MAKING OBSERVATIONS AND MODELS AGREE IN SPRING SNOWMELT FORECASTING

759-84

by

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INTRODUCTION

Hydrologic models are often judged by the goodness of fit between the computed and observed hydrograph running over some extended period of time. In real-time forecasting, however, the ease with which the model can be adjusted to match observed conditions is an equally important measure of a model's fitness for operational use. In the Pacific Northwest, the National Weather Service (NWS) uses the Streamflow Simulation and Reservoir Regulation (SSARR) model for streamflow and flood forecasting. The SSARR model has been carefully developed to balance model complexity and ease by which model variables can be changed in real-time forecasting.

FORECAST PRODUCTS

General

The National Weather Service hydrologic program has two main parts: a flood forecasting service and a water management information service. The flood forecasting service includes responsibilities for (1) flood forecasting at all locations with potential flood damage on major rivers, tributaries and lakes, (2) cooperating with federal, state and local agencies to develop and operate local flood warning systems, and (3) providing a flash flood watch and warning service. The water management information service includes responsibility to serve a wide range of federal, state, local and private users of hydrometeorological data and river forecast information for water management purposes such as water supply, reservoir operations, recreation, hydropower generation, agriculture, fish management, and the like. The Northwest River Forecast Center (NWRFC) in Portland, Oregon, has forecast responsibility for the Columbia River basin, Oregon and Washington coastal drainages, and a portion of the Great Basin in southeastern Oregon.

The spring melt season usually provides the highest flows on the Columbia River mainstem and on its eastern tributaries. During this period, the NWS issues a number of products.

Seasonal Water Supply Forecasts

Forecasts of seasonal water supply are prepared by the NWRFC for 173 points in the Pacific Northwest, including the portion of the Columbia River basin in British Columbia. Seasonal volume forecasts are generally prepared from December 1 to June 1. "First-of-the-month" forecasts from January 1 to May 1 are carefully coordinated with other agencies which may have "primary" responsibility at certain points, such as the Soil Conservation Service, British Columbia Hydro and Power Authority, and operating agencies such as the Corps of Engineers and the Bureau of Reclamation. The forecast preparation and coordination process is fairly time consuming, and official "first-of-the-month" forecasts are usually available for public release between the sixth and ninth day of the month. These forecasts are published jointly by the National Weather Service and the Soil Conservation Service in the monthly bulletin, _Water Supply Outlook for the Western United States_, January 1 through May 1. The NWRFC also prepares mid-month (around the 15th) and "early-bird" (between the 28th and the 2nd) water supply forecasts. The intermediate forecasts use accumulated precipitation (and to some extent, observed snow water equivalent) to bring seasonal volume forecasts up to current knowledge, using the coordinated first-of-the-month forecast as an anchor point from which to trend up or down. The forecast procedure is such that a single equation is used for the entire year, so that updates move smoothly from the first of one month to the

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first of the next month without "yo-yoing" such as occurs when different forecast procedures are used each month. The procedure can use either a precipitation index, a snow index, or an optimal combination of both. The basic technique was reported by Schermerhorn and Barton (1968). During the 1976-77 drought year, water supply updates were made weekly. For the past 15 years, mid-month and "early-bird" volume forecasts have been provided primarily to major operating agencies such as the Corps of Engineers, Bureau of Reclamation, and Bonneville Power Administration. The need for broader dissemination of these intermediate forecasts is now being evaluated.

Season Peak Stage/Flow Outlook

Once the winter snowpack starts to accumulate, the National Weather Service periodically issues outlooks for peak stages and/or flows expected to occur during the spring melt period. Outlooks are generally issued monthly beginning March 1, but additional bulletins are issued as unusually heavy winter precipitation and snow pack dictate. In the Pacific Northwest, outlooks are issued as a range within which the actual peak has 50% probability of occurrence. The NWRFC uses two basic ways to forecast seasonal peak stage or flow. The primary method uses cross-plot relations between historical peaks and the seasonal water supply volume. The cross-plot for the Big Wood River at Hailey, Idaho, is shown in Figure 1. This is most useful early in the melt season for unregulated points. The second method uses the daily flow forecast model, evaluating basin response under the variety of future melt sequences which might occur. This technique is more appropriate for regulated forecast points which are subject to significant differences in early season storage upstream from one year to the next. Also, the model technique is more effective later in the season when the model is able to incorporate the knowledge that, for example, an unusually high or low runoff to date has occurred. Both methods are used at most sites.

Peak stage flow outlooks give early warning of major flood possibilities. This allows local residents to take steps to reduce flood damages. As a result of early warning of potential record streamflows on the Big Wood River at Hailey, Idaho, in the spring of 1983, thousands of sandbags and tons of rip-rap were stockpiled. When the flood peak arrived on May 30, 1983, the community was ready. Although several hundred trees, several bridges, and large amounts of river bank were lost, no homes were lost to the river. Early forecast runs and peak flow range outlooks are shown in Figure 2. The location of the Big Wood River is shown in Figure 3.

Daily Spring River Forecasts

Routine river forecasts are made daily, or more often as required. These use six-hourly forecasts of precipitation for the next three days and forecasts of daily maximum temperature for the next seven days. Flows and lake elevations are forecasted for every six hours for the first three days, then for daily values only for the next 30, 60, 90 or 120 days. Forecasts at controlled points are made cooperatively by the National Weather Service and the U.S. Army Corps of Enginers (USCE), with some additional support by the Bonneville Power Administration (BPA). Cooperation among these agencies for preparation and use of cooperative forecasts is through the Columbia River Forecast Service (CRFS), an affiliation established by memorandum of understanding over a decade ago. Forecast runs on different days each week use different temperature sequences, locally known as "WOWs", beginning the eighth day out. In a typical week, there will be runs with 30-day forecasts using "early hot", "late hot", "cool", and "moderate" WOWs, and a 90-day forecast using a moderate WOW. Sample WOWs are shown in Figure 4.

