THE DEVELOPMENT AND APPLICATION OF A HYDROLOGIC MODEL AS AN OPERATIONAL TOOL

By

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During the Spring of 1969, a record-breaking Sierra Nevada snowpack produced snowmelt flooding which threatened cities and inundated many acres of rich agricultural lands in California's San Joaquin Valley.

The San Joaquin Valley covers the southern two-thirds of the Great Central Valley of California. It is bounded on the east by the Sierra Nevada, and on the west by the Coast Range. The valley is 250 miles long and averages about 40 miles in width, the greatest width being 55 miles. The area of the valley floor is approximately 10,000 square miles.

The northern half of the valley, the San Joaquin River Basin, drains through the San Joaquin River northward to San Francisco Bay. The southern half of the valley, the Tulare Lake Basin, is an interior drainage tributary to evaporation sumps in the trough of the valley, chiefly Tulare and Buena Vista Lake Beds. These two basins contain about 40 percent of the irrigable lands of the State. Together they comprise the greatest and most productive single irrigated agricultural area of the State.

January Storms

During January 1969, California experienced one of the greatest storms on record in the San Joaquin Valley. Grant Grove in the Kings River Drainage had 38.18 inches or 582 percent of its January normal, while Giant Forest in the Kaweah River drainage had 49.55 inches or about 650 percent of normal.

Throughout a major portion of the January storms, precipitation occurred as snow at the higher elevations. By February 1, the mountainous areas tributary to Tulare Lake Basin had an accumulated snowpack measuring approximately 150 percent of the April 1 normal, and over 250 percent of normal for February 1.

January runoff filled reservoirs to levels above permissible storage for that particular time of the season. Above average releases from these reservoirs coupled with local inflow had flooded 8000 acres with about 30,000 acre-feet in the highly developed agricultural area of Tulare Lake.

February Storms

February storms resulted in heavy accumulations of snow throughout the southern Sierra. Many stations received 250 percent of their normal monthly accumulation. Heavy runoff during February prevented operators from lowering reservoirs to desireable levels. By the end of February, 30,000 acres of Tulare Lake Basin were flooded with about 315,000 acre-feet. Although precipitation during March was only 60 percent of normal, by the end of March there were 73,000 acres flooded with about 540,000 acre-feet stored in the flooded area.

Need For Additional Forecasting Capabilities

With a record snowpack above the 6000 foot elevation, with the valley floor partially flooded and saturated from heavy rains, and with all regulating reservoirs encroaching heavily into flood control storage, it was obvious that in addition to the forecast of total runoff volume currently prepared by the California Department of Water

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Resources, forecasts for instantaneous discharge and probable time-distribution of the record breaking runoff would be essential in project operation. In late February, the Department retained a consulting firm, Sierra Hydrotech, to assist in development of continuous flow forecasting technique for application to the Kings River Basin. More specifically, Sierra Hydrotech was to develop a hydrologic computer model of the Kings River Basin to simulate runoff from the record breaking Sierra snowpack based upon temperature, precipitation, snowpack, and other readily available hydrologic parameters. This project was to be accomplished under extreme deadline conditions with a projected May 1 date for operational forecasting. The model was to be based upon a similar model developed for several smaller watersheds located in the Upper American River watershed. Differences in elevations, drainage areas, and other pertinent watershed characteristics had to be determined and taken into account and applied to the basic hydrologic model in order to develop an operational tool for the Kings River by the deadline date.

Kings River Snowmelt Model

The snowmelt model originally prepared by Sierra Hydrotech was developed for a watershed of approximately 80 square miles in the upper reaches of the American River Basin. Elevations ranged from about 4500 to 9500 feet. The Kings River on the other hand has a watershed of approximately 1600 square miles and elevations ranging from 1000 to 14,000 feet. Although it would have been preferable to develop a series of snowmelt models to cover the wide range of elevations in the Kings River watershed, time limitations made it necessary to develop a single model for the entire watershed.

