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ST. ANTHONY FALLS HYDRAULIC LABORATORY

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EVALUATION OF SNOWMELT FLOOD FORECASTING TECHNIQUES FOR THE UPPER MIDWEST

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I. INTRODUCTION

A. Background

Engineers throughout the country are constantly faced with the problem of providing adequate supplies of water to meet local requirements and safely removing overabundant supplies. The proper management of our water resources is an important function of local, state, and federal governments.

Certain areas of the midwestern United States are normally blessed with sufficient quantities of water to adequately meet the needs of agriculture, urban population centers, industry, recreation, navigation, and wildlife. Within recent years, however, melt water from the winter snowpack and early spring rains have combined to produce excessive volumes of runoff, causing extensive flooding. This overabundance of water during the springs of 1965 and 1969 caused a combined total of more than $300 million in damage. The monetary figure includes damage to urban areas, agricultural losses, and disruption of transportation and communication networks as well as municipal, lock and dam, and other unclassified losses. This figure can in no way indicate the great personal anguish of the thousands of people who were driven from their homes by rising flood waters.

Both in 1965 and in 1969, early warnings of the snowmelt floods greatly reduced the amount of physical damage that occurred. These flood forecasts allowed preparations to be made which substantially reduced losses. In 1969 Operation Foresight, a joint flood relief effort spearheaded by the Corps of Engineers, reduced damages by more than $100 million at a cost of $15 million.

Accurate forecasts of floods are necessary not only to permit general warnings to the public, but also to facilitate proper design of emergency dikes and pumping stations, floodproofing, personnel evacuation, and proper operation of existing flood control structures and navigation facilities.

Although emergency flood relief measures based on flood forecasts greatly reduce flood damage, they are only a temporary solution to flood problems. However, even with permanent flood control structures, accurate forecasts will continue to be needed for proper operation of reservoirs and interior drainage facilities and for floodproofing and other operations.

The purpose of this study was to evaluate the performance of some of the available comprehensive mathematical models with respect to their usefulness in predicting snowmelt and rainfall floods in the Upper Midwest.

B. Flood Forecasting Techniques

The reliability of flood forecasts has increased over the years as the factors that contribute to flood formation have become better understood. Early settlers of this country had only personal observations of local conditions and word-of-mouth reports from neighboring villages on which to base flood relief activities. Undoubtedly, such notice was less than adequate, and the wise settler located far enough above the banks of the local water course that he would not be affected by flooding. With population increases came increased use of the floodplain for industrial and commercial purposes. Although the damage sustained was greater than before, there was little change in flood forecasting. Improved communications and recording of hydrometeorological data provided better information on floods. With improved hydrometeorlogical data and the development of scientific hydrology came the possibility of predicting in advance the severity of rainfall and snowmelt floods. In the late 1940's in the Upper Midwest the Corps of Engineers began preparing, on a routine basis, maps of snow surveys giving the water equivalent in the snowpack. From water equivalent snowpack data and predictions of additional precipitation, runoff volumes were found by applying estimated loss rates. The resulting runoff volume was used with a unit hydrograph, derived from previous flood events, to develop the discharge for specific watersheds. By routing downstream and combining with flow from additional basins, a flood forecast could be made. Until the advent of the digital computer, the computations for a flood prediction were generally done by hand with desk calculators and graphical aids. Such calculations were laborious and time-consuming, and this limited the number of alternate snowmelt and rainfall patterns that could be evaluated before a forecast was made.

As the actual flood runoff takes place the forecaster can use additional data on actual precipitation and actual runoff from basins to revise his previous estimate. Such a procedure of updating will finally result in a very good forecast of the crest of the flood. These same general procedures have been adapted to the digital computer. Thus the forecaster, freed from the burden of the calculations, can now investigate a far greater variety of melt and precipitation patterns, include more input data, and use more thorough techniques than he could previously.

Adapting a given method to a computer always entails the danger of inexperienced persons using it either with invalid input data or in inappropriate applications. In many cases a person with experience in forecasting in a given area may be able to produce a more reliable forecast without the aid of the computer than an inexperienced person using a sophisticated computer approach. In all cases the most reliable forecast results from a combination of experienced judgment of existing runoff conditions and the use of the latest communications and computational techniques.

The ability of modern digital computers to handle large amounts of data and to rapidly perform a variety of mathematical functions with the data provides the potential for greatly improved analysis of flood phenomena. Methods which were previously impractical have become attractive approaches to flood prediction, and in addition a larger amount of hydrometeorological input data can be used in a given analysis. The comprehensive mathematical model for flood forecasting makes use of both of these attributes of the digital computer. The developer of the mathematical model strives to represent as closely as is required, or possible, the processes which affect runoff.

The idea of representing each step in the production of runoff from a watershed in mathematical terms is not new. Practical implementation of such a procedure, however, was not possible until modern digital computers became available.

One of the earliest comprehensive watershed programs was the Stanford model in 1962. Since its inception the Stanford model has undergone many changes as better procedures have been developed for representing different phases of the runoff process.

A great many models have been developed using a variety of approaches. The approach used to model a given process varies considerably, depending on the purpose of the model, the significance of the process in the overall model, and the judgments of the author.

One comprehensive model that was developed with flood forecasting, as well as other purposes, in mind is the Streamflow Synthesis and Reservoir Regulation (SSARR) model. This model was developed in a joint effort by the North Pacific Division of the Corps of Engineers and the National Weather Service River Forecast Unit at Portland, Oregon. The SSARR model has also undergone various changes from its original form. This model is capable of computing continuous runoff from a basin, routing through streams and reservoirs, and combining with other basin discharges. The model will consider snowmelt as well as rainfall runoff. A further discussion of the SSARR model is given in Section II.

The Corps of Engineers has prepared its standard design procedures for runoff computations and flood routing in the form of a multipurpose computer program. The program, Flood Hydrograph Package (HEC-1), while originally intended for design applications, can be used for limited-duration flood forecasting. This routine is capable of computing runoff from a basin, routing through streams and reservoirs, and combining with other basin discharges as well as other functions. Snowmelt and rainfall runoff can be simulated. A further discussion of HEC-1 is given in Section III.

The developer of a comprehensive model may strive to make the model generally applicable to a variety of watersheds. Often, however, some of the functions used to represent certain phases of the runoff process are poorly suited to some watersheds. In addition, a simple representation of a particular process may be entirely adequate for one purpose, but inadequate in another application. It is therefore necessary to evaluate a general comprehensive model and determine its applicability to a given area for a given purpose. In this study the SSARR model and HEC-1 were evaluated for their applicability as flood forecast tools in the Upper Midwest.

II. SSARR MODEL

This section contains a brief discussion of the SSARR model. Certain components which are particularly significant in snowmelt flood forecasting are discussed more fully. For detailed discussion of all components of the model and the required input data the reader is referred to Refs. [1] and [3].

A. General

A block diagram of the functions performed by the SSARR model is shown in Fig. 1. The source of moisture may be precipitation as rainfall or precipitation as snowfall with subsequent snowmelt. Both the degree-day melt coefficient method and the energy budget method are available for determining the amount of snowmelt. Several options are available for the accounting of melt from different elevation bands, or areas where only a portion of the watershed is covered by snow.

After the total amount of water available for runoff is determined, a distinction is made between water which will eventually appear in the outflow stream (i.e., runoff) and water which is permanently lost from streamflow (i.e., evapotranspiration, deep percolation). This separation is based on the soil moisture index (SMI), which indicates the current moisture condition of the soil. A low SMI indicates soil with water content near the wilting point, yielding a low percentage of runoff. A high SMI indicates near-saturated conditions with a high percentage of runoff. Water which does not run off is added to soil moisture, which raises the SMI. Water is continuously removed from the soil at a specified evapotranspiration rate, reducing the SMI. The exact form of the relationship between the SMI and the percentage of runoff is specified by the user. A typical relationship is given in Fig. 2.

Once the total volume of runoff has been determined, it is necessary to translate that volume into a stream hydrograph. Water from different portions of the watershed will arrive at the outflow point at different times depending on its distance from the outlet, whether a surface or a subsurface path is taken, the slope of the path, the cross-sectional geometry and roughness of the path, the presence of other water in the path, and many other factors.

The SSARR model uses a synthetic reservoir to simulate the movement of the water to the outlet. First the water is divided into three phases:

1. Water which travels relatively rapidly to the outlet--termed the surface phase;
2. Water which travels at a slower rate--termed the subsurface phase; and
3. Water which has a relatively long time of flow to the outlet--termed base flow.

The split between these various phases is governed by functions input by the user. The portion of the total runoff which becomes baseflow depends on a baseflow-infiltration index (BII). When this index is low, the baseflow is a large portion of the total runoff. An example of this function is given in Fig. 3. The remaining volume, direct runoff, is then divided into surface and subsurface phases depending on the volume of direct runoff. Figure 4 shows how the surface phase is determined from the total surface-subsurface runoff.

Once the volumes of water have been determined for the three phases, they must be transformed into flow at the outlet. Three synthetic reservoir systems are set up, each corresponding to one of the three phases.

To transform the volume of surface runoff into a stream hydrograph, the volume is passed through a reservoir system that has a relatively short time delay. This component is characterized by a relatively short time to peak and steep rising and falling limbs. The subsurface flow and baseflow are handled similarly using synthetic reservoir systems which yield relatively longer times to peak and flatter rising and falling limbs. The total response at the outlet, then, is the sum of the surface, subsurface, and baseflow hydrographs. These components are illustrated in Fig. 5.

The computations described above are made for each computation interval for the total duration of the simulation. The computation interval can be set by the user depending on the sizes of the watersheds and other considerations.

A similar analysis is made for each sub-watershed in a study area. Sub-watersheds can then be routed downstream and combined to produce a composite runoff hydrograph for a large area.

Several options are available for controlling the routing of flow through reservoirs. The results at any point in the system can be compared with observed flows, if available, and plotted for a visual display.

B. Snowmelt Options

As stated previously, the functions available to the user for melting the snow are the degree-day coefficient method and an energy budget method. While it was originally intended that both these approaches be evaluated during the study, time permitted the use of the degree-day method only, whereby

$$\text{Melt} = \text{COEF} \times (\text{TEMP} - \text{BASE})$$

TEMP is usually taken as the mean daily air temperature, but may be maximum daily or some other temperature. BASE is some base temperature above which melting occurs. The value used for BASE depends on what is used for TEMP. COEF is a melt coefficient multiplied by the excess temperature above the base temperature to yield the amount of melt. The SSARR model allows the user the flexibility of a varying melt rate coefficient. The coefficient may vary with time or with conditions in the watershed. If COEF is to vary with time, the user can specify the specific value to use starting at a given time. This value is then used until another value is specified at a later time. Thus in early spring a low value can be given, and then as melt proceeds and the snowpack ripens a larger coefficient can be specified.

Alternately, the melt coefficient can be specified as a function of the percentage of the seasonal runoff which has occurred. In early spring, with only a low percentage of the annual runoff having occurred, a low coefficient would be used. As runoff percentage increased, the melt coefficient would normally be increased. This manner of varying the melt coefficient is preferable to basing it on time alone for areas where the beginning of melt varies from year to year. However, it requires an estimate of annual runoff to be made.

The basic options available for determining what portions of the watershed are snow-covered are the elevation band method and the snow cover depletion method.

With the elevation band method, the watershed can be divided into one or more elevation bands. Each band can be treated as a separate watershed for the purpose of snowmelt computation. The precipitation falling on a given band can be either rain or snow, depending on the air temperature at the center of the band. If it occurs as rain, it immediately becomes moisture available for runoff. If it occurs as snow it is added to the snowpack. Also, depending on air temperatures (i.e., for the degree-day melt method), snowmelt may occur in a given elevation band. This melt water would also become moisture available for runoff. Computations would proceed for each band, and after all the snow had melted on a given band, only runoff from rain would occur.

With the snow cover depletion method, the computations may consider runoff from the snow-covered area only (one-basin approach) or from both the snow-covered and the snow-free areas (split-basin approach). With either approach the snow-covered area can be specified by the user either as a function of time or in relation to the percentage of seasonal runoff. Precipitation falling as rain on the snow-covered area becomes moisture available for runoff. Precipitation in the form of snow is not considered in the analysis. If substantial amounts of snow fall during the computation period, it must be taken into account in determining the total amount of seasonal runoff. When the split-basin approach is used, the first basin represents the portion of the basin which is covered by snow, and computations are done for this portion only. The snow-free area computations are done on a second basin. The total basin outflow is then the sum of the flow from the snow-covered area and that from the snow-free area. This approach has a marked advantage in that one set of runoff characteristics can be specified for the snow-covered area, reflecting frozen ground conditions, and a different set for the snow-free area reflecting normal ground conditions.