Extended Streamflow Predictions

Many users need to know what is the probable range of flows at some future date. Extended streamflow forecasts made by the NWS NWRFC in cooperation with operating agencies are a vital input to the water management process during spring runoff in the Columbia basin. The operation of major reservoirs on the Columbia requires management of the water resource for many competing purposes. Some of the purposes are: flood control, power generation, low flow augmentation, irrigation, navigation, recreation, and fisheries management. The conflicts between these competing demands can be diminished by accurate extended streamflow forecasts which also provide some insight into the variability of future flows. Beginning in spring of 1984, the NWS will provide this kind of information in a new public product for selected points in the Pacific Northwest. At the present time, the product is issued only for the spring runoff period and provides a tabulation of forecasted flow or stage (at fixed dates) which would result from various future temperature sequences.

SSARR MODEL STRUCTURE FOR SPRING RUNOFF FORECASTING

The SSARR model is well known, and has been thoroughly reported. A program user manual has been published by the U.S. Army Corps of Engineers (1975), and a good user-oriented paper was given by Schermerhorn and Kuehl (1968). A zoned version of the SSARR is now being tested for implementation in the northwest, and was reported by Speers et al, (1978), with an application to volume forecasting reported by Kuehl (1979). At the present time, the lumped-basin model is still used in operational forecasting and all following discussion relates to use of the lumped-basin model. The logic of the lumped-basin SSARR is shown in Figure 5.

OPERATIONAL MODEL ADJUSTMENTS

General

In spring runoff forecasting, the seasonal volume is the key input to the (lumped-basin) model. It then falls to the model, along with precipitation and temperature forecasts, to provide a reasonable distribution of that volume through the runoff period. One problem that a river forecaster must face every day is that the model will give one flow and the river will say something different. Thus, it is necessary to keep the model "tuned" so that it will provide the best possible tracking of observed flows. As shown in Figure 5, the model variables which are directly observed are snow line elevation and percent of seasonal runoff. Other model variables are evaluated indirectly by how well each day's observed streamflow matches the simulated discharge. The soil moisture index (SMI, inset D of Figure 5) and the temperature melt rate (MR, inset B of Figure 5) are variables most commonly adjusted by the "indirect" evaluation method. The indirect method also lets the model give guidance on the directly observed variables of snow line elevation and percent of seasonal runoff, since these are only imperfectly known. Finally, the runoff from the three model elements of surface, subsurface and baseflow runoff are continuously adjusted to assure that they sum to the observed discharge at the basin outlet each day.

The relative "adjustability" of model variables is demonstrated by Figure 6 which shows that early season model adjustments are usually made to snow line elevation and soil moisture index and, in a lesser degree, to the melt rate. Once early season snow lines have been observed, remaining adjustments are thrown mainly into the soil moisture and melt rate variables. As the runoff season approaches the 50% point, the model performance in hitting the forecasted seasonal volume enters the picture. If melt rate, soil moisture index, and snow line elevation have to be stretched to unreasonable limits, then seasonal forecast volumes may be changed. Thus the model provides an independent means of checking reasonableness of water supply forecast volumes, and considerable poetic license (a literary term for engineering judgment) is used. As the season progresses beyond the 50% runoff point, the volume adjustment becomes the dominant element in model tracking. Beyond this point, the model essentially displaces conventional water supply procedures in forecasting the residual seasonal volume.

Running the Model in "Backup" Mode

A very key operation in river forecasting is the forecast "backup". This involves running the model from a prior set of model boundary conditions (or "initial conditions") up to the most recent discharge observation (usually a morning observation on the day of the run). An example of a backup is shown in Figure 7. Careful analysis of the backup run allows "tweaking" the model variables until a better match of the currently observed flow is obtained. The SSARR model allows adjustment of moisture input during the backup period by increasing it by a factor up to 2.0 or decreasing it down to 0.5. It is the responsibility of the duty forecaster to tweak model variables within reasonable ranges in order to keep the moisture input adjustments as close to 1.0 as possible, especially during a hot spell with a strong rise occurring. The adjustment factors can fluctuate quite a bit so these are noted each day on the forecast hydrograph so that all information is available at a glance. Backups may be run from any set of prior initial conditions, and there are times when a forecaster will want to backup a week or even longer to see how well overall the model is performing without the complication of intermediate adjustment of initial conditions. The model allows the option either to store or not to store a new set of initial conditions at the end of the backup run.

If changing the moisture input in a backup run by as much as a factor of two or a factor of 0.5 does not match the currently observed discharge, then flow values in the model's surface, subsurface and baseflow components are multiplied by the factor needed to make the remaining adjustment to force model discharge to equal observed discharge. This procedure, although somewhat crude, works with very good results as long as it is used with caution.

Changing the Soil Moisture Index

When the spring snowmelt begins, there is considerable uncertainty as to how the soil will respond to moisture input. The soil moisture index variable SMI is most effectively "tweaked" early in the spring melt. As the season progresses, soils become saturated in melt areas and the runoff approaches 100%, effectively eliminating SMI as a "knob" by which the model can be controlled.

Changing the Melt Rate

The melt rate MR is simply the factor by which basin temperature above 32° is multiplied to compute daily snowmelt in inches of water equivalent. In the SSARR model, the melt rate is functionally tied to the percent of seasonal runoff already observed, as shown in Figure 5B. There are two ways to change the melt rate. First, a temporary change can be made which will automatically trend back toward the function value of melt rate after a few days. This is often used during spring rain events when the forecaster feels that the model is not adequately representing condensation melt. The second way to change melt rate is to actually change the parameters which define its relationship with percent seasonal runoff. This is most frequently done when the late winter period is unusually cold and dry or warm and wet. Even at that, it is usually only the initial melt rate at the beginning of the season that is respecified, since the melt rate for a fully ripened snowpack is fairly consistent from year to year in any given basin. A noteable exception occurred subsequent to the eruption of Mt. St. Helens, Washington on May 18, 1980. Volcanic ash was deposited on melting mountain snowpacks in eastern Washington, the Idaho panhandle, and western Montana. Due to the decreased albedo, NWRFC staff found it necessary to increase ripe-pack melt rates for affected areas.

Changing the Snow Line Elevation

The snow covered area (SCA) is the principal "knob" by which the model is tuned during the peak runoff period. The snow line elevation is directly related to the snow covered area through the basin area-elevation curve. By design, SCA is a key parameter in the model since it is observable. Changes in the snow covered area in the model are tied to the percent of seasonal runoff, as shown in Figure 5C. The fixed parametric relation between the two is used until an observed snow covered area is input to the model. Since this will rarely fall right on the functional relation, a new functional relation is inferred which blends to convergence with the original relationship at the end of the runoff season.

