Operational streamflow forecasting with the ssarr model

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RÉSUMÉ : On décrit le modèle de l'écoulement et de la régulation par réservoir ainsi que le programme de la calculatrice qui y est associé et son application à la simulation de l'écoulement du bassin supérieur. L'ensemble du modèle a été imaginé pour synthétiser la réponse d'un système complexe de rivières à l'introduction des précipitations et des températures en tenant compte de la régulation due aux constructions dues à l'homme. Le modèle permet certaines alternatives introduisant rotamement l'action de précipitations sous forme de neige dans les zones supérieures du bassin. On présente aussi un essai d'ajustement des prévisions internes aux conditions observées.

SYNOPSIS: The Streamflow Synthesis and Reservoir Regulation (SSARR) Model and the associated computer program and its application to headwater basin runoff simulation is described. The complete model was developed to synthesize the response of a complex river system to the input of precipitation and temperature plus the regulation by man-made structures. An alternate multi-zone mode of basin runoff computation provides snow accounting by sub-areas of the basin. An approach to adjustment of internal computation to observed conditions is presented.

INTRODUCTION

There are several considerations in the river forecasting operation that loom so important they tend to place severe restrictions on the design of an operational model as compared to a research model. In the past era of manual streamflow forecast computations these consideration also had a tremendous influence on the type of models used.

The most important consideration in operational streamflow forecasting is that time is of the essence. A flood forecast is a product whose utility is time related; that is, the value of a perfect forecast decreases with time until the value is zero at the time of the event.

The second consideration which makes operational streamflow forecasting somewhat unique is the great importance of initial conditions. In historical computations the effect of the initial conditions can be minimized by selection of the optimum startup time. However, in streamflow forecasting the computation is re-started each day and it must have continuity with the antecedent computation and with the actual observed conditions.

The third consideration is that a forecast model must operate on data inputs which are inadequate samples of antecedent hydrologic events and forecasts of future events. Current reporting networks generally do not provide adequate data to completely define the current basin rainfall patterns. As the runoff computation is extended into the future the hydrologic input consists of precipitation and temperature forecasts which are subject to well recognized limitations.

It is easy to see how these considerations influence the design of a model for use in operational streamflow forecasting. There must be a compromise between complexity and theoretically desirable refinements in order to deliver the most useful forecast, considering timeliness and accuracy. The amount of necessary manual processing and preparation of input must be held to the minimum.

Often forecasts must be issued without all the reports which would be desirable to define the precipitation event. In this case a model must be flexible as to input requirements.
Also, when the reported precipitation or computed snowmelt departs from the actual amount, as evidenced by the inability of the model to "explain" the observed hydrograph up to forecast time, there must be a capacity to adjust the internal calculations so as to reflect the existing discharge conditions.

The need to minimize the lag in forecast preparation and the fact that the input is subject to inaccuracies work together to urge the acceptance of working simplifications in the model if thereby significant saving in processing time can be achieved and still maintain a level of accuracy consistent with limits imposed by quality of hydrologic inputs.

EVOLUTION OF THE SSARR MODEL

The SSARR model is a very general and flexible model designed originally to perform streamflow synthesis for planning, study-type functions and the daily operational forecasting. For all of these functions the model in conjunction with the computer program must be able to reconstruct the historical streamflow events from hydro-climatic data with acceptable accuracy. However, in addition, the system must have the flexibility and provisions to solve the problems introduced by the considerations discussed above.

The application of the SSARR model and associated program to historical data and planning type operations has been described by Lewis, Rockwood and Nelson [1] [2]. Discussion and demonstration of the provisions which made the model usable for basin simulation in a forecast situation will follow a brief review of the makeup of the basin synthesis portion of the model.

The present SSARR model and associated computer program is a third generation of the basic model designed in 1957 by Rockwood [3] [4] and executed on the IBM model 650 computer. The second generation was adapted to the IBM model 1920 and was in use by the Cooperative Columbia River Forecast Unit 1 from 1962 through 1967.

In each revision the improvements which were evident from using the model were incorporated together with additional refinements which became possible because of the additional capability of the newer computing hardware. The latest major redesign as well as the subsequent refinements is a cooperative effort of the Corps of Engineers, North Pacific Division and River Forecast Center, ESSA Weather Bureau.

The current reprogramming was part of the Corps of Engineers cooperation with the Mekong Committee in connection with the training in system analysis [5]. Besides adding several powerful refinements to the basin rainfall-runoff, and channel backwater simulation, the program was reorganized to increase its flexibility in handling larger quantities of input data. Since the first application in early 1967, the model and the program have undergone continuous evolution. Because the model and the associated program were developed by the systems analysis approach, there is provision for maximum flexibility and ease in modification.