C. Revisions for Midwest

Of the melt accounting options that are available, the split-basin snow-cover-depletion approach has the most advantages for application to the Upper Midwest. The multiple-elevation-band approach is unnecessary, as elevation differences within the watersheds are usually no greater than one thousand feet and are often less.

With the split-basin snow-cover-depletion option, the amount of area covered by snow is made a function of the percentage of seasonal runoff. For the Midwest it was more appropriate to base the snow-covered area on the water equivalent of the snowpack. A function was used wherein a value of water equivalent greater than one inch indicated that one hundred per cent of the basin would be covered by snow. In the absence of specific data on snow-covered area and water equivalent, the function was made to decrease linearly to zero for water equivalents less than one. This function is illustrated in Fig. 6.

In addition, making the melt rate coefficient in the degree-day method a function of percentage of seasonal runoff did not appear to provide the most desirable relationship. A change was made so that the melt coefficient depended on the percentage of the snowpack melted. This function is illustrated in Fig. 7. Although this formulation was used in the study and gave usable results, it is believed that a better relationship would result from making the melt coefficient a function of a moving accumulation of degree-days. That formulation has not been evaluated.

A third change which was made in the SSARR model allowed the snow cover depletion option to properly accumulate precipitation in the form of snow in the snowpack.

A revision which appears desirable for computations during the summer runoff period concerns the evapotranspiration function. Presently, evapotranspiration occurs at the potential rate on non-precipitation days regardless of how much moisture exists in the soil. An improved function should reduce evapotranspiration as the SMI approaches zero.

The version of the SSARR model used on the University of Minnesota's CDC 6600 computing system was obtained on magnetic tape from Rocky Mountain Forest Experiment Station at Colorado State University through the Portland, Oregon division of the U.S. Army Corps of Engineers. Some changes had been made at the Forest Experiment Station to adapt the program to their CDC 6400 computer.

When first compiled on the 6600, the CDC Fortran Extended (FTN) compiler produced incorrect binary code. All future runs were made with the CDC FUN compiler. The form of the EØF check required alteration, as the original form was not valid with the FUN compiler. Due to the manner in which the 6600 executes code, certain operations may be done in parallel to save execution time. The use of EQUIVALENCE in the routine LAKRT caused the compiler to produce incorrect code. This was remedied by adding new variable names and forcing a sequential execution.

One error was found in an input (DECODE) statement changed by the Forest Experiment Station.

Due to the unavailability of random access disk storage at Colorado State, this storage feature of the SSARR model had to be replaced with a limited amount of core storage. At the University of Minnesota the random access disk storage feature was restored.

The subsequent changes alter the numerical results of the SSARR model due to changes in the model functions. Three such changes were made. In each case they required changes in the routine BASINE only. The purpose of the changes is described in a previous section.

Due to changes in the model functions, slight alterations in the meanings of input data variables were required.

III. HEC-1 MODEL

A. General

Flood Hydrograph Package HEC-1 is a composite of several individual functions which are needed to perform a hydrologic analysis of a watershed. For a detailed discussion of all the techniques incorporated and the input data specifications see Ref. [2]. The following is a brief discussion of the functions available for generating watershed hydrographs.

Included in this program are functions for manipulating data from one or more precipitation stations to yield basin average precipitation. Several options are also available for specifying basin average precipitation and formation of design storms for standard project and probable maximum analysis. If snowmelt is desired, either the degree-day melt coefficient method or an energy budget method can be used. Loss rates can be computed using either an initial increment loss followed by a uniform loss rate or a loss rate function that changes throughout the storm period as soil moisture increases. These loss functions are designed to work only during one sustained runoff event. There is no provision for restoring the watershed to day conditions as would occur between normal runoff events. A unit hydrograph is used to transform the excess moisture over the watershed into a streamflow hydrograph at the outlet. Baseflow is constrained to an exponential recession below a specified discharge.

Hydrographs produced by the above techniques can then be routed downstream and combined with other hydrographs to produce a composite basin runoff analysis. Several streamflow routing options are available in addition to reservoir routing with a fixed outlet condition.

HEC-1 has the valuable option of determining an optimum fit for various coefficients that describe the unit hydrograph, snowmelt rate, loss rate, and streamflow routing. When the user supplies observed conditions of precipitation and discharge, HEC-1 will determine the best-fit unit hydrograph and loss rate variables that will simulate gaged flow.

B. Snowmelt Options

As indicated, either the degree-day coefficient method or an energy budget can be used to calculate snowmelt. In the degree-day equation (using the notation from Ref. [2]),

$$\mathrm{MELT} = \mathrm{COEF}(\mathrm{TEMPR} - \mathrm{FRZTP})$$

the user can specify the values of COEF and FRZTP. Both of these values are fixed for all computations. If the optimization routine is used, the best-fit values of the variables are found by the program.

In the energy budget method, dew point, wind, and solar radiation are considered in addition to mean air temperature. The energy budget was not used in this study.

Up to ten elevation bands can be specified to account for temperature variations with elevation. For applications in the Upper Midwest only a single band was used due to the limited relief of the area. Precipitation may fall as either rain or snow in any of the specified elevation bands. Precipitation as snow is added to the snowpack, while precipitation as rain is added to the snowmelt. A temperature two degrees greater than the base temperature (FRZTP) is used to distinguish between precipitation as rain and precipitation as snow.

Either of two loss rate analyses can be used. The first one consists of an initial loss followed by loss at a uniform rate. No runoff can occur until the initial volume has been satisfied. The remaining precipitation is then subject to the uniform loss rate. Although Ref. [2] indicates that a separate uniform rate can be used for snow-free and snow-covered areas, the program uses the variable STRTL as the initial volume for both snowmelt and rain. This loss rate option was not used in this study.

The second loss rate option is a function which varies with the accumulated loss (soil moisture). The basic relationship is

$$\text{LOSS RATE} = (\text{AK} + \text{DLTK})\ \text{PRCP}^{\text{ERAIN}} \tag{1}$$

The power ERAIN is fixed for a given area. Unless this is determined by the user through optimization, a value of 0.7 is recommended. The PRCP is the total amount of moisture from both rainfall and snowmelt. AK is determined by an exponentially decreasing function of the accumulated loss during the storm. At the beginning of a storm DLTK can be used as an additional function to allow for very high initial loss rates.

The manner in which AK is determined depends on (1) whether snowmelt is to be considered in the computations, (2) whether any snowmelt has occurred during the given time period, and (3) the total duration of the hydrograph computations.

The value of AK is determined from one of the following relationships:

$$\text{AK} = \frac{\text{STRKS}}{(\text{RTIOK})^{.1\ \text{CUML(J)}}} \tag{2}$$

where STRKS = Starting value
RTIOK = Slope
CUML(J) = Accumulated loss for J^{th} elevation band

$$\text{AK} = \text{STRKR}*(1.0 + 0.0004*(\text{CUMTM})) \tag{3}$$

where STRKR = Starting value

CUMTM = Cumulative time since beginning of computations, in hours

$$AK = \frac{STRKR}{(RTIOL)^{.1\ CUML(J)}} + DLTK \qquad (4)$$

where STRKR = Starting value

RTIOL = Slope

CUML(J) = Accumulated loss for J^{th} elevation band

DLTK = Additional high rate loss for rain event

Table 1 shows which of these relationships is used to determine AK based on the given conditions.

TABLE 1

Relationship Used for AK under Given Conditions

TOTAL COMPUTATION TIME: ⟶	SNOWMELT CONSIDERED		SNOWMELT NOT CONSIDERED
	<700 hours	>700 hours	---
Snowmelt this period	Eq. (2)	Eq. (2)	---
No snowmelt this period	Eq. (4) DLTK = 0	Eq. (3)	Eq. (4)

The value determined for AK is then used with Eq. (1) to determine the loss rate. Figure 8 shows typical functions for determining AK. Moisture which does not run off is added to the accumulated loss.

It can be seen in Table 1 that a snowmelt run made with 29 days' data (less than 700 hours) would be analyzed with Eq. (4) during periods without snowmelt, while the same set with one additional day's data (greater than 700 hours) would use Eq. (3) during periods without snowmelt.

Regardless of the duration of the total computation time, it can be seen from Table 1 that the loss analysis used may switch between functions from one period to another, depending on snowmelt. With one inch of rain and one one-hundredth of an inch of snowmelt, Eq. (2) would be used. With one inch of rain and zero snowmelt either Eq. (3) or Eq. (4) would be used. This may lead to irrational results if the functional values of AK from the equations are substantially different.

C. Revisions for Midwest

The arbitrary change from Eq. (4) to Eq. (3) when the total computation time exceeded 700 hours produced inconsistent results. The program for HEC-1 was altered so that the user could specify the equation to be used regardless of the computation time. This change was implemented by extending the definition of variable ISNOW. All subsequent modeling work used Eq. (2) for snowmelt periods and Eq. (4) for non-snowmelt periods.

Since an abrupt change in the loss function could be produced by the change from a snowmelt period to a non-snowmelt period, the function variables in Eqs. (2) and (4) were set nearly equal to each other. This had the same effect as using only a single loss function which was applied to both snowmelt and non-snowmelt periods. During optimization runs the values STRKS, STRKR, RTIOK, and RTIOL were all allowed to take on their optimum values. Judgment was then used to set both STRKS and STRKR equal to the same constant, and this value was used in the final computations. This approach required no program changes.

During optimization the values for RTIOK and RTIOL are constrained to be greater than or equal to one. This limits the slope of the curve in Fig. 8 to a horizontal line yielding either a constant or a decreasing function. In snowmelt loss analysis during the period of frost melt in the ground the loss rates may actually increase. To properly account for this, the optimization should allow RTIOL and RTIOK to take on reasonable values less than one during snowmelt optimization.

This change was not evaluated. However, in several cases the program was used with values assigned to RTIOL and RTIOK which were less than one. This gave good results.

IV. DATA REQUIREMENTS

The data used in this study were obtained largely in connection with a complementary Office of Water Resources Research (OWRR) project. These data were obtained from the U.S. Geological Survey (USGS) and the National Weather Service (NWS) on magnetic tape. The availability of the data in a form usable by computer was a major factor in the successful completion of this project.

The large-scale application of flood forecasting techniques requires the handling of large amounts of hydrometeorological data. During the reconstitution of observed floods, predicted discharges based on water-equivalent snow surveys, recorded precipitation, maximum and minimum air temperatures, and other parameters are compared with observed discharges.

Within the 16,000-square-mile area used in this study, a total of 15 USGS streamflow gaging stations were required for verification and fitting of basin sub-areas. Mean daily discharges were used for portions of four different years at each of the 15 gaging stations. In all, more than 10,000 mean daily discharges were used.

Even larger amounts of meteorological data were required to specify each sub-basin's mean daily precipitation and air temperature. Approximately 45 daily precipitation stations were used to determine the mean precipitation for the 15 sub-areas, and this required the handling of more than 30,000 precipitation values. Only one temperature station was used to determine the average daily air temperature for each sub-area. Using an average of daily minima and maxima, this involved the handling of 20,000 air temperatures.

In addition to the above data, the water equivalent of the snowpack prior to spring melt was needed. This information was obtained from the St. Paul District Corps of Engineers office and the Minneapolis-St. Paul office of the National Weather Service. Under the OWRR project, the data on the snow survey maps were encoded at a rectangular grid spacing. Specified grid points lying in or around a given sub-basin were then averaged to determine sub-basin water equivalent.

Each type of data used to reconstitute observed floods has certain errors associated with it. In addition, the methods used to extrapolate the data to represent watershed averages introduce further errors.

The observed discharges obtained from the USGS at established gaging stations are generally considered to be reliable data. Some uncertainties may be introduced where debris, ice jams, and river bed scouring during a large flood make discharge determinations difficult. These data are used directly at the location at which they are obtained.

The observed precipitation values obtained by Weather Bureau and cooperative observers represent those occurring at the gage location. The gage reading may be in slight error due to exposure location, wind effects, reading errors, and other problems. However, the errors associated with the gaged value at a point are insignificant compared to the errors introduced in determining the basin average precipitation from a limited number of point values. Within the area used in this study, precipitation stations had a mean spacing of about 18 miles between gages. Large variations in precipitation can occur within only a mile or two. Under certain storm conditions a weighted average of several precipitation stations may adequately define the actual basin average, but it is equally likely that for some storm patterns the average thus obtained is in error by 20 per cent or more.

The validity of extrapolating observed point air temperatures to an entire basin depends on the level of atmospheric turbulent (wind), the local exposure of the air temperature station, elevation changes, the presence of weather fronts, and other factors. For snowmelt purposes in flat areas under normal circumstances, the air temperature at a point in a basin is a fairly good index to the average temperature over the basin.

A valid determination of the water equivalent in the snowpack requires a large number of samples taken over the watershed. The Corps of Engineers uses a trained survey crew to collect data on water equivalent. More extensive surveys are made in areas with greater amounts of water content which pose a significant flood threat than in areas where water content is low. For this reason, data on areas with one to two inches of water equivalent or less may not be as reliable as data where the water equivalent is from eight to ten inches.