Snow covered area is obtained in five ways. The first three ways are observational: through ground based reports of snow line elevation, by aircraft overflight to determine snow line elevation, or by determination of snow covered area (percentage) from satellite imagery. The fourth is simply by setting reasonable values on other model variables and seeing what snow covered area is needed to match observed streamflows. The fifth is by interbasin comparison of snow line elevations from one year to the next. In practice, all five techniques are used. When aircraft or satellite observations of SCA are received, the attempt is made to move the model SCA toward that value. The problem is that the new SCA may not greatly improve the model's agreement with observed flow, and may even hinder it. Furthermore, interbasin comparison of snow line elevations may show the observed values to be relatively disparate from previous observed modelled snow line elevations. Figure 8 shows an example of the interbasin comparison of snow line elevations. The relative difference between snow line elevations in adjacent basins at the same time each season is fairly dependable. Thus it falls to the forecaster to make a subjective judgment in changing snow covered area, balancing aircraft and satellite observations against model performance and interbasin comparison history.

Changing Seasonal Volume in Modelled Basins

The independent forecast of seasonal volume is fundamental to the lumped-basin SSARR. Both the melt rate and the snow covered area are functionally tied to the percent of seasonal runoff to date. The forecast seasonal volume has more the essence of a model parameter rather than a model variable, since it is a fixed quantity unless changed externally. Seasonal volume becomes a prominent adjustment point after half of the seasonal runoff has occurred. The "percent seasonal runoff" is the ratio of the runoff in inches generated by the model for the season to date divided by the forecasted seasonal volume. For most of the Columbia basin, the volumes used in the model are for the April-July period. The April-August volumes are used for the more northerly basins, while March-July volumes are used for a few southerly basins subject to typical early spring thaws.

There are two aspects to making seasonal volume adjustments. The first is adjustment of model-generated runoff to match observed runoff. The second aspect involves using the model as guidance in changing the forecasted seasonal volume. Both of these are demonstrated in Figure 9 , which is a plot showing accumulated seasonal runoff and normal accumulated seasonal runoff for the Big Wood River at Hailey, Idaho.

In order to explain the adjustment of model generated runoff, reference is made back to Figure 5. The accumulated seasonal runoff is that volume which has been input to the surface, subsurface and baseflow routing processes. The model accumulated seasonal runoff minus the volume enroute to the basin outflow point should equal the observed volume to date at the basin outlet. That is:

$$\begin{matrix}\text{observed (gaged)}\\ \text{seasonal runoff}\end{matrix} + \begin{matrix}\text{volume in}\\ \text{routing}\end{matrix} = \begin{matrix}\text{model generated}\\ \text{seasonal runoff}\end{matrix} = \begin{matrix}\text{melt accumulated}\\ \text{runoff (MLAR)}\end{matrix} + \begin{matrix}\text{rain accumulated}\\ \text{Runoff (RNAR)}\end{matrix}$$

The volume in routing is computed easily since the SSARR basin routing method uses cascaded linear reservoirs in each runoff phase. The runoff volumes in each "reservoir" are known and can be summed to get the total volume of water in transit through the routing process. Reference to Figure 9 shows that adjustments to model runoff were made on May 1, June 1, and June 20. The heavy solid line shows the normal seasonal accumulation of runoff at Hailey. The lighter line shows the actual runoff accumulation observed in 1983. The squares show the observed runoff to date plus the volume in routing to the basin outlet. The plus ("+") and the solid circles are model values of melt accumulated runoff (MLAR) and total accumulated runoff (the sum of melt accumulated runoff MLAR plus rain accumulated RNAR) respectively. After the points are plotted, the MLAR and RNAR terms are manually adjusted so that the model value of (RNAR+MLAR) equals the observed runoff to date plus the volume in routing. In terms of Figure 9 , adjustment forces the solid circle to plot on top of the square, bringing the model runoff in line with observed.

The second type of volume change, as mentioned earlier, uses the model output as guidance to changing the seasonal volume forecast itself. The model is run out to the end of the volume forecast period to see if the model prematurely runs dry or if it generates too much melt to meet the forecasted seasonal volume. If the target volume cannot be met with reasonable values of model variables, this is a strong indication that the forecasted volume itself needs revision. The forecasted April-July volume for the Big Wood River at Hailey is plotted across the top of Figure 9 . The standard water supply forecast figures were used in the model subsequent to April 1 (450,000 acre feet), May 1 (470,000 acre feet) and June 1 (464,000 acre feet). It took only a few days, however, to see that the model could not generate the runoff called for by the June 1 forecast. The forecast seasonal volume was then reduced back to 450,000 acre feet and the new figure used for the remainder of June. No further adjustments were made since model guidance was discontinued shortly thereafter. For critical water management situations, up to three or four additional volume adjustments may be made during the recession period.

Volume-Peak Model Checks

Another tool utilized in the real-time forecasting as a check and balance in the model is the volume-peak forecast. Since the volume-peak program predicts an independent estimate of the most probable peak range for individual basins, it is an extremely valuable tool to use in comparison with SSARR model basin results. At times, the basin model parameters will be adjusted to insure that the model can generate a peak within the expected peak range.

River Model Accumulator

The previous sections discussed model volume adjustments in headwater basins which use the simulation model. Not all of the pieces in a total river model, however, use the basin simulation model. The contribution from many smaller ungaged areas or from areas with relatively small surface runoff is estimated and given seasonal shaping based on historical records. Many such areas may even have average negative contributions. The net effect of the "specified" and "basin" pieces is seen when the SSARR adds up all flows as they are routed downstream.

In the standard SSARR operating model, several special dummy accumulator stations have been defined. The "stations" simply add the unregulated daily flow at particular sites into an accumulator for the volume forecast period and compare the accumulated flow to the forecasted water supply volume for that location. The volumes in the accumulators are periodically checked and adjusted to actual runoff to date. These in-season adjustments provide insight on how well the non-basin river model segments are performing and may suggest revision of the way non-basin flows are specified for the remainder of the season.