Figure 1 is a flow chart representing operation of the Kings River watershed model. The model was developed on an IBM 360, Model 30 computer and is now run operationally on the Department's CDC 3300. Input was restricted to basic data readily available on a daily basis from stations in and adjacent to the Kings River watershed. Model input includes estimates of daily precipitation over the watershed and daily temperatures throughout the watershed. Estimated precipitation was based upon the historic relationship between precipitation stations available and the reaction of the watershed. A temperature index for the basin was estimated from daily measurements of maximum and minimum temperatures at two stations, first adjusted to the 7000 foot elevation, and then related on an historical basis to the effect of temperatures upon runoff. Mean daily inflow to Pine Flat Reservoir was used when available as input to a water inventory as well as a comparison with mean daily flows computed by the program.

The other essential item of basic data required for model operation is quantity of water in the snowpack available to melt and produce runoff. This quantity is based upon snow survey data obtained by the Department of Water Resources and its cooperators. Accuracy of this estimate is important in operation of the model and contingent upon accuracy of measurements made in the field by snow surveyors.

Output from the model consists of a hydrograph of total basin runoff on a daily basis. The computer plots a daily hydrograph and tabulates input and output information for analysis. (Figure 2) Items indicated on the output plot are: (1) Actual daily runoff in cfs when available, (2) runoff in cfs as computed by the model, (3) daily precipitation in inches, (4) weighted mean temperature in degrees Fahrenheit, corrected to the 7000 foot elevation. The runoff plot also includes information for determining what portion of the total daily runoff results from snowmelt, precipitation, and other sources.

The overall model is composed of five basic sub-models, each producing its own hydrograph of daily runoff, the sum of which represents total outflow from the basin. These hydrographs include summer and winter base flows, flow directly from precipitation, flow directly from snowmelt, and a recession flow resulting from precipitation and snowmelt which have passed through temporary storage in the watershed (Figure 1).

Summer Base Flow. Summer base flow represents minimum discharge expected toward the end of the water year after snowmelt and recession flow have been depleted. A relationship was developed between minimum flow and total volume of runoff from snowmelt. Even in a year like 1969, summer base flow accounted for only about 300 cfs of the total flow.

Winter Base Flow. Analysis defined a relationship between runoff to date in a given water year and minimum daily discharge during the winter months. Many factors influence this daily minimum discharge, including precipitation, snowmelt, and freezing