In making an actual prediction, the forecaster would have available current snow survey maps, daily air temperatures, daily precipitation, and observed runoff up to the time of the forecast. In addition, unknown values of precipitation and air temperature would be required from the time of the forecast until the time of the flood crest. Choosing the values to be used for these unknown data can be an extremely important process if the forecast is being made relatively far in advance of the actual event (i.e., two or more weeks). The larger the impending flood, the more important it is to make a forecast as early as possible so that there is sufficient time to carry out emergency flood protection operations. The earlier the forecast, the higher the degree of uncertainty of the predicted value. As the melt actually occurs, current data become available on melt and runoff rates, giving a basis for a revised, more reliable forecast. Thus a day or two before the flood crest on a large (10,000 sq mile) river, a very good forecast of maximum discharge is possible.

The time available to assemble data and prepare a flood forecast varies with the size of the area and the source of the moisture. With large accumulations of snow over the winter, a relatively long time exists between the first warnings of an impending flood and its actual occurrence. A water equivalent in the snowpack of 5 or more inches over a watershed at the beginning of March may be an indication of an impending spring flood. If no additional precipitation occurs during March or early April, and conditions during the melt favor slow release of melt water and high loss rates, little or no flooding may occur. However, if substantial additional precipitation occurs and at the same time there is rapid melting with little loss, record floods may be produced.

This wide variation between possible outcomes makes the preparation of an early forecast a difficult matter. The unknown conditions at the time of the melt are the final determining factors as to the severity of flooding. A forecast made three to four weeks ahead of the date of the flood crest must rely on both data known at that time and data on predicted conditions between the time of the forecast and the time of the crest. The determination of the best values to use for the predicted data is of paramount importance to the forecast. This study did not include any work on the determination of such predicted data.

V. APPLICATION

Both of the models discussed in the previous sections were applied to the Minnesota River Watershed. The Minnesota River, shown in Fig. 9, drains an area of approximately 16,200 square miles in southwestern Minnesota and small areas of South Dakota and Iowa. The watershed has a general west-to-east orientation. The greater portion of the watershed is used for agricultural purposes; corn, oats, soybeans and alfalfa are typical field crops.

The highest area of watershed is along the western edge in South Dakota, at an elevation of approximately 2000 ft. Along the main stem the river valley drops from an elevation of 964 ft at Big Stone Lake to 690 ft at Jordan, Minnesota, near the basin outlet, about 200 miles away. The mean slope along the river valley is about 1.4 ft per mile.

For the purposes of this study the area was divided into 15 sub-basins, shown in Fig. 10, coincident with the locations of selected USGS stream-gaging stations. There are two main stem reservoirs in the upper third of the watershed. In addition, a substantial amount of natural lake storage exists in the sub-basins contributing from the north side of the main stem. Sub-watersheds to the west and south of the main stem have relatively little or no surface storage.

Glacial outwash plains of sand and gravel are prevalent on the western edge of the watershed. The remaining portion of the watershed is covered by other glacial drift. Fertile agricultural soil overlies most of the watershed, particularly in the central and eastern areas. Forest cover is sparce and is situated mostly in strips along the valleys of watercourses, near farmyards, and in other scattered locations.

To illustrate typical results, each model will be discussed in terms of its application to the Chippewa River Basin. This sub-basin is basin number 7 in Fig. 10.

The period of computation used with the SSARR began on March 10, 1969 and continued through August 31, 1969. The upper half of Fig. 11 shows the results of computations performed for the portion of the watershed which is covered with snow. At the top of the output are shown the station number and name, the evapotranspiration index (ETI), the melt rate on the first day of the month, the basin area, and the month and year of the computations. The remainder of the output consists of several columns beginning and ending with columns showing the day of the month and the hour of the day. A detailed explanation of each of the intervening 20 columns is given in Table 2. The lower half of Fig. 11 shows the computations that pertain to the area which is free of snow. From April 1 until April 17 the basin has 100 per cent snow-covered area (SCA). Therefore, all computations are effectively performed on the snow basin only. On April 18, 34 per cent of the basin has snow and 66 per cent is snow-free. By the following day all the snow has melted, and all computations are carried out on the rain basin only. On a typical snowmelt day, such as April 10, the basin received an average of 0.36 inches of precipitation (see upper part of Fig. 11). Based on the air temperature, this would have fallen as rain over 100 per cent (RA) of the basin. The accumulated amount of runoff from rainwater is then 0.48 inches. A total of 0.78 inches of water had been melted from the snowpack

TABLE 2

Explanations of Figure 11 Column Headings

PCPN - Average basin precipitation for this time interval (inches)

RA - Percentage of area on which rain may occur

RN-AR - Accumulated runoff from rainfall only (inches)

ML-AR - Accumulated snowmelt only (inches)

AR - Percentage of snowpack melted

ELEV - Elevation of snow line (feet)

SCA - Percentage of snow-covered area

D-DY - Degree-day (i.e., difference between temperature at elevation of snow-covered area and base temperature) (°F-day)

MA - Percentage of area on which snowmelt may occur

MELT - Melt from snowpack (inches)

MI - Average moisture over basin from both rainfall and snowmelt (inches)

SMI - Soil Moisture Index (inches)

ROP - Runoff percentage (a function of SMI)

RGP - Runoff generated in period (the product of ROP and MI) (inches)

BII - Baseflow Infiltration Index (inches)

BFP - Baseflow percentage (a function of BII)

BASEF - Baseflow component of flow (cfs)

SUBSF - Subsurface component of flow (cfs)

SURF - Surface component of flow (cfs)

DISCH - Stream discharge (the sum of the three components) (cfs)

DAY and HOUR

by the end of this time period. This represents 10 per cent of the amount of water equivalent that was in the snowpack. The elevation of the snow line would nominally be 990 ft. The percentage of snow-covered area in the basin is 100. There were 15 degree-days causing melt on 100 per cent of the area, yielding 0.15 inches of melt. The combined moisture available for runoff is then 0.36 inches from rain and 0.15 inches from snowmelt, giving 0.51 inches total. Although the soil moisture index (SMI) has a value of 0.59, the runoff percentage (ROP) has been set at a constant 35 per cent. This yields a total runoff amount of 0.18 inches. Based on a base flow infiltration index of 0.10 inches, 23 per cent of this runoff is allocated to the baseflow phase. The baseflow, subsurface, and surface flows are respectively 66, 960, and 1968 cfs, giving a total stream discharge of 2995 cfs. Similar computations are performed for each time interval. The total flow from the Chippewa River Basin will then be the sum of the discharges from the snow basin and the rain basin.

For April 10 on the rain portion of the basin (lower half of Fig. 11), the 0.36 inches of precipitation have no effect because the percentage of rain area is zero. The only contribution from the rain basin is a negligible amount of baseflow, 7 cfs, that resulted from a small initial value given when computations first began in mid-March.

The results of using HEC-1 to generate runoff covering the period of March 22, 1969 to May 30, 1969 are shown in Fig. 12. The upper portion, Part A, gives constant data that indicate the loss analysis variables, unit hydrograph, initial water equivalent in the snowpack, and other required variables. A more detailed description of the pertinent variables is given in Table 3. Part of Fig. 12 gives the computations for each day of the simulation period. To the left of the time period number, the calendar

TABLE 3

Explanations of Figure 12 Variables

NHR - Number of hours in each computation interval

NQ - Total number of points on discharge hydrograph

ISNOW - Index to specify snowmelt computations are to be performed

ISTAQ - Stream station location identification number

NP - Number of precipitation items to be read on H cards

QRCSN - Flow below which hydrograph recession is constrained (cfs)

RTIOR - Ratio of recession flow to that ten periods later

STRTQ - Flow at start of storm (cfs)

TLAPS - Temperature lapse rate for snowmelt computations (°F per 1000-ft elevation zone)

SNOW - Average water equivalent of snowpack at start of storm, only one elevation band used (inches)

AREA - Drainage area (square miles)

NAP - Normal precipitation (any non-zero value) (inches)

TC - Time of concentration (hours)

R - Clark unit hydrograph storage coefficient (hours)

COEF - Snowmelt coefficient (inches per degree-day)

STRKR - Starting value of loss coefficient on exponential recession curve for rain losses

STRKS - Starting value of loss coefficient on exponential recession curve for snowmelt losses

RTIOK - Slope of snowmelt loss coefficient curve

ERAIN - Exponent of precipitation for rain loss function

FRZTP - Base temperature at bottom of zone for snowmelt (°F)

DLTKR - Amount of initial accumulated rain loss during which loss coefficient is increased

RTIOL - Slope of rain loss coefficient curve

Unit Hydrograph Ordinates

PRECIP - Basin average precipitation (inches per period)

TEMP - Air temperature at bottom of lowest elevation zone (°F)

SNOMLT - Snowmelt (inches)

SNOW EX - Excess from snowmelt (inches)

RAIN - Rainfall (inches)

RAIN EX - Excess from rainfall (inches)

COMP Q - Computed discharge (cfs)

date has been inserted. The precipitation in interval 7 (March 28) occurred as snowfall, because the mean air temperature was only 32°. The snow was then added to the water equivalent of the snowpack. Later, on a day like April 10, interval 20, a rainfall of 0.36 inches occurred. On the same day, due to a mean air temperature of 47°F, a total of 0.99 inches of melt also occurred. The total moisture of 1.35 inches of water caused 0.59 inches of runoff. The corresponding discharge for this day is 8342 cfs.

Although the loss analysis in HEC-1 allows the loss coefficient to vary with accumulated loss, this feature was not used. During the snowmelt period in the Midwest the frost in the ground plays an important role in determining the infiltration loss. At the same time as the snow is melting, the frost in the ground is also melting. This may cause an increase in, or at least maintain, a given basin-wide infiltration rate. Such behavior is contrary to what normally happens during a summer runoff event, where losses decrease from the beginning to the end of the event.

In addition, there is no provision for the accumulated loss, which is an index to soil moisture, to dry out or recover during periods of no precipitation or melt. This limits the period of time over which the analysis can be used. Snowmelt computations may continue for as long as two months. Due to the preceding reasons, the loss rate coefficients RTIOL and RTIOK were set equal to 1.0 in most watersheds, making the loss rate "k" independent of accumulated loss. The effect of this is to make the runoff a function of the intensity of precipitation or snowmelt only. The runoff can then be expressed as a percentage of the precipitation and snowmelt. This relationship for the Chippewa River Basin is shown in Fig. 13. The runoff percentage used for the snow basin portion of the SSARR model is also shown in the figure. This same information, in the form of a rainfall-runoff relationship, is plotted for comparison purposes on the standard Soil Conservation Service runoff curves in Fig. 14. It is interesting to observe that the relationships used by the SCS and this special case of the HEC-1 loss analysis yield results which are reasonably similar. In Fig. 14 the curve from the HEC-1 analysis could be made more nearly the same as a given SCS curve if other values were selected for the variables STRKR and ERAIN. The basic relationships do differ, however, and can be made similar only in a limited region.

In the Minnesota River Basin the two largest floods of record occurred in 1965 and 1969. In the upper two-thirds of the basin, the largest flood of record was the 1969 event, while in the lower third the 1965 flood was the largest. Other substantial floods in recent times occurred in 1951 and 1952. Due to the unavailability of necessary hydrometeorological data on magnetic tape prior to October 1963, only the events since that time were considered for study.

The procedure used in applying the two models was to select certain portions of the historical record to be used for determining necessary watershed parameters. These fitted parameters were then used to predict a separate portion of the historical record as an independent evaluation of model performance. Historical runoff events in 1965, 1966, and 1967 were used to fit the models. The flood of 1969 was then predicted using the fitted variables and compared with the observed runoff.

Initially, the period June 1967 was used so that proficiency in using the SSARR model could first be developed for a summer period without snowmelt. When a sufficient understanding of the model had been attained, the entire year of 1967 was simulated, including snowmelt. The year 1966 was then included in the fitting period, and finally the major flood year of 1965.

The final fitting runs were made so that the snowmelt flood of 1965 was given the most weight in determining the fitted variables for the SSARR model.

Figure 15 shows a comparison between predicted and observed hydrographs at selected locations in the Minnesota River Basin. The melting was predicted somewhat late on certain basins. This is attributed to the form of the melt-rate-coefficient-vs.-percentage-of-snowpack-melted function. As stated in Section II, it is anticipated that a more reliable relationship would result from making the melt rate coefficient a function of a moving accumulation of degree-days. The same values for the basin characteristics as had been used to give the best simulation for the fitted years were then used to predict the major flood of 1969. The results of this are shown in Fig. 16. In this case all the basins showed predicted snowmelt later than actual melt. This is again due to the melt rate coefficient function. In addition, it may be noted that several basins in the east portion of the watershed gave a predicted peak discharge substantially higher than the observed peak. This is directly related to the event of 1965, on which the SSARR model basin coefficients were most heavily based.