1. This unit was formed in 1962 by formal agreement between the Weather Bureau, ESSA, and the Corps of Engineers, U.S. Army, to make the best use of the streamflow forecasting capabilities of the Portland River Forecast Center of the Weather Bureau and the North Pacific Division office of the Corps of Engineers. The unit prepares flood forecasts and streamflow and reservoir inflow forecasts for the entire Columbia Basin, and the adjacent coastal areas in Washington and Oregon. The forecasts are used to satisfy the public service responsibilities of the Weather Bureau as well as the Corps of Engineers' requirements for forecasts for project operation. Forecasts are supplied to agencies, both public and private in United States and Canada, which have river-related activities and responsibilities.
BASIC TYPES OF SIMULATION IN THE SSARR MODEL

The component elements of the SSARR model simulate the responses of channels, lakes, reservoirs, and basins. The basic method used in each of the components to synthesize the storage effects is multi-phase lake routing [6]. Simulation of channel backwater effects is accomplished on the basis of a three-variable table relating discharge to two water surface elevations along a river channel [7]. Irrigation diversion and local area inflows can be synthesized as a function of the flow in a channel and return flow can be simulated as a function of total diversion less usage.

In order to superimpose the artificial regulation produced by man-made structures, provisions are made for specifying regulations in terms of outflow, storage, or reservoir elevation, all within limiting bounds of reservoir elevation [8]. In historical operation the actual regulations can be removed to produce natural conditions.

BASIN SIMULATION

The runoff computation can be summarized in the schematic flow chart in figure 1. The first computation is essentially the rainfall-runoff relation which converts a portion of the moisture input \((MI)\) into runoff \((RO)\). The remainder of the moisture input is added to the soil moisture, to be removed only by evapo-transpiration \((E/T)\). After the period runoff volume has been determined, it is ultimately divided into three components, baseflow, sub-surface and surface volume for distribution with time.

**RUNOFF COMPUTATION**

In figure 2 the right graph shows the relation of runoff coefficient \((ROP)\) as a function of soil moisture index \((SMI)\). For a given soil moisture index the related runoff coefficient is the percent of the moisture input which is to appear ultimately as basin discharge.
The complement of this percent is added to soil moisture. The \( SMI \) is computed as follows:

\[
SMI_2 = SMI_1 + (MI - RO) - KE(E/T)
\]

where \( E/T \) is the evapo-transpiration which during periods of rain is reduced by a factor \( KE \) which in turn is a function of rainfall amount. The evapo-transpiration values are specified as monthly averages. An alternate method of computing daily \( E/T \) from meteorological data is now being programmed. The calculation of \( SMI \) and all other basin computations is done on a period basis. The time period is variable from 24 hours to as little as 0.1 hours.

The remainder of the basin computation distributes the period runoff volume in time to produce the synthesized basin discharge. The conversion of the period runoff volume is accomplished in the SSARR model by routing three flow components: surface, sub-surface and baseflow. These separate components are routed individually and then combined as basin discharge.

The baseflow component is the first portion of the runoff to be separated (fig. 1). This is done on the basis of a relation of Baseflow Percent (BFP) as a function of a Baseflow Infiltration Index (BII). Figure 2, left graph, shows the generalized type of this baseflow relationship. The baseflow volume is analogous to that portion of the discharge hydrograph which can be isolated by standard baseflow separation techniques to obtain "direct storm runoff".

The Baseflow Infiltration Index is a synthetic value (with units of inches per day) of weighted antecedent runoff. This device simulates the high infiltration at the beginning of a storm which soon approaches a minimum as the storm progresses.

The remaining period runoff volume, designated "Direct Runoff" is divided into surface and sub-surface components by a two-variable relation with an argument of runoff intensity. This technique accomplishes what many hydrologists simulate with variable-peaked unit hydrographs. The final phase of the conversion of period runoff volume to discharge is accomplished by routing each of these three components separately by multi-phase lake routing.

![Figure 2](image-url)
SNOW ACCOUNTING BY MULTI-ZONE BASIN

In earlier versions of the SSARR model snow accounting was limited to depletion of an existing semi-permanent snowpack. A simple basin, illustrated in figure 3 by an area-elevation curve, was divided on the basis of temperature. The temperature at the observation stations is lapsed either up or down to determine the critical elevations separating the various areas. The lapse rate and the critical temperatures are specified as basin constants.