In mid- to late-season, the volumes computed in the accumulators become quite useful, especially in the upper and middle Snake River drainages. The SSARR model uses the latest basin volume forecasts from the water supply program, the latest operating plans for the projects and the latest irrigation diversion plans to generate the expected flows up to 90 days in the future. In the Snake River basin in particular, the volumes in the accumulators at the end of the forecast period are better late season estimates of the expected water supply volume than the standard water supply forecast. The accumulators provide an independent cross-check on the water supply volume forecasts for key mainstem points like the Snake River at Brownlee and Lower Granite projects and the Columbia at Grand Coulee and The Dalles projects.

APPLICATION EXAMPLE: BOISE RIVER, 1983

Early in the 1983 water supply season, it became evident that a large volume runoff year was in store for the Boise River system (see Figure 3). The operation of the Boise reservoir system was planned accordingly, with the Lucky Peak outflow set near bankfull levels for most of the period from January through March. Early in April the NWRFC, in cooperation with the U.S. Army Corps of Engineers and the Bureau of Reclamation, made a number of long-term SSARR runs to assess the possibility of the reservoir system having to fill and spill. From early April until the 26th of May, all of the forecast results showed that the system had the potential to fill and spill, except for the results from a cool temperature sequence. Indications were that the Glenwood Bridge flow could be as low as 8700 cfs or as high as 11,000 cfs. The design flow for the levee system is near 10,000 cfs. Damage begins in unprotected areas when the downstream flow reaches 7000 cfs at Glenwood Bridge. Figure 10 shows the forecast Boise R. inflow hydrograph and resulting expected fill and spill which was indicated by a forecast run on May 18th. Figure 10 also shows the snow covered area value and adjustments used during the melt season.

By the end of May and the first two days of June, the model began to indicate that the snowpack had diminished to the point that filling and spilling the Boise River system was less likely. However, on June 3rd, a snowflight was made by Walla Walla District Corps of Engineers indicating that the basin snowcover was substantially greater than that in the model (30 versus 15%). This information was input to the model and the results from June 3rd through June 8th again indicated a high likelihood of fill and spill. The resultant flow at Glenwood Bridge ranged from 9500 cfs to 12,400 cfs. Consequently, the outflow from Lucky Peak Dam was raised to 11,200 cfs which produced an after diversion flow of 7500 cfs at Glenwood Bridge. The forecasts made on June 6th indicated that warming temperatures would raise the Lucky Peak natural flow from 15,000 cfs to 18,000 cfs (the actual peak on June 11th was near 18,000 cfs). With the outflow of Lucky Peak at 11,200 cfs, the reservoir would fill causing uncontrolled spill. A coordinated effort between the Corps of Engineers, the Bureau of Reclamation and the National Weather Service to plan a gradual increase in Lucky Peak's outflow was made. The aim was to increase the outflow a controlled amount but prevent uncontrolled spill and even more serious flooding. Numerous SSARR forecast runs were made on June 6th through June 8th to test various outflow schedules. Also, test runs were made which considered "what if" rain events. After weighing all the results, a coordinated press release was made which advised the public of the schedule of outflow increases necessary. The outflow of Lucky Peak was raised to 13,200 cfs by June 12th, producing a peak flow of 9,500 cfs at Glenwood Bridge. The design capacity of the levee system is 10,000 cfs-- so the fit was very tight! Some flooding did occur at a few weak points and low spots in the levee, but major flooding was prevented. Overall, the operation is an outstanding example of the federal agencies working together to manage the water resource.

SUMMARY

A wide range of forecast products is issued by the National Weather Service, many in cooperation with other federal agencies. A universal problem is that models are imperfect and require constant attention to keep them tracking the real world. The immense value of improved flood warning and water management shows that the many checks and balances built into the forecasting system are clearly worth the effort.

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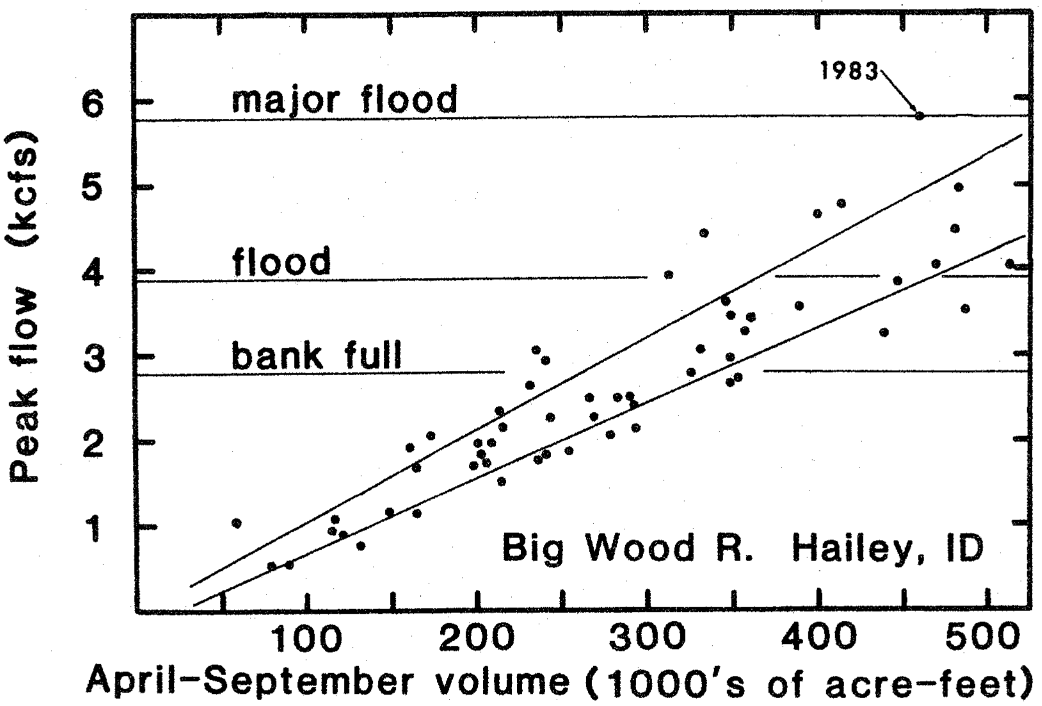