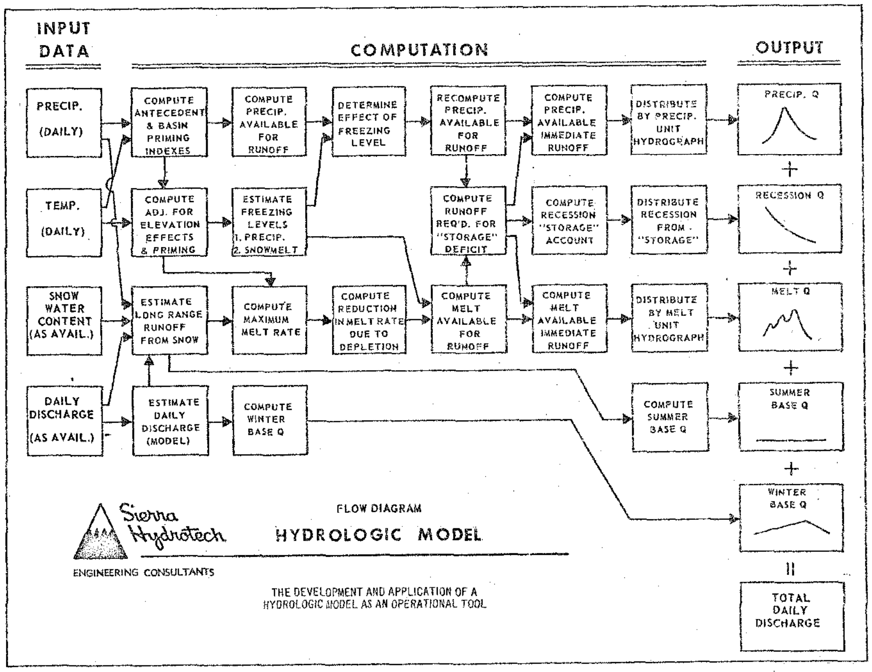

FIGURE 1

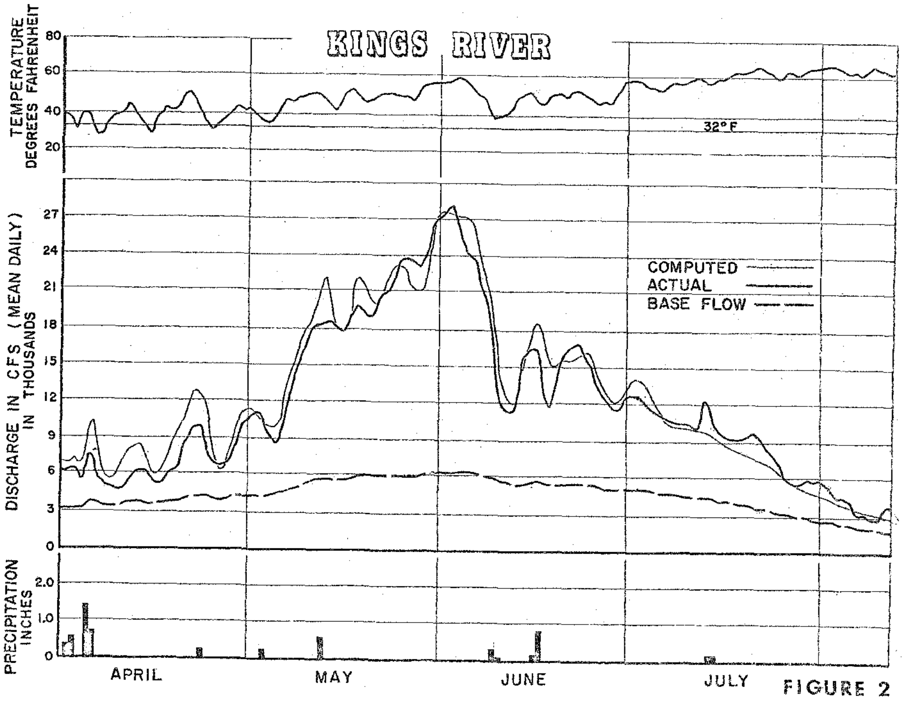

FIGURE 2

conditions. However, it was possible to establish an envelope line delineating the minimum daily flow as related to total volume of discharge to date, representing a winter base flow dependent on overall basin wetness. Winter base flow was found to build consistently into the snowmelt season, and then to decay at a rate consistent with the amount of snow left to melt in the watershed. The maximum value of winter base flow in 1969 was only 800 cfs, while the maximum combined flow during the snowmelt season was approximately 28,000 cfs. In years where total amount of snow available to melt is less, this discharge becomes a more significant proportion of overall runoff.

Recession Flow. Recession flow is that runoff resulting from snowmelt or precipitation which passes through temporary natural storage in the watershed and runs off at a variable but predictable rate. This storage could be in lakes, river channels, snowpack, soils, or any other natural storage in the watershed which prevents a portion of the runoff from producing an immediate effect upon the hydrograph. The maximum volume of this transient storage on the Kings River watershed during 1969 was found to build as great as 180,000 acre-feet. In drier years this volume would be much smaller.

There are two important features relating to recession flow. First there is a controlled rate of inflow to storage. Rate of inflow is controlled first by rate of snowmelt or runoff from precipitation, and second by volume of water currently in storage. As amount of water in storage increases, the rate of inflow of storage decreases, forcing more runoff from snowmelt or precipitation to occur as direct rather than delayed runoff. The second feature is a controlled rate of outflow from storage dependent upon the amount of water in storage at the time.

Recession flow suppresses the hydrograph from direct runoff and distributes the volume of water over a longer time period. One effect of recession flow is to compensate for the rather short four-day hydrographs used to describe distribution of snowmelt and direct runoff from precipitation.

Precipitation Runoff. Precipitation runoff is that runoff resulting directly from precipitation. This runoff is normally rather small in the higher elevation southern Sierra streams where most precipitation from winter storms occurs as snow. This particular study was directed at runoff during the snowmelt season when precipitation is normally light, so those relationships dealing with precipitation and runoff were not stressed. However, since there was some possibility of heavy precipitation as late as May during the snowmelt season, it was necessary to include a means of evaluating this effect. Heavy precipitation did not materialize during the 1969 snowmelt season.