Two complementary areas representing snowfall and rainfall and two additional complementary areas above the snowline representing where the snow is melting and not melting are determined by the elevation of specified critical temperatures. Runoff calculations began with the quantity of precipitation in the rainfall area plus the snowmelt from the melt area. Both the snow-covered area and the amount of moisture in the snowpack were decreased automatically by the effects of snowmelt, but never increased due to new snowfall.

In the basin which has ephemeral snow, provision must be made for accounting for both snow accumulation and snow-covered area increase. In order to accomplish this the SSARR model and program have been revised to provide for dividing a basin into a number of elevation layers or zones. In the multi-zone mode each zone is analysed, for each time period, the same as the simple basin shown in figure 3. However, in addition, the snowfall is added to the accumulated snowpack, if any, and the snow line is lowered to the lowest zone which had snowfall.

One important working assumption is employed; any zone is either 100 percent snow-covered or is entirely snow-free. Therefore, the number of zones and the elevation span of each must be so selected that this working assumption is acceptable. Individual
computation of Soil Moisture and Baseflow Infiltration Indexes as well as the period runoff volumes is made for each zone. These volumes for each zone are summed into totals for each of the three components: surface, sub-surface and baseflow. The storage routing is then performed for each component and the results summed to form the basin discharge.

TOTAL HYDROGRAPH RECONSTITUTION

The specific coefficients and constants which tailor the model and program to simulate a particular basin response could be derived and optimized by machine methods. However, to date the tests have used a trial and error approach with five to ten years of record.

Most of the coefficients and relationships in the model are such that hydrologic experience and knowledge of the basin can be used to set initial trial values for the necessary coefficients. Satisfactory reconstitutions have been accomplished by the single basin mode for ten basins in the Columbia Basin. These range from a pure rainfall-runoff basin to nearly pure snowmelt areas such as headwaters of the Columbia River in Canada [7]. The model has been applied by others in the single basin mode to basins in Eastern United States, Alaska, and the Mekong [9].

Anderson first applied the model to a research-size and instrumented basin in the multi-zone mode [10]. The first application of this method of computation to a forecast size and instrumented basin was to a portion of the McKenzie River above Coburg, Oregon. The basin drains 1,337 square miles of the Cascade Mountains in Western Oregon. The portion of the basin which was used to test the multi-zone computation was the Coburg Local Area; the area above Coburg and below Cougar Dam and McKenzie Bridge, drainage area 781 square miles. Because of the geology of the area above McKenzie Bridge the flow at this point is composed largely of baseflow. This area was eliminated from the study and the model applied to the remaining homogenous area. Data from two rainfall stations and one temperature station in the area were used.

Sample results of the reconstitution for the Coburg Local Area for two of the five years used in the study are shown on figure 4. The years 1961 and 1965 are the two poorest years as far as the accuracy of the reconstitution. Figure 5 summarizes and magnifies the bias in all of the five years studied. Deviations are presented as accumulated monthly mass curves expressed in percent of the yearly total runoff. In order to show the approximate distribution of runoff during the year, the 1961-1965 average runoff is plotted on bottom of the graph. There is till some small amount of bias remaining, this is particularly evident in the period April through June. Further reduction in this remaining bias will result when coefficients are refined in conjunction with tests in other adjacent basins.

ADJUSTMENT OF COMPUTATION TO MATCH OBSERVED CONDITIONS

The adjustment of the internal computation of discharge to agree with the observed value, prior to extending the computation ahead in time, is a necessary and very desirable feature of any model to be used in forecast operations. If the reported discharge from a basin is accepted as the true quantity of flow at a given time, then any extension of the discharge forward in time must begin with this value. This is not just for the sake of appearance, but rather because a forecast, to have a high degree of reliability, must “explain” or reproduce the conditions observed up to forecast time. In other words, a forecast computation which fails to compute the immediate past discharge has reduced its chances to correctly extend the computation into the future.

Lake and reservoir elevation and discharge are single-valued elements and the adjustment presents no problem. Some whatmore complicated is the adjustment of the channel
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Figure 4
routing computations to match the observed conditions. Here the SSARR prorates the departures of inflow and outflow throughout the reach.

In the SSARR the adjustment in the basin computation maintains all the indexes and computational quantities consistent with the observed discharge. If the adjustment is to be done automatically (without manual intervention) some assumptions have to be made as to the cause of the deviation of the forecast from the observed quantity. Valid assumptions might be: (1) the quantity of the precipitation or snowmelt used in the computation is deficient (or excessive), or (2) the quantity is correct but the assumed distribution (timing) deviates from the actual.

![Accumulated Monthly Deviations](image)

**Figure 5**

In areas with limited reporting networks the observed timing of the precipitation is probably more dependable than the total quantity. With the help of radar observations this is more surely true. Therefore, the SSARR program assumes that the timing as observed is correct but the quantity is subject to adjustment within limits.