Figure 1. Peak flow versus seasonal volume cross plot

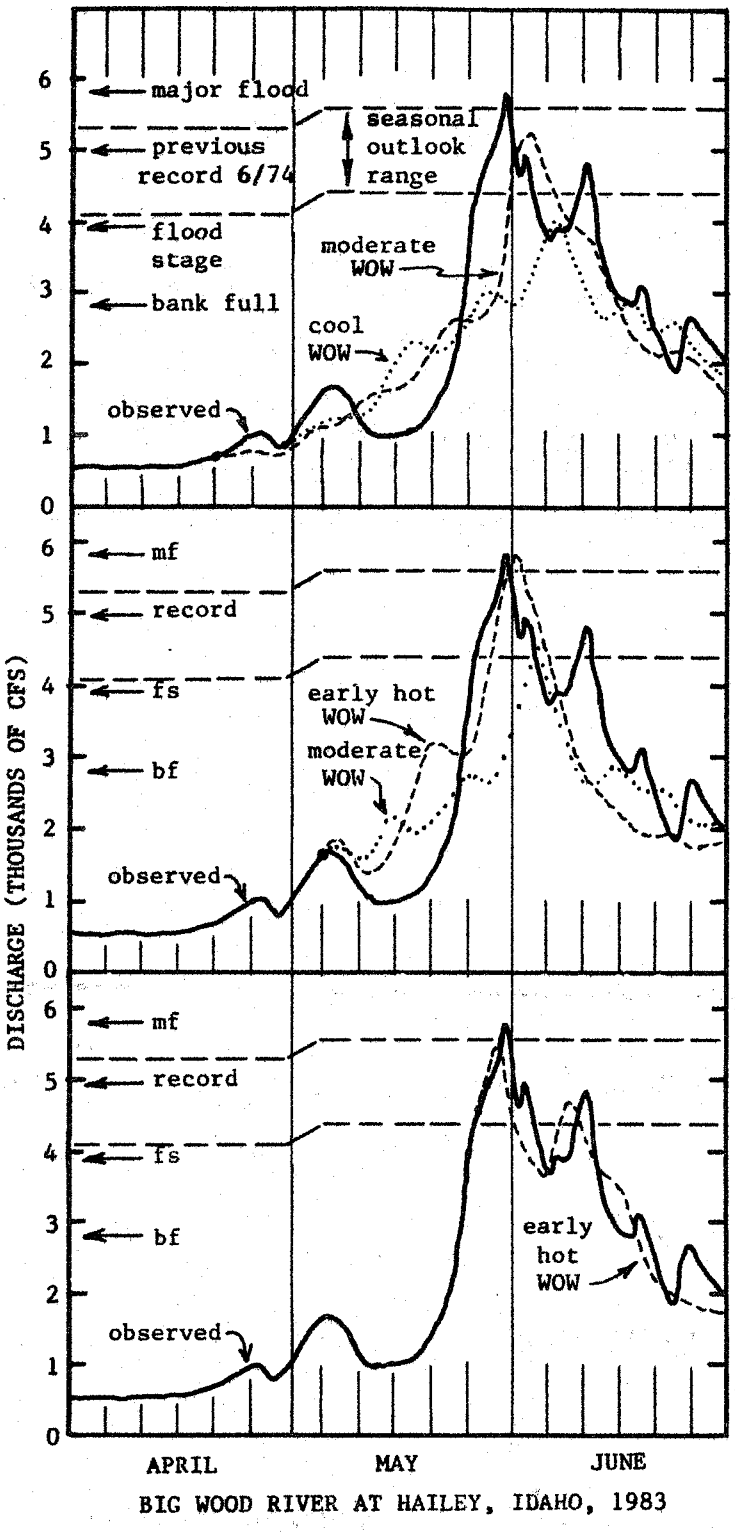

Figure 2. Seasonal peak flow outlook and SSARR model forecast runs gave early warning of Big Wood River flooding.

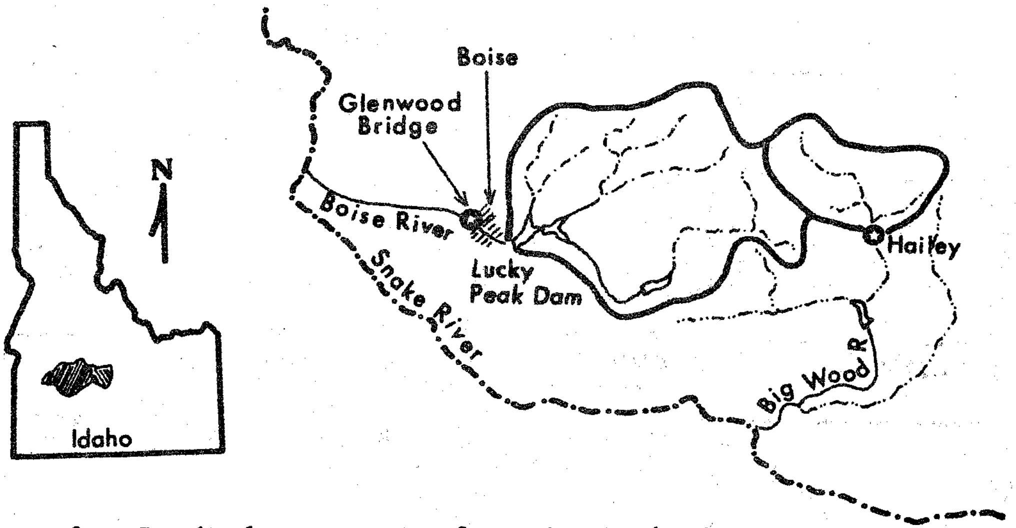

Figure 3. Basin locator map for Big Wood River at Hailey, Idaho, and Boise River at Glenwood Bridge, ID.

