models include options for sub-basin partitioning and snowpack energy budget calculations, these options are rarely used for lack of sufficient data.

Current hydrologic models employ a relatively large number of parameters; the most sensitive of these simulate underground soil physics and are not amenable to sensing in the field. Those variables which are available for sensing and have high sensitivity values (ratio of percent change in run-off to percent change in variable) are, in approximate order of importance:

1) Precipitation amount
2) Upper Zone Soil Moisture content
3) Snowpack area, Water Equivalence
4) Insolation, Air Temperature, Wind Speed.

Most models do not obtain the data for item 4). Water equivalence of the snowpack is currently sampled by pressure pillows (and manual surveys) and is sometimes used in estimating total seasonal runoff. Other aspects of the snowpack structure which are vital to daily inflow forecasts and to time lag estimates between precipitation and inflow can be sensed with radio isotope/ microwave profilers, but these are not in operational use. Snow depth, density profile and liquid water content profile, which are strong indicators of pack maturity, can be sensed with these devices. These snowpack parameters rank in importance between items 1) and 2) during the snowmelt season.

Because many variables contribute to the overall accuracy (variance) of the model, a large improvement in any one variable will not reduce total variance appreciably.

Short term streamflow predictions on the basis of hydromet modeling of watershed runoff phenomena are used only by a few major hydropower operators, but the use of such models is gradually being extended. Programs should be initiated to encourage and support the extension of information systems using this technology to a broader sector of the hydropower industry.

4. Synoptic Models

A number of investigators have developed relationships between fraction of total seasonal runoff and the fraction of basin area covered by the snowpack, based primarily on LANDSAT MSS data. Good correlations have been obtained for selected watersheds for one or two snow seasons. If a high degree of correlation can be obtained over a number of years of observations, the relationships would help improve refill strategies for reservoirs, particularly those that derive a major fraction of season inflow from the snowpack. Data gathering for this purpose has been impaired by lack of cloud-free viewing time over major watersheds in the Pacific Northwest, which is the major producer of hydropower in the United States.

5. Weather Forecasting

Weather forecasting shows rapidly decreasing accuracy with time and quantity of precipitation; accuracy levels seldom exceed 30 percent, and predictions generally are limited to 2 - 3 days. Since high inflow events must be forecast with reasonable accuracy for improved hydropower benefits, both of these characteristics reduce its effectiveness. Use of historical records for local weather patterns (the "MOS" technique) can yield improvements, both with regard to precipitation probability and amount, and to factors such as wind and air temperature. The MOS technique is presently being tested for use in the Columbia River Basin. The use of remote sensors for enhancing weather predictions for hydropower uses does not appear promising for the near term.

6. Remote Sensors

The only significant and proven remote application of air/spaceborne sensors to date is the use of visible and IR photoimaging for the sensing of snowpack area. These sensors are operationally limited by cloud and forest cover and by the requirement for sufficiently low altitude for good imaging. The latter results in low frequency satellite coverage, which exacerbates the cloud problem. Nevertheless, MSS sensors are useful for updating snowpack areal extent when such sensing is feasible.

The extent of forest cover and other hydrologic model parameters can be sensed by these sensors but there is little cost incentive for such sensing because most such parameters are relatively unchanging. IR sensors can detect meltwater on snow, but such meltwater is a diurnal occurence and no particular indicator of snowpack maturity.

Remote microwave sensors are in the initial stages of some promising developments, but considerable theoretical and developmental efforts are required to make these sensors operationally useful. Both passive and active sensors can be potentially effective in the frequency bands less than 10 GHZ, although dense foilage will always present problems; passive microwave at orbital altitudes suffers from poor resolution and low signal power.

Basic difficulties for both types of microwave sensing arise from the complex nature of the snowpack and its interface with the ground hydrologic system, and the extreme non-uniform conditions over the watershed. It may be possible to develop simple, inexpensive reflectors placed at various heights above the ground, and distributed at key watershed locations, to enhance the effectiveness of active air/spaceborne microwave "probes."

With a few exceptions, there is a lack of quantitative data, either from analytical or experimental studies, to perform a detailed assessment of the feasibility of measuring hydrometeorologic model variables with air/spaceborne microwave sensors.

7. Information System Concept for the Near Term (to 1985)

Based on a review of sensor requirements and state of the art and near term capabilities, it appears that improvements in information systems for hydropower operations will depend primarily on more extensive use of ground based sensors in conjunction with better ground and snowpack hydrologic models, MOS weather forecast techniques, and satellite data collection systems. The Columbia River Operation Hydromet Management System (CROHMS) incorporates many of these elements, or is planning to do so. The basic hydrologic model of the SSARR type contains the requisite snowmelt and split watershed options. A denser sensor net and correlation of field data with that obtained from heavily instrumented reference stations in the area would support such options and would reduce sampling errors, which are a major error source for these models. In addition, recent ground sensor developments, such as the microwave liquid water profiler and the radio-isotope density gage, make possible a much more adequate treatment of snowpack structure and maturity than heretofore. MSS supplied snowpack areal extent information is desirable, updated as frequently as is feasible. MOS weather forecast techniques would tend to increase high inflow anticipation.

Recommendations

In addition to on-going activities discussed above, the following recommendations are made for new analyses and R&D program activities.

1) Reformulate watershed runoff models to include snowpack parameters such as density and water content profiles and water equivalence. Adequately subdivide a heterogeneous watershed into subregions.

2) Initiate demonstration tests of selected air/spaceborne microwave sensors for measuring snowpack state conditions including passive "reflector" aids.

3) Develop reliable, low cost ground based sensors for measurement of precipitation and soil moisture.

4) Expand the use of satellite data relay systems techniques for selected projects and for specific regions.

5) Determine the effectiveness of MOS outputs for snowmelt prediction.

6) Establish through analyses the inflow forecast reliability necessary for the hydropower operator to use such forecasts regularly in his determination of reservoir release policy.

7) Determine acceptable forecast reliabilities for reducing reservoir flood control space in response to these forecasts.

8) Initiate a nationwide program for the use of advanced hydromet information systems for control of relatively short term high inflow events. Specifically:

   a. Extend survey of hydropower installations to determine types of hydromet information systems required, and the number of installations requiring each type; the analysis methodology outlined on page 2 is well suited for this purpose.

   b. Initiate and support a program to disseminate the modeling, instrumentation, and computer-communications system technology to the user community defined in (a).

c. Encourage and support the development of efficient, inexpensive instrumentation to monitor snowpack conditions.

d. Encourage and support the development of more effective hydromet modeling technique for the user community identified in (a). These are the prime elements in predicting dynamic inflow events.

e. Prepare and disseminate to the user community planning implementation guidelines manuals for hydromet information systems including data acquisition, transmission and processing.

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