In the SSARR system as now applied to forecast operations the computations begin a given period of time prior to the forecast time. Thereby the model applies observed amounts and timing of rainfall and conditions of temperature to the initial conditions at the beginning of antecedent computations. If the resulting computed discharge does not match the observed within assigned limits (lesser of a percentage or an absolute discharge), the program iterates with an adjustment to the moisture input amount until the values match. There is program control on the number of iterations and the amount of the adjustment.

The basic assumption is that the estimates of rainfall timing based on current reports are several orders of magnitude more conservative than the estimate of the rainfall total quantity. In small basins manual intervention is necessary if the amount of adjustment is unacceptable or if the fit of the antecedent hydrograph indicates that the actual rainfall distribution departed materially from the first estimates. Unacceptable adjustments may
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McKENZIE RIVER
NEAR
COBURG, OREGON
FEBRUARY 1961

Figure 6
also point out situations where the reported discharge is in error, in which case manual intervention is called for.

Application of this technique to forecast situations is illustrated in figures 6 and 7; one case of over computation and one of under computation when the computation is performed with all data known. In the left graph of figure 6 the observed discharge hydrograph is shown in solid line and the reconstituted hydrograph is shown in a dashed line. In the right half of figure 6 the forecast extensions of the hydrograph beyond the time of the forecast use observed precipitation. Therefore, at 1800 on February 9 a forecast would call for 60,000 cfs by the next morning and an ultimate peak of 95,000 cfs.

The following morning at point “A” in the hydrograph an observed discharge of 35,000 cfs compares to the computed 60,000 cfs. This deviation can be due to the precipitation observed at the reporting stations being much earlier than that which fell over most of the basin or the quantity over most of the basin was much lighter than the stations reported.

The program is given antecedent precipitation and the observed discharge and will attempt to make the computation match the observed 35,000 cfs by adjusting the quantity of the antecedent precipitation. In this case, after five iterations the precipitation was reduced by a factor of 0.75 and the computation matched the observed. A forecast extension of the hydrograph from point “A” called for a discharge of 62,000 cfs that evening at 1800 and an ultimate peak of 68,000 cfs. With the benefit of hindsight this was a desirable modification of the peak forecast.

At forecast time “B” the adjustment factor applied to match the observed discharge was 0.84, and the extended forecast called for a peak discharge four hours later of 74,000 cfs.

Figure 7 shows another example of the adjustment routine, this time with a flood which was undercomputed in the reconstitution with all data known. Forecasts were made at times C, D, and E, requiring adjustment factors of 1.1, 1.2 and 1.0, respectively. The resulting forecast extensions are shown for comparison with the observed peak.

It must be emphasized that in these illustrations the precipitation subsequent to the time of the forecast is the amount as later observed; so this is not meant to be an illustration of operational forecast accuracy. Any errors in prediction of the precipitation amount and timing must be superimposed on the indicated deviation of the model performance.

In forecast operations situations will arise when the computer adjustments are unacceptable or when, after ten iterations, the computation is too far from the observed. Here manual intervention is necessary to make the adjustments necessary to make the computation consistent with hydrologic judgment. In the SSARR program internally stored values of snow covered area, accumulated snow, soil moisture and baseflow infiltration indexes as well as the input data such as temperature, precipitation amount and distribution can be changed and the computation re-run.

CONCLUSION

The SSARR model and program have been tested on total hydrograph reconstitution in the single basin mode under many varied conditions of locations, topography and snow-rain situations and the results are comparable to that shown for the McKenzie River Basin. The performance compares favorably with other existing models and is adequate for operational forecasting.

In the multi-zone mode the SSARR in its first test on the McKenzie Basin demonstrated the ability to simulate snow accumulation and depletion in an area which has a semi-permanent seasonal snow pack as well as ephemeral snow.
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**Figure 7**

**McKENZIE RIVER**
NEAR COBURG, OREGON
DECEMBER 1964

**DISCHARGE IN 10^3 C.F.S.**

**PRECIPITATION**

- OBSERVED
- COMPUTED
In forecasting experience of one season the SSARR program adjustment routine has shown that it is a practical solution to the need to match the internal computations and the observed discharge.

The SSARR model and program have also demonstrated that they can perform well in a forecast situation where time is of the essence, and where rainfall and temperature estimates are less than adequate.

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Mr. Edward Davis, Corps of Engineers Programmer and Systems Analyst, must be recognized for converting the SSARR model into a computer program. His many suggestions have added materially to the flexibility and power of the SSARR program.

REFERENCES