In the snowmelt flood of 1965, particularly in the southeast portion of the Minnesota basin, conditions produced runoff equal to or more than 90 per cent of available surface moisture. These high runoff amounts were due to a well-frozen soil profile as well as a glazed ice crust on the ground surface. Some pre-season melt and subsequent refreezing had caused the ice layer on the surface. This was followed by heavy late-season snow. A rapid melt and accompanying rain yielded unusually high runoff conditions. Basin coefficients reflecting this type of high runoff production in 1965 gave a high prediction of peak discharge when applied to the snowpack data of 1969.

This would indicate that if ground conditions had been the same as they were in 1965, the lower reaches of the watershed would have experienced far greater flooding than they actually did.

In making the prediction for 1969, the actual precipitation and air temperature data were used, although in a real prediction situation these data would be unknown at the time of the prediction.

A slightly different approach was used in applying HEC-1 to the Minnesota basin. Three events were chosen from which best-fit variables were determined. These events were April 1965, March 1967, and June 1967. A weighted average of the variables was then used as the overall best-fit variable. The weights given to the events were in a ratio of 2:2:1 respectively. This gave greater weight to the snowmelt floods in determining hydrograph and loss characteristics and not so much weight to the 1965 event as was given in applying the SSARR model. As could be expected, the average basin characteristics so determined underpredicted the unusual event of 1965 with its glazed ice conditions; see Fig. 17. However, these average values did predict the event of 1969 surprisingly well, as shown in Fig. 18. In most sub-watersheds HEC-1 predicted the time of the melt more accurately than the revised function in the SSARR model.

VI. CONCLUSIONS AND RECOMMENDATIONS

The following accomplishments and conclusions have resulted from this study:

1. Hydrometeorological data pertinent to snowmelt flood forecasting were prepared in proper format for the SSARR model and HEC-1.

2. The performance of the SSARR model and that of HEC-1 were evaluated with respect to their usefulness in computing snowmelt floods on a medium-sized upper midwestern watershed. The SSARR model was initially more difficult to understand than HEC-1 due to its use of somewhat unfamiliar techniques, the relatively large number of variables that are required to describe a basin, and the lack of an internal optimization routine for the fitting of variables. Its very large size restricts its practical use to large computers. However, the continuous-accounting feature of the SSARR model makes it very valuable for simulating records containing a series of wet and dry periods. For snowmelt computations in the Midwest the SSARR model's ability to represent an area as a split basin with differing characteristics and to gradually change from one representation to the other is a marked advantage. In the SSARR model a reduction in the number of fitted input variables needed to describe a basin would be desirable. This could be accomplished by relating certain variables to measurable basin characteristics and utilizing a set of dimensionless functions to generate the present characteristic tables. HEC-1 is more easily understood than the SSARR model because it uses standard techniques. Its optimization routine makes it easier to apply, provided the results are interpreted properly. HEC-1 can be run on medium-sized computers. It cannot be used over sustained periods, however, as there is no provision for recovery of the loss rate function. With certain modifications, either model will adequately perform snowmelt flood predictions in the Upper Midwest. Where personnel can be assigned full time to flood forecasting operations, the use of the SSARR model might be desirable. Under such circumstances

the responsible individuals could devote sufficient time to become familiar with the parameters and learn to utilize the special functions of the SSARR model. Where flood forecasting is of a more seasonal or part-time nature, the more easily applied and used HEC-1 model would be recommended. The most significant current weakness of any snowmelt flood forecast in the Upper Midwest is due to the inability to factually quantify the surface runoff potential and relate it to model parameters.

3. To improve the accuracy of snowmelt flood computations in the Upper Midwest, certain model functions should be revised. In the SSARR model the degree-day melt coefficient should be made a function of a moving accumulation of degree-days. The determination of snow-covered area should be based on the water equivalent of snow on the ground or a similar variable.

   In HEC-1 the degree-day melt coefficient should also be made a function of a moving accumulation of degree-days rather than a constant value. The loss rate function for snowmelt should be revised to allow the user to specify explicitly the equation to be used. The loss rate optimization procedure should allow the slope of the loss rate function to reflect a change from lower to higher loss rates.

4. Several of the adaptations noted above were made in the SSARR and HEC-1 models to improve their applicability to snowmelt flood forecasting in the Midwest. These and the other changes recommended should be tested on additional upper midwestern watersheds.

5. It is desirable to allow the forecast model to adjust input initial conditions and runoff functions so that forecast discharges are in agreement with observed discharges during an actual runoff event. This procedure is available in the SSARR model. Due to insufficient time this option was not evaluated. Where HEC-1 is used for flood forecasting, this option should also be available.

As a result of applying these models to the Minnesota River Basin, certain additional conclusions can be drawn.

The average water equivalent in the snowpack, the expected additional precipitation, the expected air temperatures, and the existing surface and frost conditions must all be known for a reliable forecast. Variations in these critical items could alter a predicted peak discharge by 50 to 100 per cent.

The flooding that resulted from the large amount of water equivalent in the snowpack in 1969 could easily have been more severe. If a glazed surface and tightly frozen ground conditions had existed in 1969, the peak discharge near the mouth of the Minnesota River could possibly have been 168,000 cfs--twice the observed peak.

Comprehensive mathematical models of runoff can be useful tools for the prediction of flood forecasts. Their proper use requires careful analysis to determine whether each method being used in the model best represents the model phenomena as they occur in the region under study. If necessary, the model should be altered to properly reflect the processes in the region under study. The blanket application of a general model may lead to inappropriate results.

The greatest uncertainty in current forecasts, apart from the prediction of future meteorological conditions, is the determination of the runoff potential in a given area. Presently the flood forecaster must use his judgment to select model parameters to reflect basin runoff potential for a specific event.

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[3] U.S. Army Corps of Engineers. 1972. Program description and user manual; streamflow synthesis and reservoir regulation. North Pacific Division, Corps of Engineers. Portland, Oregon. July

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Anderson, David B. and Harlan H. Schwob. 1970. Floods of April-May 1969 in upper midwestern United States. Open-file report. U.S. Geological Survey. St. Paul, Minnesota. February

Baker, Donald G. 1971. Snow cover and winter soil temperatures at St. Paul, Minnesota. Bulletin 37, Water Resources Research Center. University of Minnesota. Minneapolis, Minnesota. June

Paulhus, J. L. H. 1971. The March-April 1969 snowmelt floods in the Red River of the North, Upper Mississippi and Missouri basins. NOAA Technical Report NWS 13. National Weather Service. Silver Spring, Maryland. April

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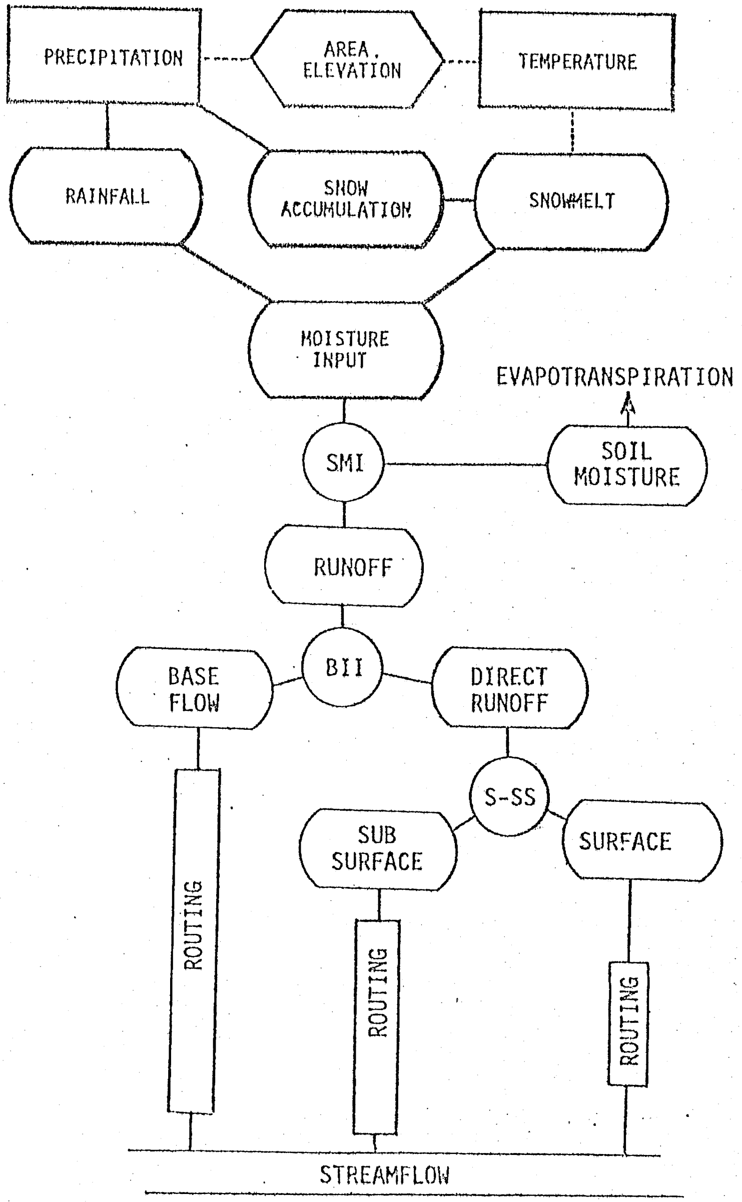