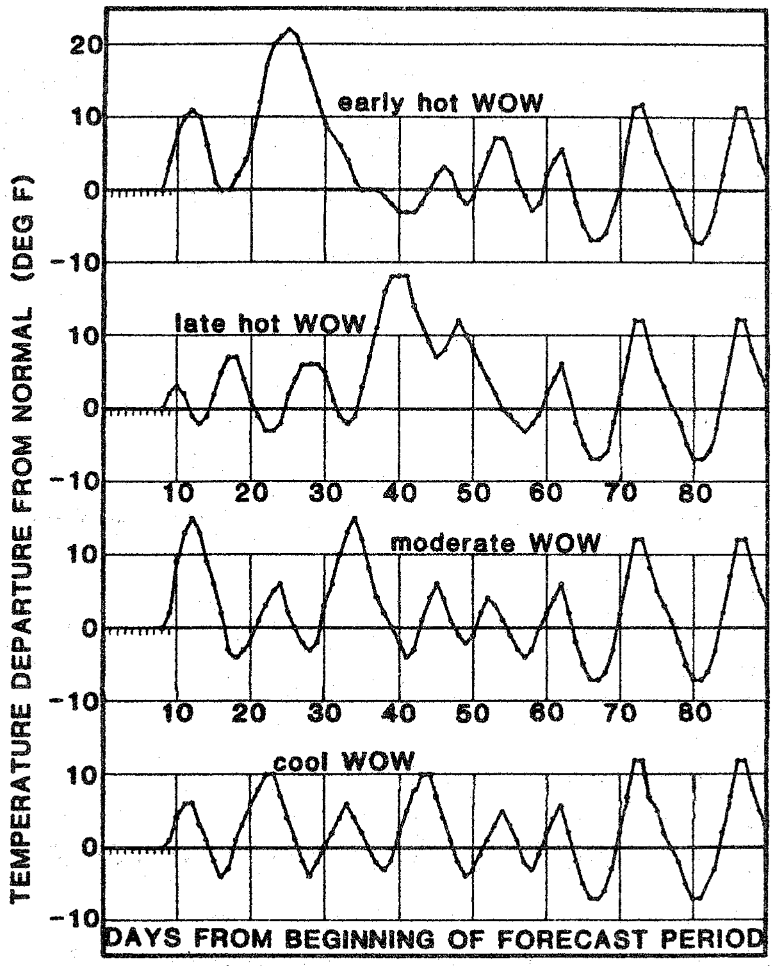

Figure 4. Future temperature sequences (WOW's) used in Columbia River.

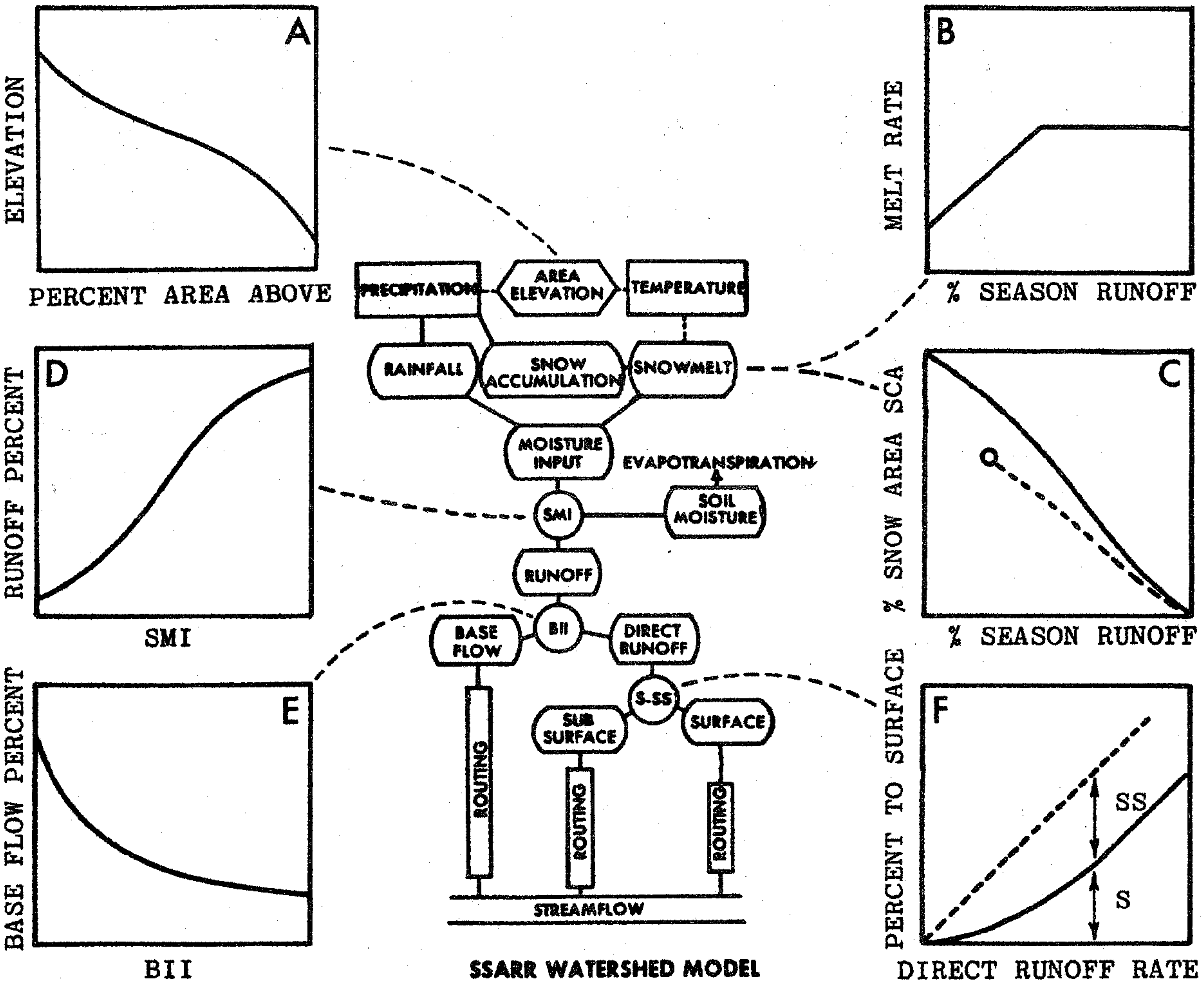

Figure 5. Lumped-basin SSARR logic.