Runoff resulting from precipitation is related to precipitation by variable rates dependent upon the following: (1) Overall basin wetness, expressed in antecedent index, is used to estimate rates of loss to direct runoff as a storm progresses. (2) Total amount of runoff resulting from basin wide precipitation is dependent upon freezing level, since precipitation which falls as snow will remain as part of the snowpack until temperatures become high enough to release it as runoff. (3) As the volume of recession storage increases, the rate of inflow to that storage decreases, thereby increasing the volume of direct runoff. After direct runoff is computed on a daily basis from daily precipitation and temperature, it is distributed time-wise by a four-day hydrograph developed from historic records. During periods of major flood producing storms, the four-day hydrograph does not peak adequately, and flows in excess of a selected base were distributed by a supplementary two-day hydrograph to achieve the required peak. The remainder of direct runoff from precipitation passes through temporary storage and appears as recession flow, extending the effective length of the basic four-day hydrograph.

Snowmelt. Runoff resulting from snowmelt is probably the most important single unit of contribution to the Kings River hydrograph. This was especially true during the Spring of 1969.

Air temperatures index both priming of snowpack and rate of melt, but must be used in conjunction with other factors to fully describe the snowmelt hydrograph. Maximum and minimum daily air temperature were used as basic data, since these data have been available over a number of years and it was possible to establish a satisfactory historical relationship with discharge. Temperature data from several stations were adjusted to a single elevation, permitting the model to operate even though all stations may not report on a given day.

The maximum potential rate of melt is related to many factors including snowpack volume and area available to melt, amount of priming, and amount of energy input to the snowpack. Snowpack volume was estimated from historical snow survey data. A relationship was developed between amount of snow available to melt and maximum potential rate of melt per unit of energy input (Figure 3, Curve I). The unit of energy input is derived from air temperatures as an index to total energy available to the snowpack.

The basin does not achieve maximum potential rate of melt immediately during the snowmelt season, as the snowpack must become primed to achieve this rate. Figure 4 delineates a typical example of the relationship between priming and time. Priming varies from zero to 100%. Note that this does not imply that the entire basin becomes fully primed at the same time. As the snowline increases in elevation so does the effect of priming, tending to stabilize the potential maximum melt rate. When 100% is reached, the maximum rate of melt for that season may be achieved, dependent upon temperatures encountered.

The basic melt rate curve is closely related to time. A priming effect, dependent upon accumulative temperature with a fixed decay rate, is superimposed on the basic curve. Regardless of recorded temperatures, there appears to be a minimum rate of priming related to time. Perhaps this rate of priming represents energy input from radiation which may be less variable from year to year than air temperature. Note that the temperature effect is additive, but that a series of cold days may cause the net temperature effect to decrease. As a consequence of the multiple effects upon priming, the date at which the watershed reaches its maximum priming effect may vary from late April to late May.

A second curve relating remaining snowpack to rate of melt per unit energy input is shown in Figure 3, Curve II. The rate of melt follows this curve as volume of snowpack decreases, until by the end of the snowmelt season, the rate had dropped to zero. This is actually a three dimensional curve which is difficult to show in graph form with the third dimension related to depth of the snowpack. Two years with the same quantity of water in snowpack may have different area distributions of snowpack. One year may have deep pack over a small area while another year may have shallow pack over a large area even though the net runoff from snowmelt may be the same in each year. Since the amount of snowpack remaining is related to total snowmelt runoff after date of forecast, the computed volume of remaining runoff is used to determine the position on Figure 3, Curve II.

It is possible that the maximum potential melt rate indicated on Figure 3, Curve I may never actually be achieved in a given year if the <u>area</u> of snowpack subject to melt decreases faster than priming increases the <u>rate</u> of melt. This condition often occurs in years of light snowpack.