Fig. 1 - Schematic representation of the SSARR model

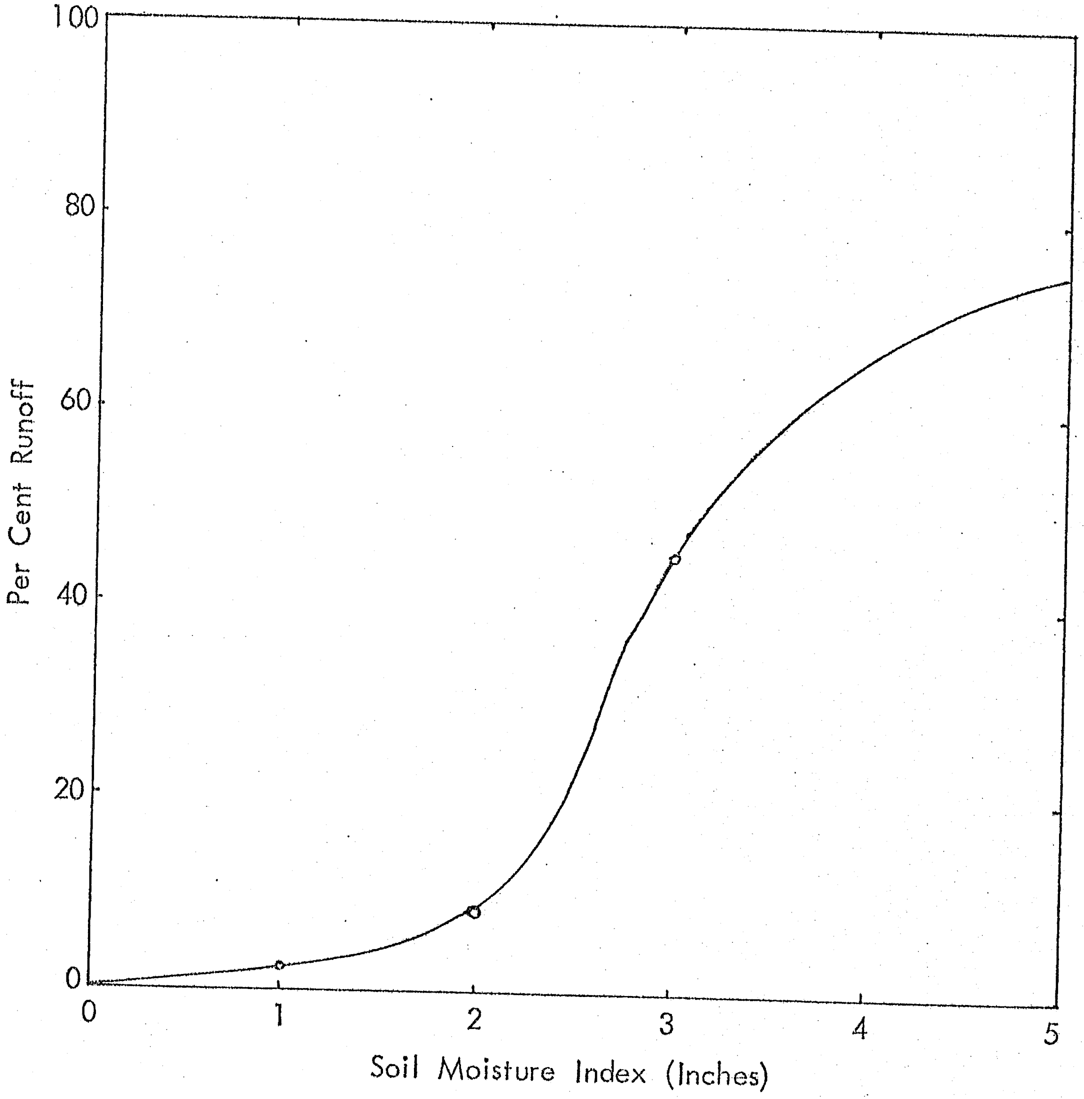

Fig. 2 - Typical Soil Moisture Index and Runoff Percentage Relationship

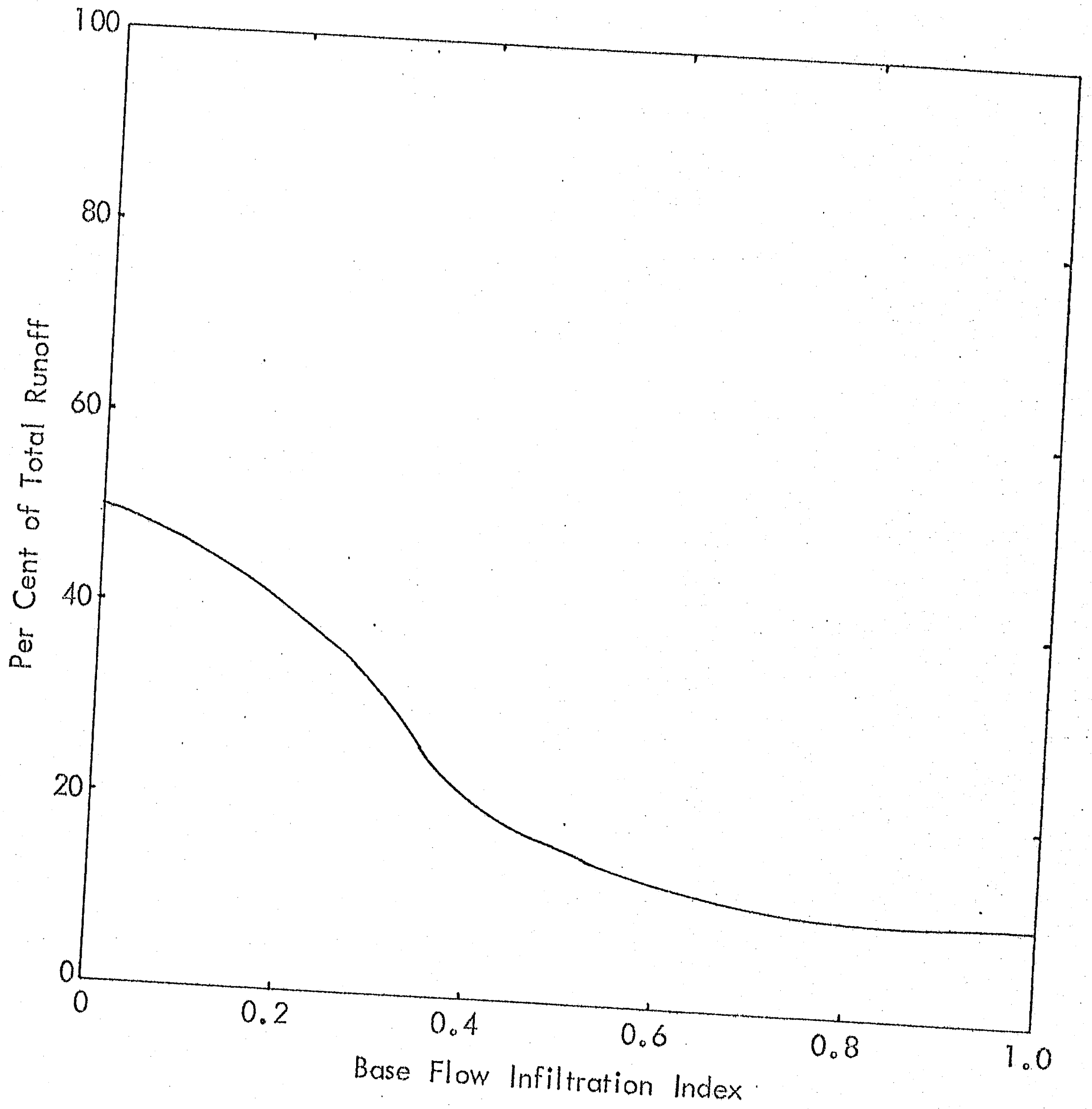

Fig. 3 - Typical relationship giving the percentage of the total runoff which will become baseflow as a function of baseflow infiltration index

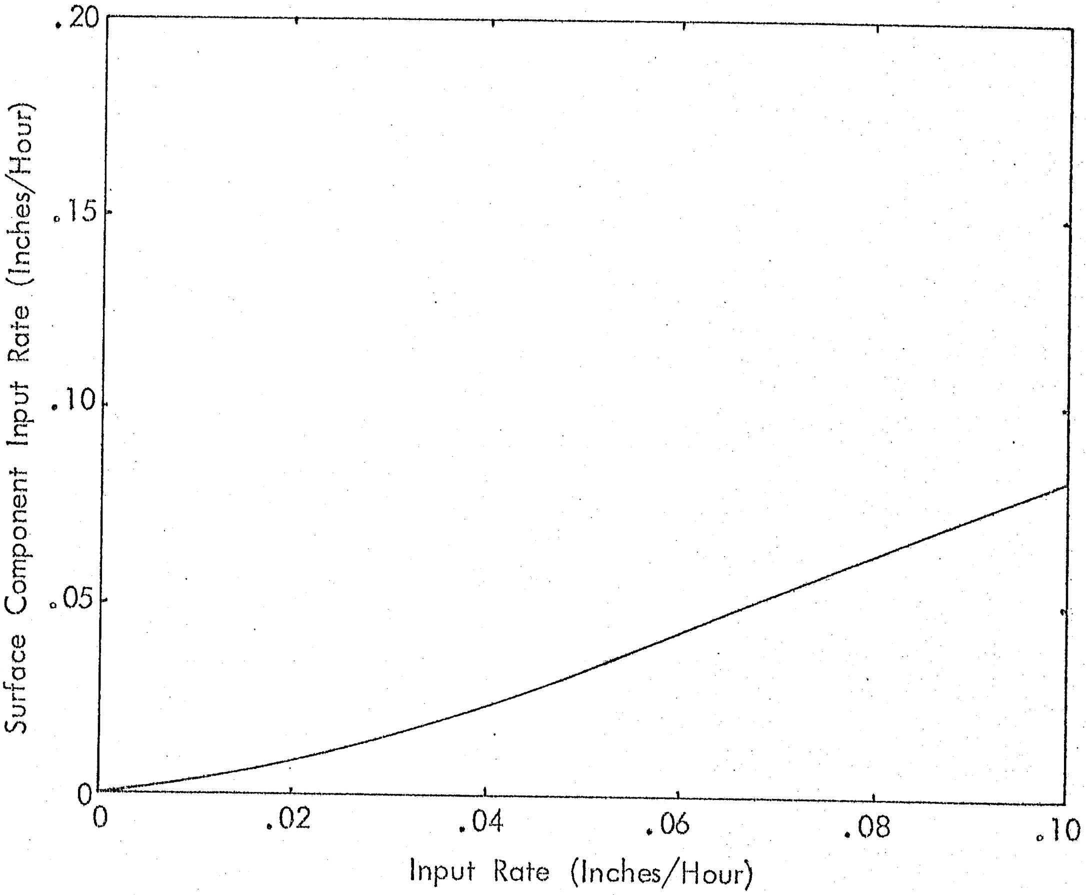

Fig. 4 - Typical function showing division of direct runoff into surface and sub-surface components