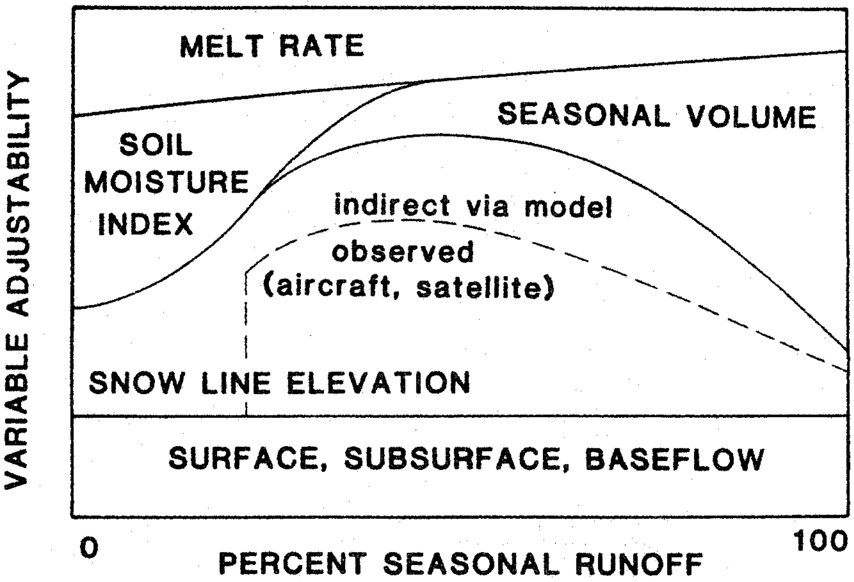

Figure 6. Relative utility of model variables to keep model tracking during runoff season.

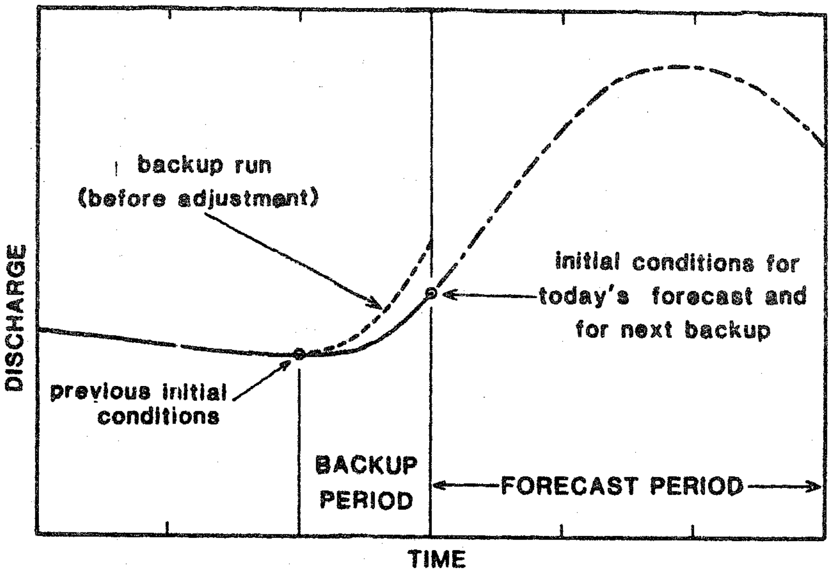

Figure 7. Example of model backup.

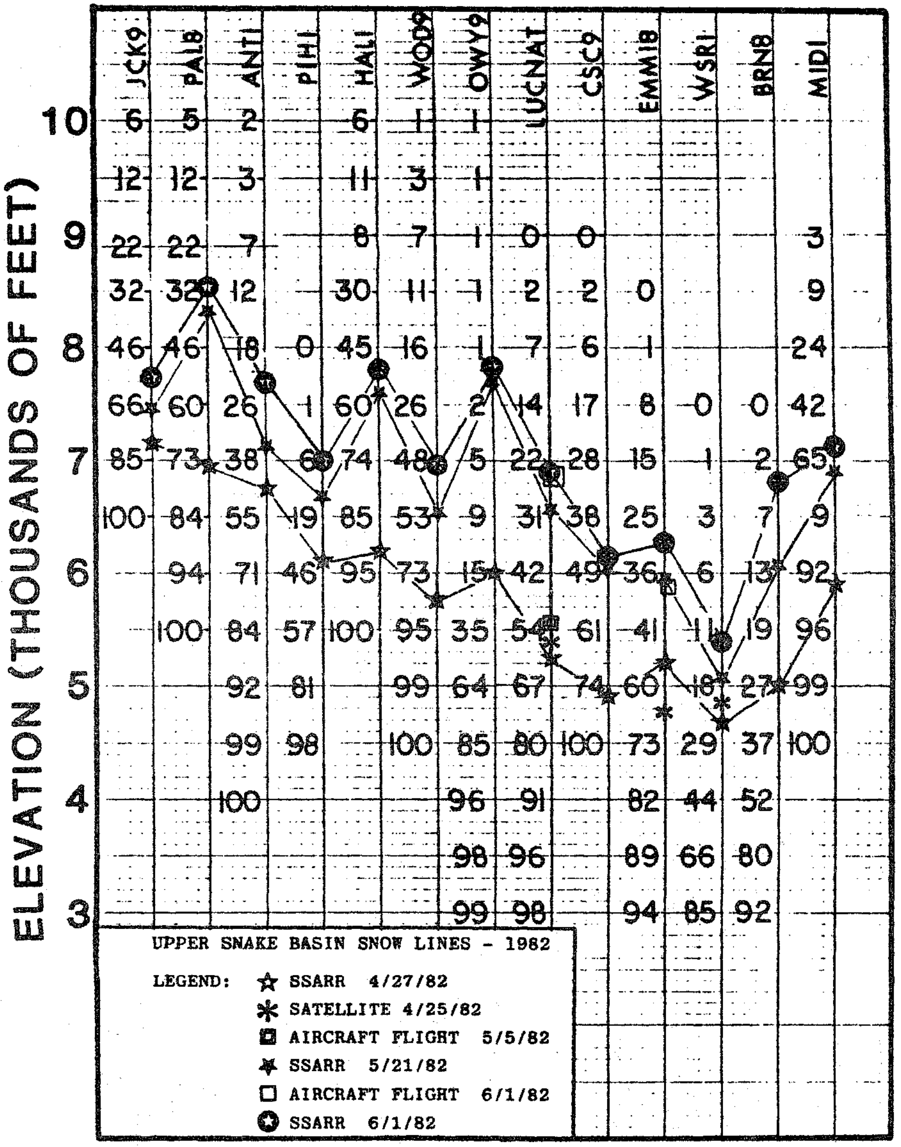

Figure 8. Interbasin comparison of snow line elevations in the upper and middle Snake R. drainages.