Progression of melt rate per unit of energy input throughout the 1969 season is delineated in Figure 4. The rate increases during priming to the maximum potential melt rate about May 15 and then starts to decrease about May 28 as snowpack dwindles. Once this rate starts to fall, higher and higher temperatures are required to maintain constant quantities of melt.

After the degree of priming, maximum potential melt rate, and snowpack remaining to be melted are determined, it is possible to compute the total volume of snowmelt for a given day using adjusted temperature data. Figure 5, Curve A, delineates the total daily melt for the date on which it was computed to have occurred. After total daily volume of melt is computed, volume of water in recession storage is tested and a portion of the melt is put into recession storage. The remainder is subjected to distribution by a four-day hydrograph. In the case of the Kings River, different four-day hydrographs were required to distribute the direct runoff from snowmelt and precipitation, suggesting a moderating effect of the snowpack itself upon snowmelt runoff. The computed runoff after distribution by hydrograph and recession, including base flows, is delineated in Figure 5, Curve B.

<u>Total Flow</u>. Total flow is computed as the sumation of the five sub-models -- summer base flow, winter base flow, recession flow, precipitation flow, and snowmelt flow. These five basic sub-models appear to adequately cover the range of contribution to total flow encountered in the twenty-year development period on the Kings River watershed. Elimination of any one of these sub-models made it virtually impossible to achieve good simulation. Figure 2 represents the simulated flow for April through August 1969 as compared with actual flow. Modeled flow is based upon actual conditions of temperature and precipitation for the entire season. The hydrograph shown below the main hydrograph represents the summation of summer base, winter base, and recession flow.