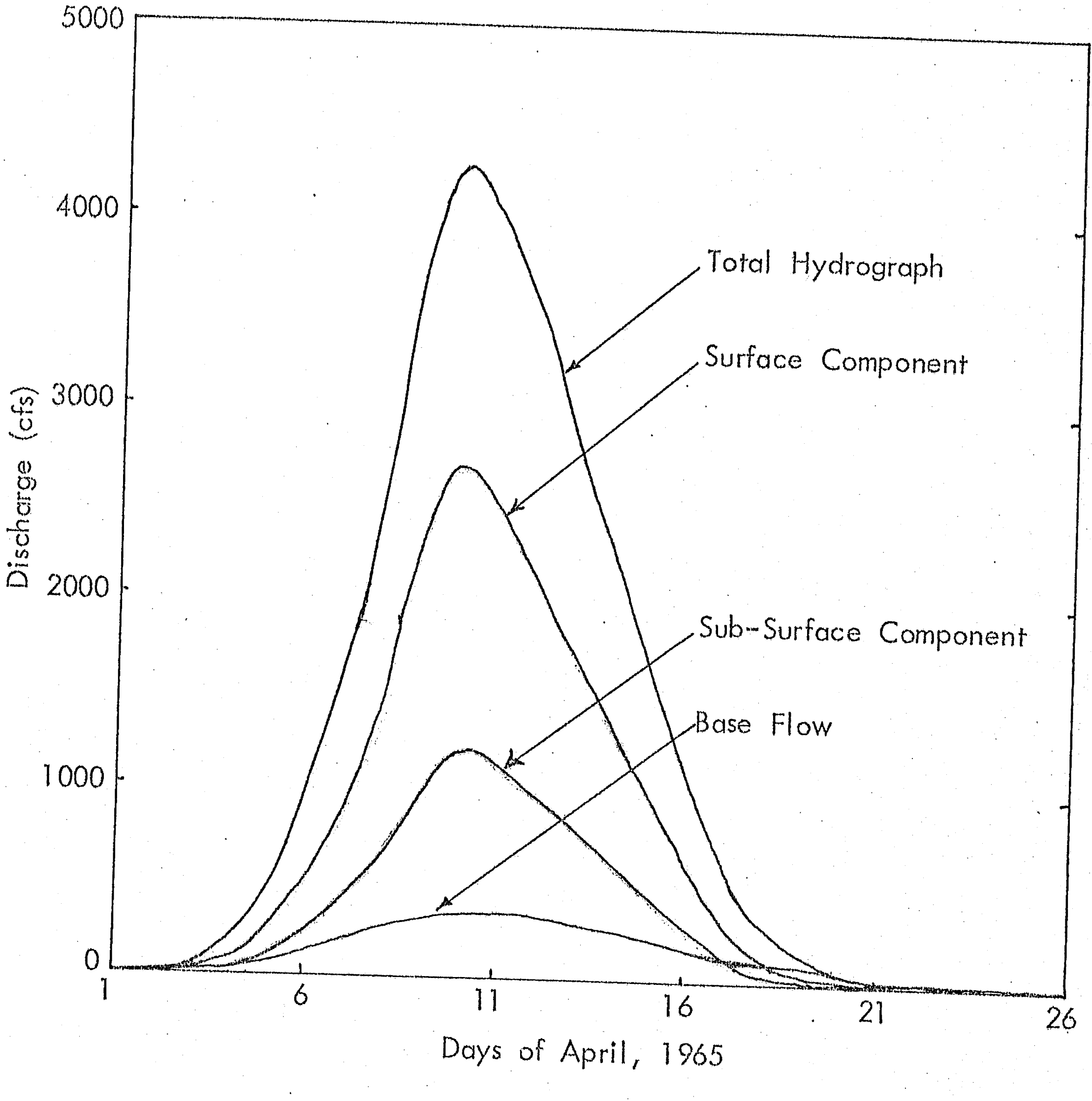

Fig. 5 - Relative magnitudes of Surface, Sub-surface, and Baseflow Hydrographs

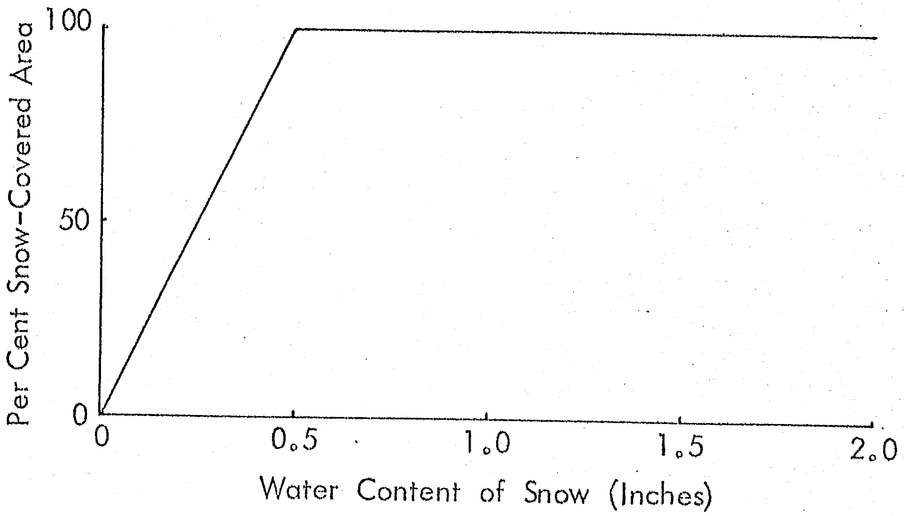

Fig. 6 - Snow-Covered Area as a function of Water Equivalent in Snowpack

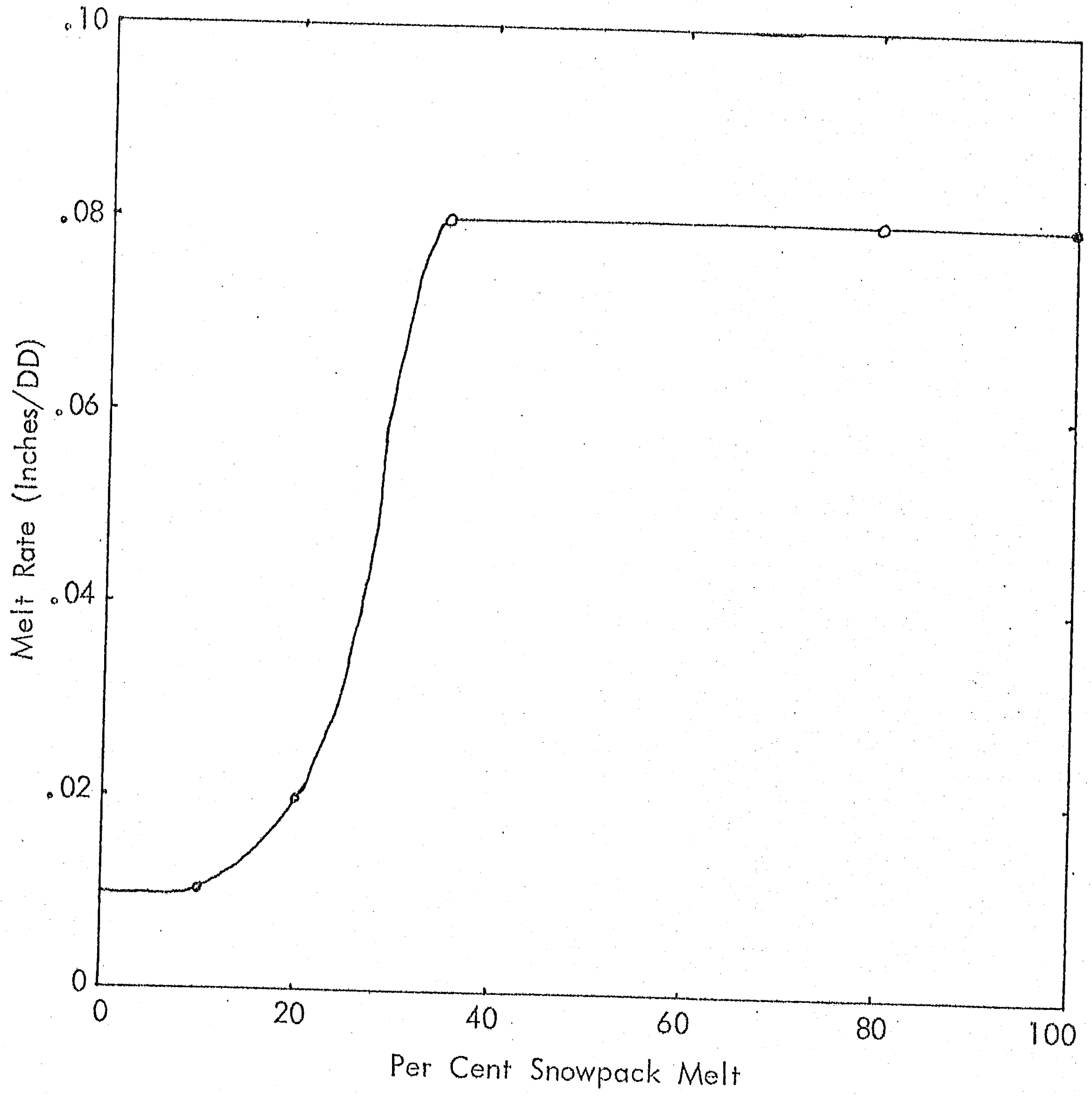

Fig. 7 - Melt Rate Coefficient as a function of percentage of Snowpack Melted

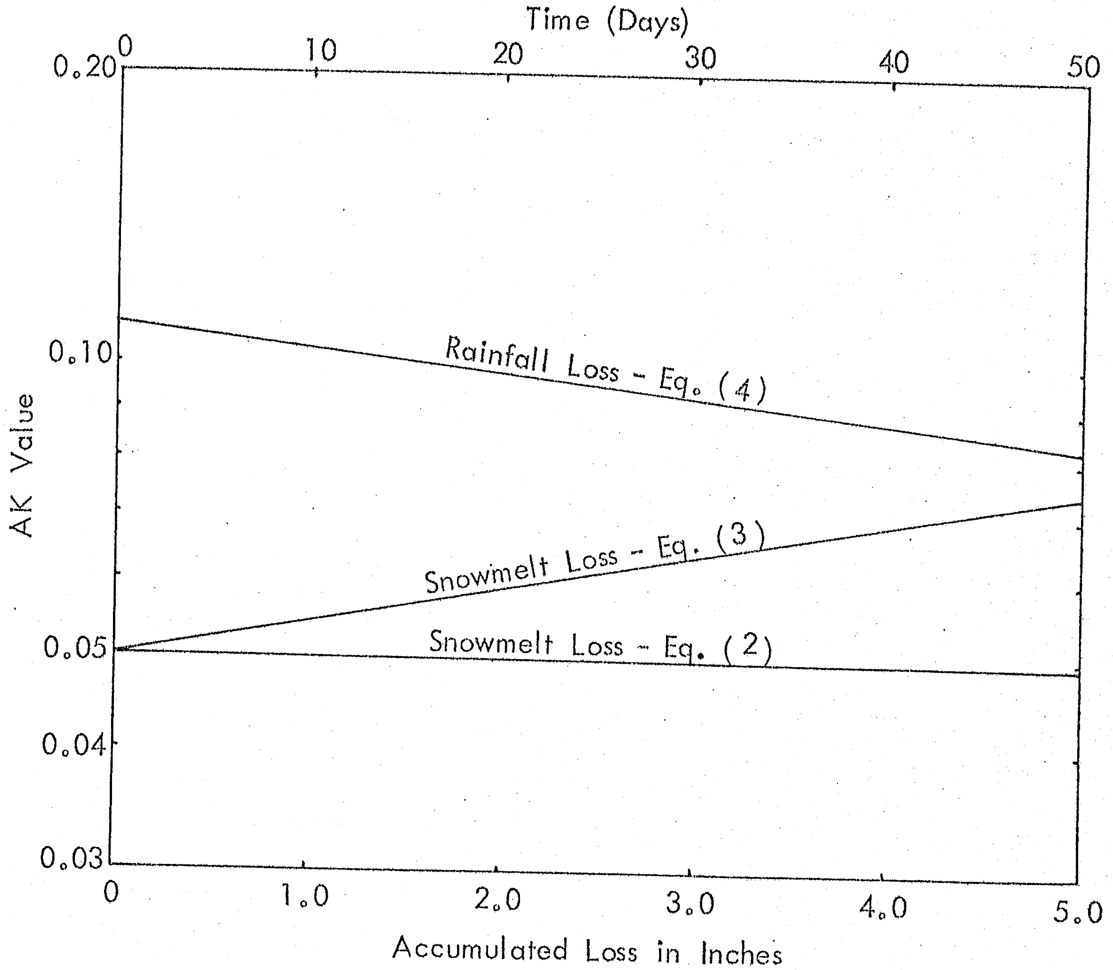

Fig. 8 - Typical Loss Coefficient relationships used in HEC-1

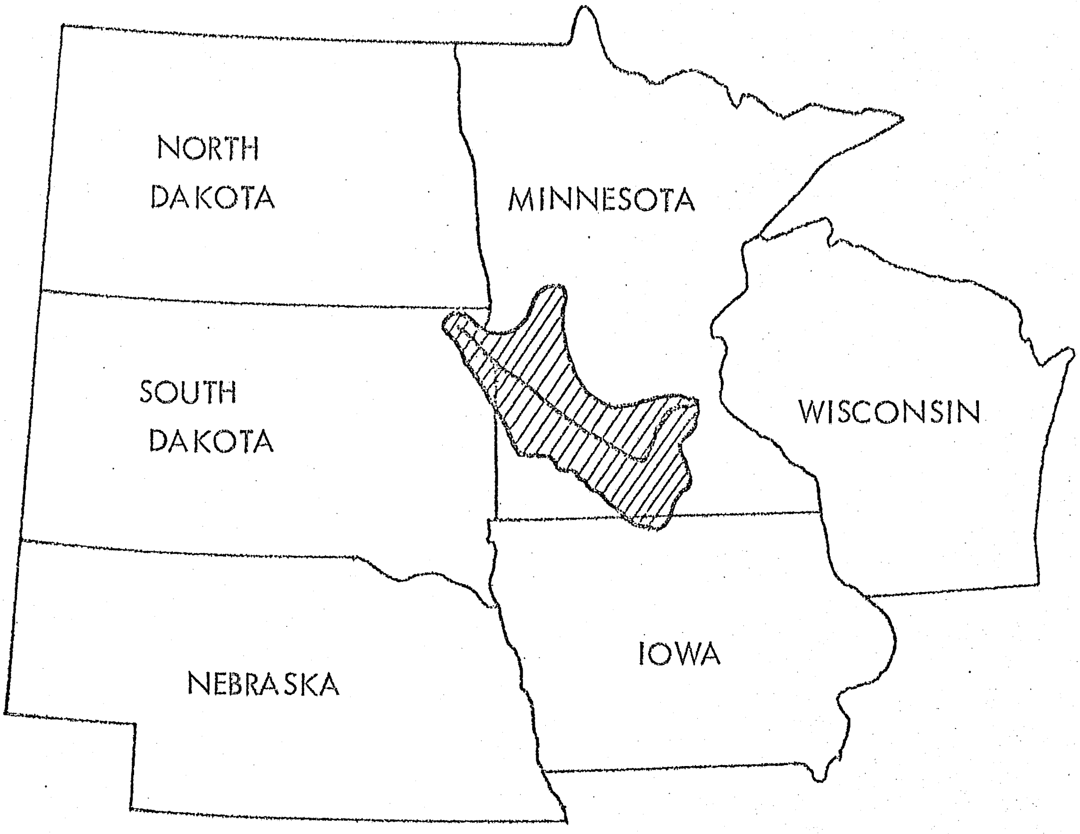

Fig. 9 - Location of Minnesota River Watershed

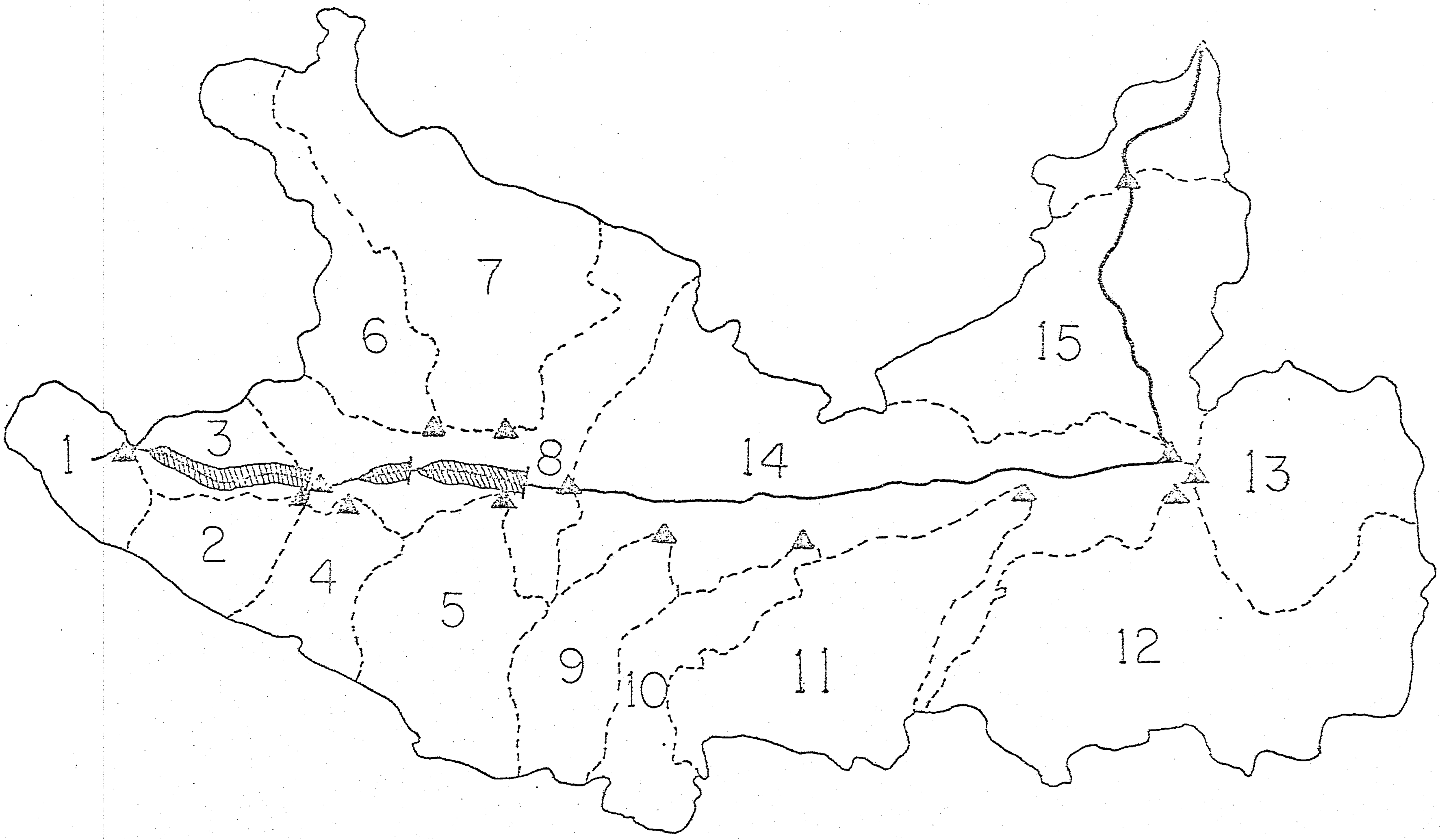

Fig. 10 - Sub-watersheds of Minnesota River Watershed

135454

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                    BASIN RESULTS - STATION        700.0 CHIPPEWA RIVER SNOW

RUN DATE   RUN NO.  INITIAL DATE, HOUR           JOB DESCRIPTION
                -0     10 MAR 1969    00          -0MINNESOTA RIVER WATERSHED 1969                    N.P.D., CORPS OF ENGINEERS

                            ETI =  .10 IN./DAY, MELT RATE =  .010 IN./DEGREE-DAY, AREA = 1870.0 SQ. MI.

DAY HOUR  PCPN (RA RN-AR ML-AR (AR ELEV SCA D-DY (MA  MELT     MI    SMI ROP   RGP  BII BFP  BASEF  SUBSF   SURF   DISCH HOUR DAY
                                                                                                                  APR 1969
APR 1969
  1   00   .01   0   .05   .05   1  990 100  0.0   0  0.00  0.00  0.00  35  0.00  .10  22    18     77    158     254   00  1
  2   00  0.00 100   .05   .10   1  990 100  5.0 100   .05   .05  0.00  35   .02  .10  22    19     76    153     249   00  2
  3   00  0.00   0   .05   .10   1  990 100  0.0   0  0.00  0.00  0.00  35  0.00  .09  23    21     78    160     260   00  3
  4   00  0.00 100   .05   .15   2  990 100  5.0 100   .05   .05  0.00  35   .02  .09  23    22     83    170     276   00  4
  5   00  0.00 100   .05   .21   3  990 100  6.0 100   .06   .06  0.00  35   .02  .09  23    24    103    212     340   00  5
  6   00  0.00 100   .05   .23   3  990 100  2.0 100   .02   .02  0.00  35   .01  .09  23    26    120    247     395   00  6
  7   00  0.00 100   .05   .28   4  990 100  5.0 100   .05   .05  0.00  35   .02  .09  23    29    132    271     433   00  7
  8   00   .20 100   .12   .44   6  990 100 16.0 100   .16   .36  0.00  35   .13  .09  23    33    224    458     717   00  8
  9   00   .67 100   .35   .63   8  990 100 19.0 100   .19   .86   .13  35   .30  .09  23    46    541   1108    1696   00  9
 10   00   .36 100   .48   .78  10  990 100 15.0 100   .15   .51   .59  35   .18  .10  23    66    960   1968    2995   00 10
 11   00   .01 100   .48   .88  12  990 100 10.0 100   .10   .11   .82  35   .04  .09  23    88   1194   2447    3731   00 11
 12   00   .02 100   .49  1.03  14  990 100 13.0 100   .15   .17   .80  35   .06  .09  23   109   1236   2534    3880   00 12
 13   00   .03 100   .50  1.35  18  990 100 23.0 100   .32   .35   .81  35   .12  .09  23   131   1246   2554    3933   00 13
 14   00   .07 100   .52  1.85  25  990 100 28.0 100   .50   .57   .93  35   .20  .10  23   156   1340   2746    4243   00 14
 15   00   .09 100   .55  2.70  36  990 100 22.0 100   .85   .94  1.21  35   .33  .10  23   188   1607   3297    5093   00 15
 16   00   .04 100   .57  4.38  58  990 100 21.0 100  1.68  1.72  1.72  35   .60  .12  22   233   2183   4553    6971   00 16
 17   00  0.00 100   .57  5.98  80  990 100 20.0 100  1.60  1.60  2.73  35   .56  .13  22   295   2981   6342    9619   00 17
 18   00  0.00  33   .57  7.17  96  990  34 15.0 100  1.20  1.20  3.67  35   .42  .17  22   367   3676   7896   11940   00 18
 19   00  0.00   0   .57  7.52 100 1003   0 13.0  33  1.04   .35  5.89  35   .12  .16  21   439   3955   8516   12912   00 19
 20   00   .01   0   .57  7.52 100#0000   0  0.0   0  0.00  0.00  5.79  35  0.00  .16  21   504   3726   8027   12258   00 20
 21   00   .02   0   .57  7.52 100#0000   0  0.0   0  0.00  0.00  5.69  35  0.00  .15  21   559   3210   6918   10689   00 21
 22   00  0.00   0   .57  7.52 100#0000   0  0.0   0  0.00  0.00  5.59  35  0.00  .15  21   607   2624   5656    8889   00 22
 23   00  0.00   0   .57  7.52 100#0000   0  0.0   0  0.00  0.00  5.49  35  0.00  .14  21   647   2072   4467    7187   00 23
 24   00  0.00   0   .57  7.52 100#0000   0  0.0   0  0.00  0.00  5.39  35  0.00  .14  21   680   1596   3442    5720   00 24
 25   00   .02   0   .57  7.52 100#0000   0  0.0   0  0.00  0.00  5.29  35  0.00  .14  22   708   1207   2604    4521   00 25
 26   00   .03   0   .57  7.52 100#0000   0  0.0   0  0.00  0.00  5.19  35  0.00  .13  22   729    900   1942    3574   00 26
 27   00   .58   0   .57  7.52 100#0000   0  0.0   0  0.00  0.00  5.09  35  0.00  .13  22   746    664   1432    2844   00 27
 28   00   .56   0   .57  7.52 100#0000   0  0.0   0  0.00  0.00  4.99  35  0.00  .12  22   759    485   1046    2291   00 28
 29   00  0.00   0   .57  7.52 100#0000   0  0.0   0  0.00  0.00  4.89  35  0.00  .12  22   767    351    759    1879   00 29
 30   00  0.00   0   .57  7.52 100#0000   0  0.0   0  0.00  0.00  4.79  35  0.00  .12  22   772    253    546    1573   00 30
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135460