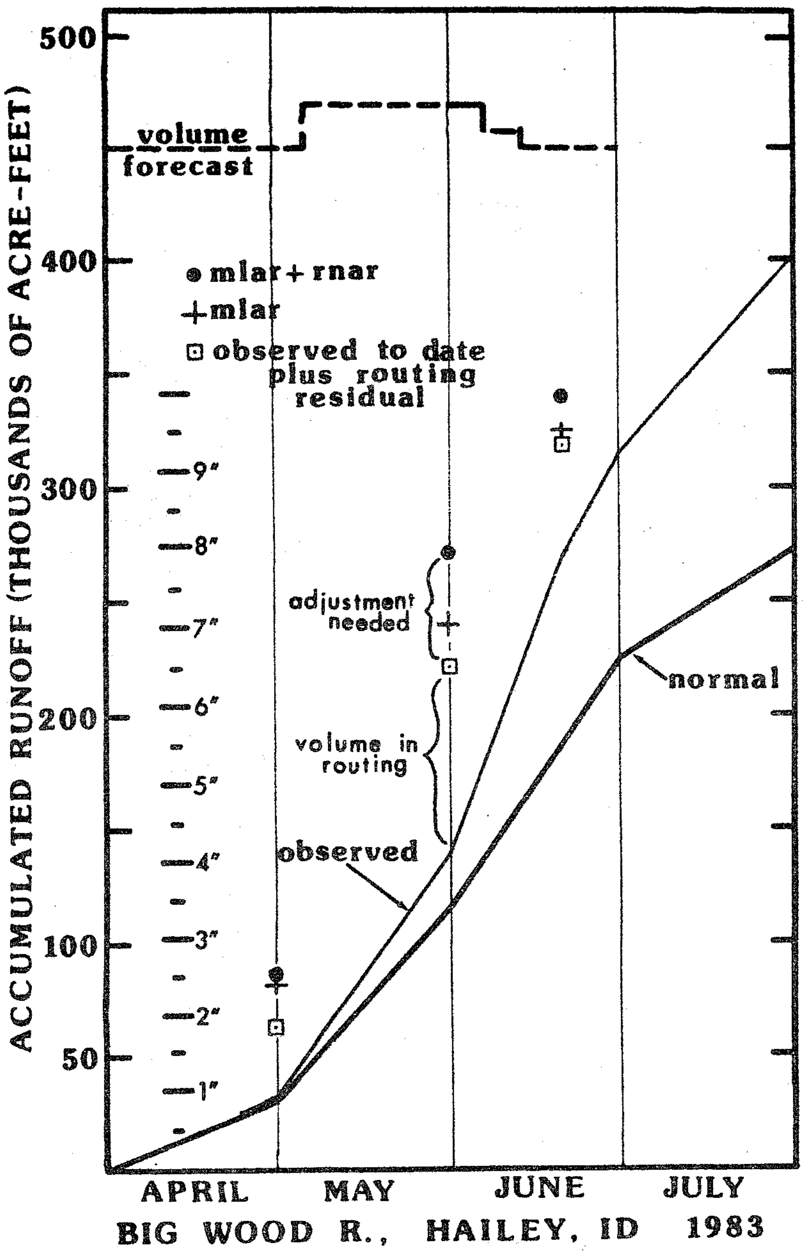

Figure 9. Model adjustment for tracking observed basin accumulated runoff.

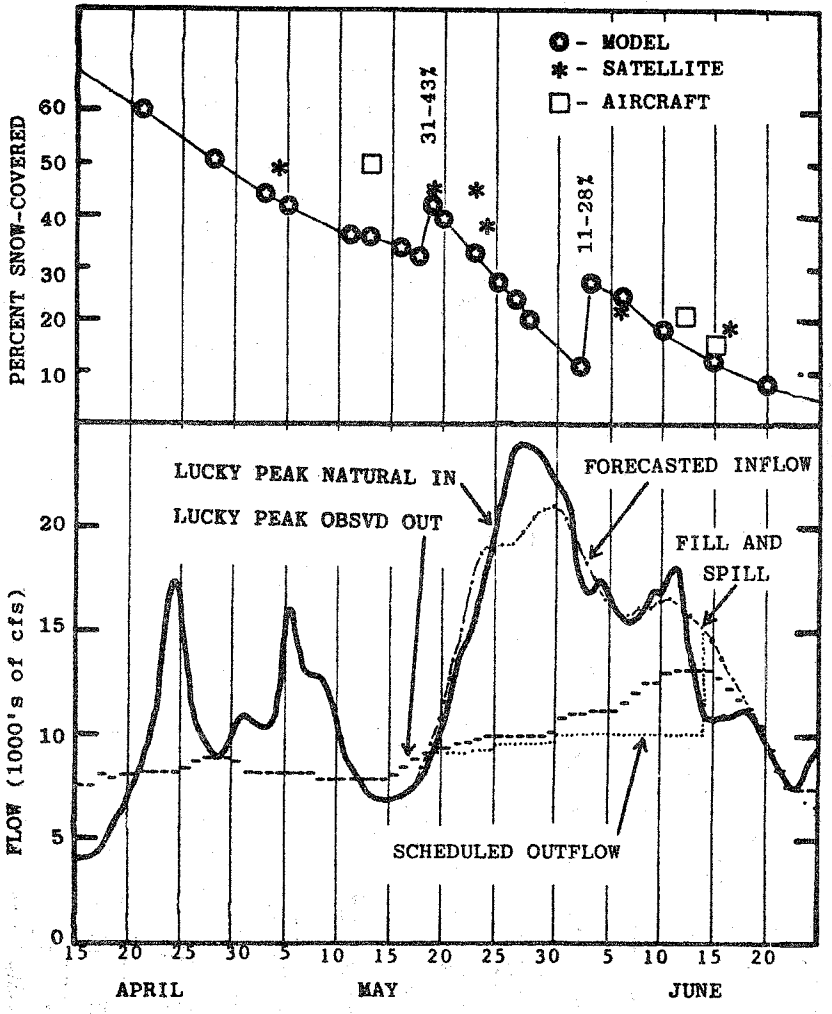

Figure 10. TOP:measured and modelled snow area. BOTTOM:Boise R. observed and forecasted flows indicating fill and spill likely.