MELT RATE CURVES

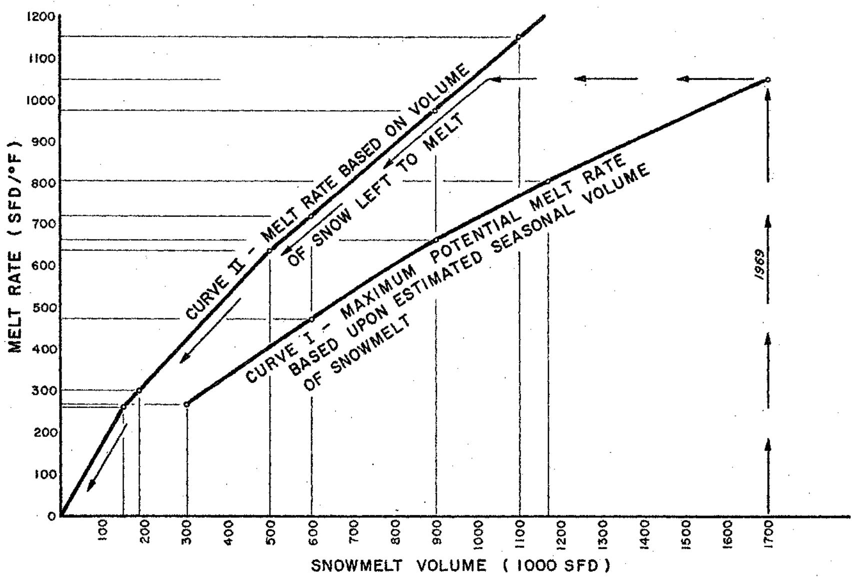

FIGURE 3

PROGRESSION OF MELT RATE WITH TIME
Kings River 1969

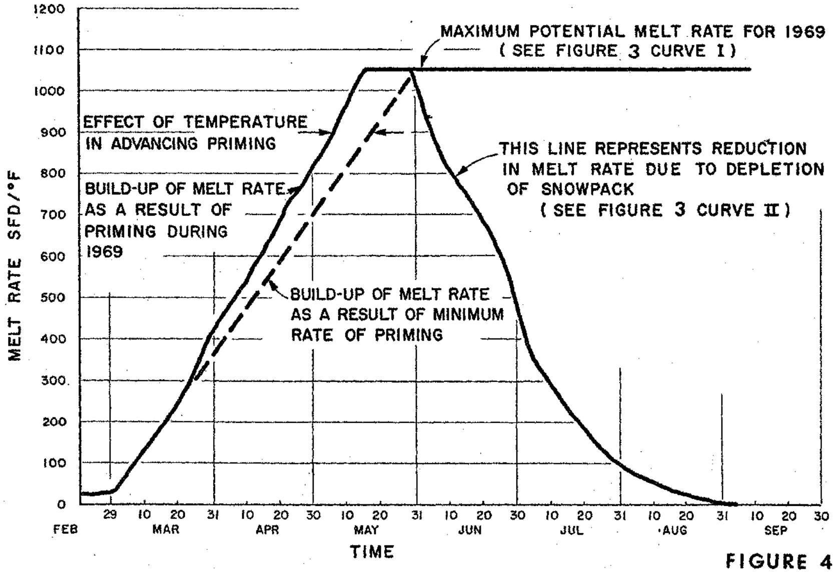

FIGURE 4

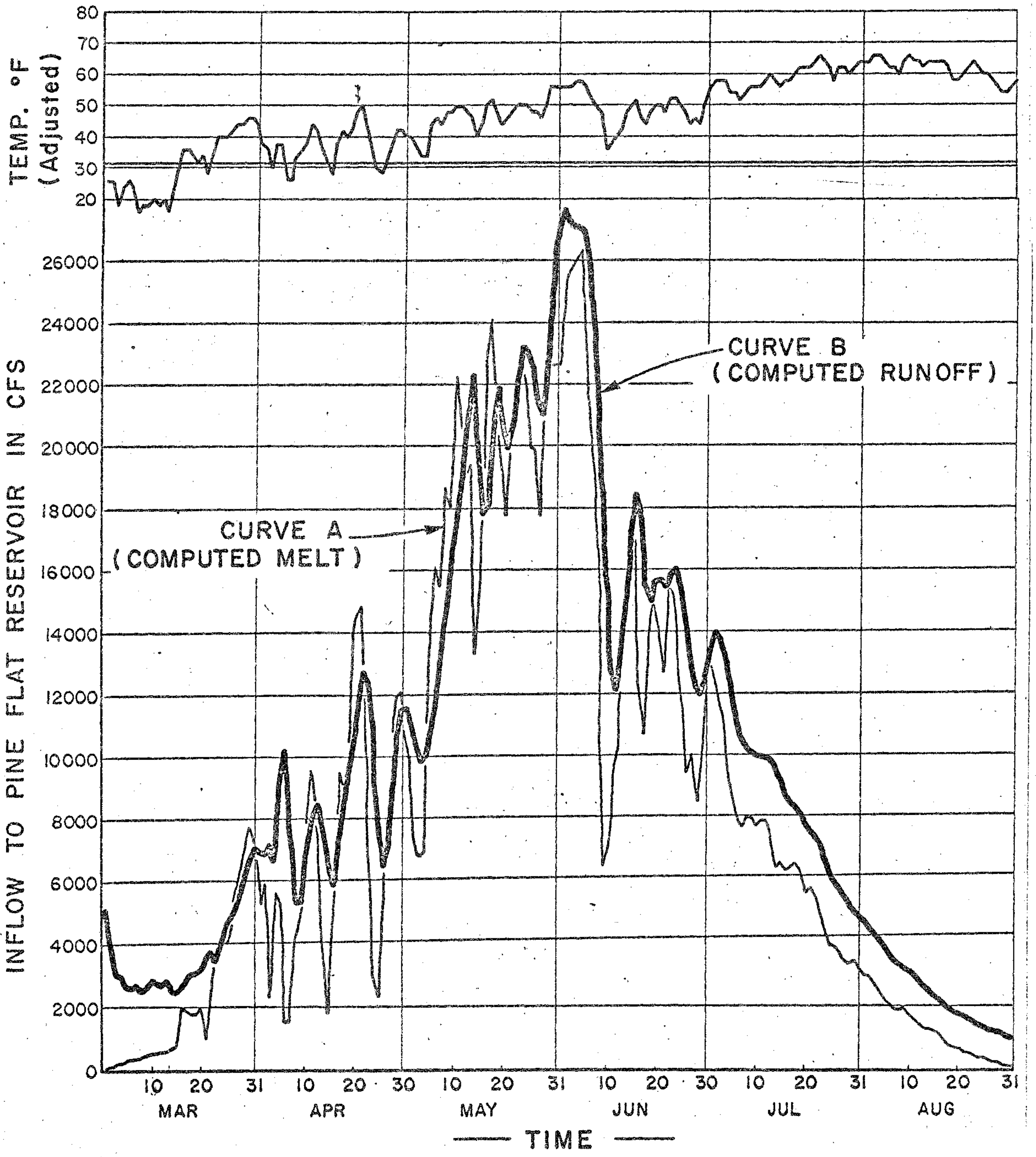

Figure 5. Comparison of Daily Melt and Daily Runoff

<u>Application of the Model</u>

The Kings River snowmelt model was operational by May 1, and on May 4,1969, the first operational forecast was prepared.

By this time, everyone in operational forecasting was in agreement that there was enough water to fill existing reservoirs two or three times. However, the important questions were those concerning time-distribution of runoff and maximum peak rates of discharge. The snowmelt model became a tool to estimate time-distribution of the runoff volume forecast by applying historical temperature regimes after the date of forecast to hydrologic conditions as they existed as of date of forecast, 1969. Historic temperatures that have occurred during runoff seasons for each of the past twenty years were applied to the model, giving a range or array of runoff conditions which might be expected. The forecast could be updated daily if necessary to account for precipitation or temperature conditions as they actually occurred.

By analysing computer output from this model for twenty years of historic input data for the period after the date of forecast, the following information was developed; (1) The date of peak runoff, (2) the maximum mean daily discharge, (3) the number of acre-feet for any time period required after the date of forecast, and (4) the approximate date upon which the flow would drop below any specific discharge.

The items above were determined for each of the twenty-years analysed, permitting development of ranges, averages, and medians for each item (Table I). By analysing daily forecast flows from the model and knowing planned reservoir releases, it was possible to estimate the date the reservoir could be expected to fill.

TABLE I

Analysis of model ouptut for 20 years of historic input data.