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RUN DATE   RUN NO.  INITIAL DATE, HOUR           JOB DESCRIPTION
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                            ETI =  .10 IN./DAY, MELT RATE = 0.000 IN./DEGREE-DAY, AREA = 1870.0 SQ. MI.

DAY HOUR  PCPN (RA RN-AR ML-AR (AR ELEV SCA D-DY (MA  MELT     MI    SMI ROP   RGP  BII BFP  BASEF  SUBSF   SURF   DISCH HOUR DAY
                                                                                                                  APR 1969
APR 1969
  1   00   .01   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  5.16  85  0.00  .10  45     8      0      0       9   00  1
  2   00  0.00   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  5.12  85  0.00  .10  45     8      0      0       9   00  2
  3   00  0.00   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  5.02  85  0.00  .09  45     8      0      0       9   00  3
  4   00  0.00   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  4.92  83  0.00  .09  45     8      0      0       8   00  4
  5   00  0.00   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  4.82  80  0.00  .09  46     8      0      0       8   00  5
  6   00  0.00   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  4.72  78  0.00  .08  46     8      0      0       8   00  6
  7   00  0.00   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  4.62  75  0.00  .08  46     8      0      0       8   00  7
  8   00   .20   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  4.52  73  0.00  .08  46     7      0      0       8   00  8
  9   00   .67   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  4.42  70  0.00  .08  46     7      0      0       8   00  9
 10   00   .36   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  4.32  68  0.00  .07  46     7      0      0       8   00 10
 11   00   .01   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  4.22  65  0.00  .07  46     7      0      0       7   00 11
 12   00   .02   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  4.12  63  0.00  .07  46     7      0      0       7   00 12
 13   00   .03   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  4.02  60  0.00  .07  47     7      0      0       7   00 13
 14   00   .07   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  3.92  58  0.00  .07  47     6      0      0       7   00 14
 15   00   .09   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  3.82  55  0.00  .06  47     6      0      0       7   00 15
 16   00   .04   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  3.72  53  0.00  .06  47     6      0      0       7   00 16
 17   00  0.00   0  0.00  0.00   0    0   0  0.0   0  0.00  0.00  3.62  50  0.00  .06  47     6      0      0       6   00 17
 18   00  0.00  66  0.00  0.00   0    0   0  0.0   0  0.00  0.00  3.52  48  0.00  .06  47     6      0      0       6   00 18
 19   00  0.00 100  0.00  0.00   0    0   0  0.0   0  0.00  0.00  3.42  45  0.00  .06  47     6      0      0       6   00 19
 20   00   .01 100   .00  0.00   0    0   0  0.0   0  0.00   .01  3.32  43   .00  .05  47     6      2      4      12   00 20
 21   00   .02 100   .01  0.00   0    0   0  0.0   0  0.00   .02  3.23  41   .01  .05  47     6      8     17      33   00 21
 22   00  0.00 100   .01  0.00   0    0   0  0.0   0  0.00  0.00  3.14  38  0.00  .05  47     6     14     30      52   00 22
 23   00  0.00 100   .01  0.00   0    0   0  0.0   0  0.00  0.00  3.04  36  0.00  .05  47     7     15     32      55   00 23
 24   00  0.00 100   .01  0.00   0    0   0  0.0   0  0.00  0.00  2.94  34  0.00  .05  48     7     14     29      52   00 24
 25   00   .02 100   .02  0.00   0    0   0  0.0   0  0.00   .02  2.84  34   .01  .05  48     8     15     31      55   00 25
 26   00   .03 100   .03  0.00   0    0   0  0.0   0  0.00   .03  2.75  33   .01  .05  48     9     22     45      77   00 26
 27   00   .58 100   .21  0.00   0    0   0  0.0   0  0.00   .58  2.67  32   .19  .05  48    16    116    237     371   00 27
 28   00   .56 100   .41  0.00   0    0   0  0.0   0  0.00   .56  2.97  35   .19  .05  48    35    327    670    1032   00 28
 29   00  0.00 100   .41  0.00   0    0   0  0.0   0  0.00  0.00  3.23  41  0.00  .05  47    58    477    978    1515   00 29
 30   00  0.00 100   .41  0.00   0    0   0  0.0   0  0.00  0.00  3.13  38  0.00  .05  47    78    491   1007    1577   00 30
```

Fig. 11   Typical Output from SSARR model, Chippewa River Watershed

```
                 MINNESOTA RIVER BASIN
                 FLOOD HYDROGRAPH PACKAGE

   NHR    NMIN      NQ   NSTAN   NSTAR   ISNOW   IDERV   IPLOT    NSTM   NPLAN
    24       0      70       0       0       1       0       1       0       0

 IPRNT   METRC   IOBST   IDAYX    IHRX   IMINX
     0      -0      -0       0       0       0

 ISTAQ   IHDGR      NP    NSTN    NSTR   NUHGQ   NCLRK   LOCAL   NCOMB    NEXT
     7       0      70       0       0       0       0       0       0      -1

  IPNT    NOMG    IBAL   INRGY   JPLOT
     0       0       0       0      -0

 STORM    SPFE     PMS   TRSPC   TRSDA   STRTL   CNSTL   RTIMP   QRCSN   RTIOR
 -0.00    0.00    0.00   -0.00    0.00   -0.00    0.00   -0.00  1500.0    1.70          A