Date of this particular model run was May 16, 1969 with actual data through May 13, 1969.

Year	Discharge (1,000 cfs)		Distribution of Runoff (1,000 AF)			
	Peak	Date	May	June	July	August
1906	24.632	6-22	840	1,085	760	152
1950	28.376	6- 3	1,075	1,085	555	126
1951	27.403	5-28	1,090	1,130	503	127
1952	24.404	6- 7	1,045	1,025	600	166
1953	23.288	6-25	803	1,045	805	185
1954	25.913	5-22	1,100	1,082	564	129
1955	29.630	6-10	1,031	1,148	520	166
1956	24.040	5-24	1,050	1,180	512	127
1957	28.878	6- 6	890	1,296	554	132
1958	21.647	6-19	1,022	1,051	602	180
1959	26.048	6-15	866	1,316	566	128
1960	31.044	6- 6	894	1,388	482	116
1961	29.925	6-18	942	1,322	510	110
1962	23.917	6-23	844	1,190	646	174
1963	23.660	5-22	1,028	1,042	598	188
1964	23.058	6-27	986	1,078	624	172
1965	22.265	6-13	916	1,055	678	194
1966	26.466	6-17	1,120	1,140	478	136
1967	26.506	5-24	1,072	926	712	160
1968	26.694	6- 5	1,008	1,280	486	106
Median	26.000	6- 8	1,030	1,107	565	142
Range	21.6/31.0	5-22/6-25	803/1,120	926/1,388	478/805	106/194

Conclusion

Modeling techniques described in this paper have resulted in detailed representations of hydrologic processes occurring in the Kings River watershed, leading to real time operational studies based upon readily available hydrologic parameters. The modeling techniques can be developed into an effective operational tool in the hands of the hydrologist, although a watershed model in itself is not a forecast procedure. Such a tool enables the hydrologist to analyse large quantities of historic data and to isolate those hydrologic relationships important to his operational problems. The effect upon runoff of any probable sequence of temperature of precipitation may then be estimated with respect to current hydrologic conditions.

Application of modeling techniques to operational problems is limited only by the imagination of the hydrologist, who, knowing hydrologic conditions as they exist today, must answer that all important question, "What would happen if . . . . ?"