 STRTQ   ALSMX   TLAPS   RATIO      TP      CP   TAREA
     8    0.00    3.30    0.00    0.00    0.00   -0.00

 SNOW=     7.5    -0.0    -0.0    -0.0    -0.0    -0.0    -0.0    -0.0    -0.0    -0.0

 AREA=  1870.0    -0.0    -0.0    -0.0    -0.0    -0.0    -0.0    -0.0    -0.0    -0.0

  NAP=     .01   -0.00   -0.00   -0.00   -0.00   -0.00   -0.00   -0.00   -0.00   -0.00

AREA=  1870.0     NAP=     .01

    TC       R    COEF   STRKR   STRKS   RTIOK   ERAIN   FRZTP   DLTKR   RTIOL
 46.00  183.00     .08     .24     .24    1.00     .70   33.00    0.00    1.00

UNIT HYDROGRAPH 42 END-OF-PERIOD ORDINATES, LAG=  50.26 HOURS, CP=  .23  VOL= 1.00
  1646    4536    5424    4757    4171    3658    3208    2813    2467    2163
  1897    1663    1459    1279    1122     984     863     756     663     582
   510     447     392     344     302     265     232     203     178     156
   137     120     105      93      81      71      62      55      48      42
    37      32

                                                            END-OF-PERIOD FLOW
        TIME PRECIP    TEMP     SNOMLT   SNOW EX     RAIN   RAIN EX   COMP Q     OBS Q
Mar. 22, 1    0.00    18.0       0.00      0.00     0.00      0.00        8
         2    0.00    30.0       0.00      0.00     0.00      0.00        7
         3    0.00    35.0        .03       .00     0.00      0.00        7
         4    0.00    31.0       0.00      0.00     0.00      0.00        6
         5    0.00    27.0       0.00      0.00     0.00      0.00        6
         6    0.00    22.0       0.00      0.00     0.00      0.00        6
         7     .26    32.0       0.00      0.00     0.00      0.00        5
         8     .04    14.0       0.00      0.00     0.00      0.00        5
         9    0.00    -6.0       0.00      0.00     0.00      0.00        5
        10    0.00     2.0       0.00      0.00     0.00      0.00        4
Apr. 1, 11     .01    17.0       0.00      0.00     0.00      0.00        4
        12    0.00    37.0        .19       .00     0.00      0.00        4
        13    0.00    28.0       0.00      0.00     0.00      0.00        4
        14    0.00    37.0        .19       .00     0.00      0.00       37
        15    0.00    38.0        .27       .02     0.00      0.00       95
        16    0.00    34.0       0.00      0.00     0.00      0.00      113
        17    0.00    37.0        .19       .00     0.00      0.00      976
        18     .20    48.0       1.07       .45      .20       .08     4108
        19     .67    51.0       1.31       .64      .67       .33     8342
Apr. 10, 20    .36    47.0        .99       .43      .36       .16    10789
        21     .01    42.0        .59       .16      .01       .00    11289
        22     .02    45.0        .83       .29      .02       .01    12312
        23     .03    55.0        .63       .76      .03       .01    13894
        24     .07    60.0        .55       .16      .07       .02    13842
        25     .09    54.0       0.00      0.00      .09      0.00    12392
        26     .04    53.0       0.00      0.00      .04      0.00    10867
        27    0.00    52.0       0.00      0.00     0.00      0.00     9530
        28    0.00    47.0       0.00      0.00     0.00      0.00     8357
        29    0.00    45.0       0.00      0.00     0.00      0.00     7328
Apr. 20, 30    .01    50.0       0.00      0.00      .01      0.00     6427
        31     .02    55.0       0.00      0.00      .02      0.00     5636
        32    0.00    51.0       0.00      0.00     0.00      0.00     4942
        33    0.00    50.0       0.00      0.00     0.00      0.00     4334
        34    0.00    49.0       0.00      0.00     0.00      0.00     3801
        35     .02    50.0       0.00      0.00      .02      0.00     3333
        36     .03    60.0       0.00      0.00      .03       .00     3178
        37     .58    55.0       0.00      0.00      .58       .15     3504          B
        38     .56    50.0       0.00      0.00      .56       .15     3745
        39    0.00    41.0       0.00      0.00     0.00      0.00     3494
Apr. 30, 40   0.00    46.0       0.00      0.00     0.00      0.00     3129
        41     .32    54.0       0.00      0.00      .32       .04     2901
        42     .27    57.0       0.00      0.00      .27       .02     2666
        43    0.00    57.0       0.00      0.00     0.00      0.00     2545
        44     .48    54.0       0.00      0.00      .48       .11     2726
        45     .46    64.0       0.00      0.00      .46       .10     2853
        46     .21    65.0       0.00      0.00      .21       .00     2648
        47    0.00    63.0       0.00      0.00     0.00      0.00     2323
        48     .07    58.0       0.00      0.00      .07      0.00     2038
        49     .01    52.0       0.00      0.00      .01      0.00     1787
May 10, 50     .06    47.0       0.00      0.00      .06       .00     1567
        51     .04    49.0       0.00      0.00      .04      0.00     1486
        52    0.00    47.0       0.00      0.00     0.00      0.00     1409
        53    0.00    50.0       0.00      0.00     0.00      0.00     1336
        54    0.00    60.0       0.00      0.00     0.00      0.00     1267
        55     .04    68.0       0.00      0.00      .04      0.00     1751
        56    1.33    73.0       0.00      0.00     1.33       .57     3297
        57     .15    55.0       0.00      0.00      .15       .00     3715
        58    0.00    51.0       0.00      0.00     0.00      0.00     3258
        59    0.00    55.0       0.00      0.00     0.00      0.00     2842
May 20, 60    0.00    56.0       0.00      0.00     0.00      0.00     2464
        61     .02    49.0       0.00      0.00      .02      0.00     2145
        62     .16    50.0       0.00      0.00      .16      0.00     1876
        63     .01    51.0       0.00      0.00      .01      0.00     1637
        64     .02    57.0       0.00      0.00      .02      0.00     1552
        65     .07    62.0       0.00      0.00      .07      0.00     1472
        66     .02    60.0       0.00      0.00      .02      0.00     1396
        67    0.00    70.0       0.00      0.00     0.00      0.00     1324
        68    0.00    82.0       0.00      0.00     0.00      0.00     1255
        69    0.00    80.0       0.00      0.00     0.00      0.00     1191
May 30, 70    0.00    68.0       0.00      0.00     0.00      0.00     1191

       SUM    6.76      48       7.84      2.91     6.45      1.75   230598

                         PEAK    10-DAY    30-DAY    90-DAY
               CFS      13894     11161      6241      3294
            INCHES                 2.22      3.73      4.59
             AC-FT               221497    371566    457618
```

Fig. 12 Typical Output from HEC-1, Chippewa River Watershed

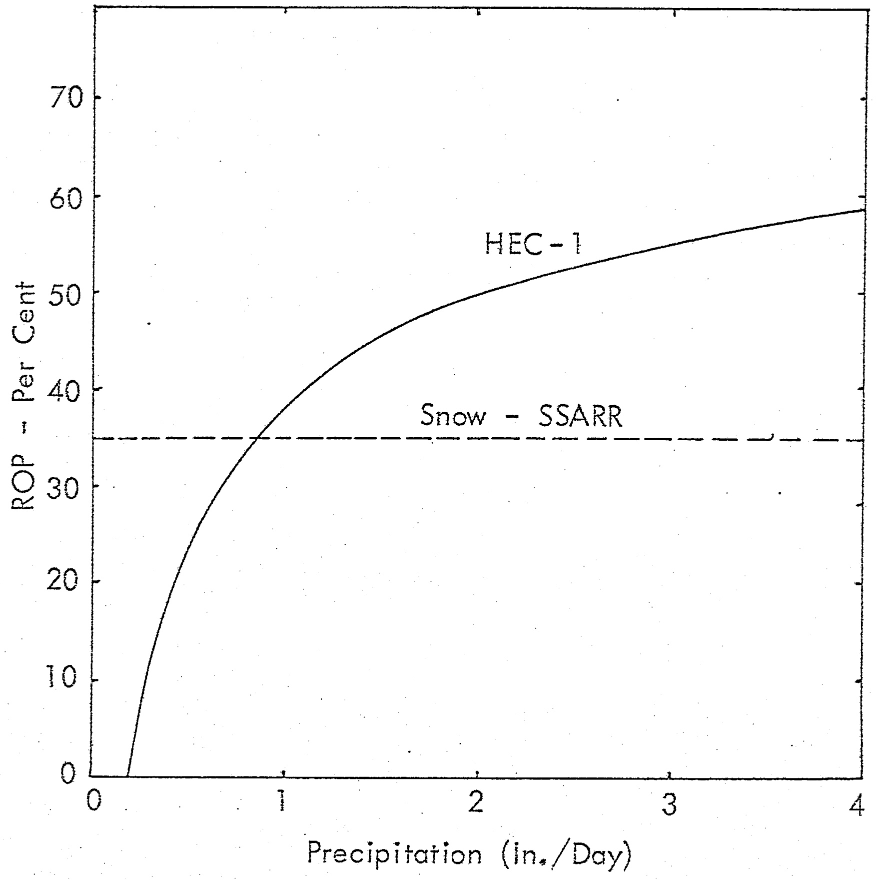

Fig. 13 - Special case of HEC-1 Loss Rate expressed as percentage of Runoff

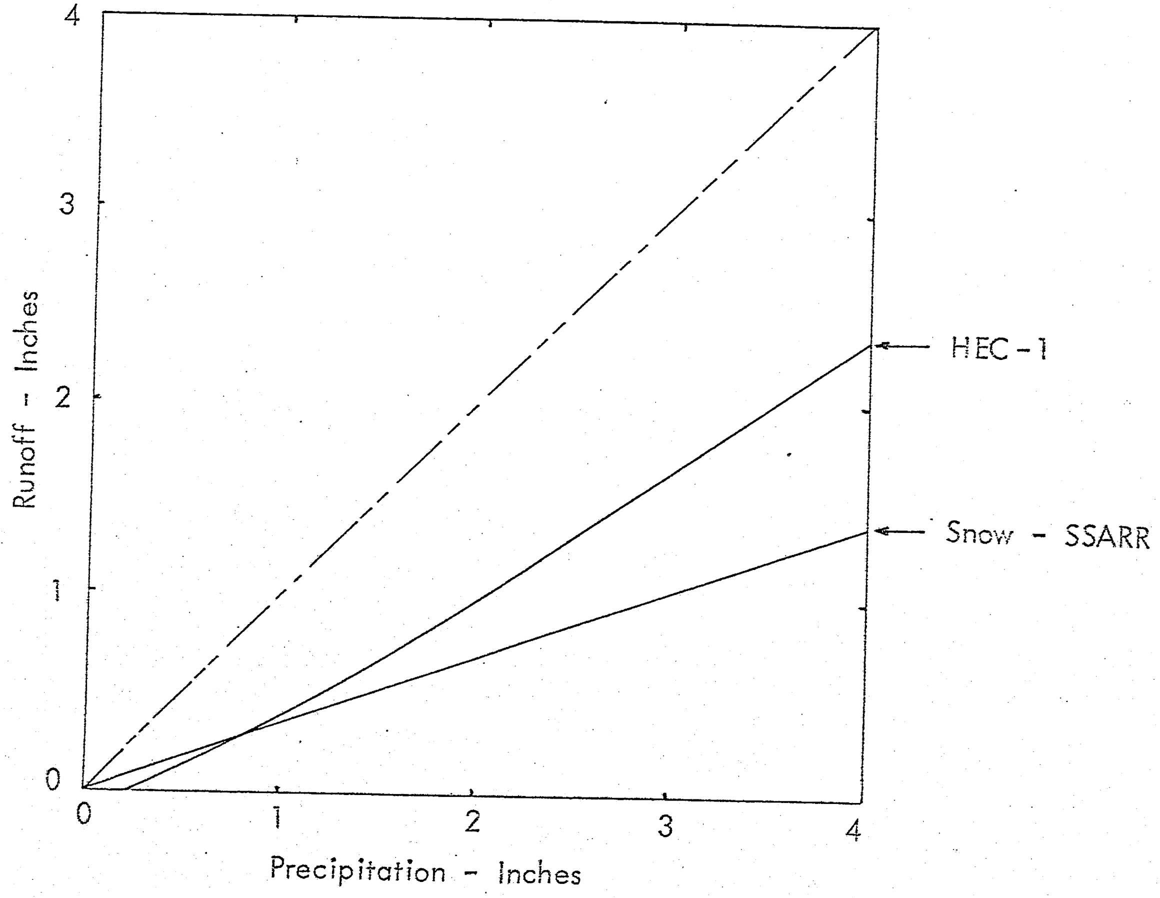

Fig. 14 - Special case of HEC-1 and constant SSARR runoff coefficients compared with SCS Rainfall-Runoff curves

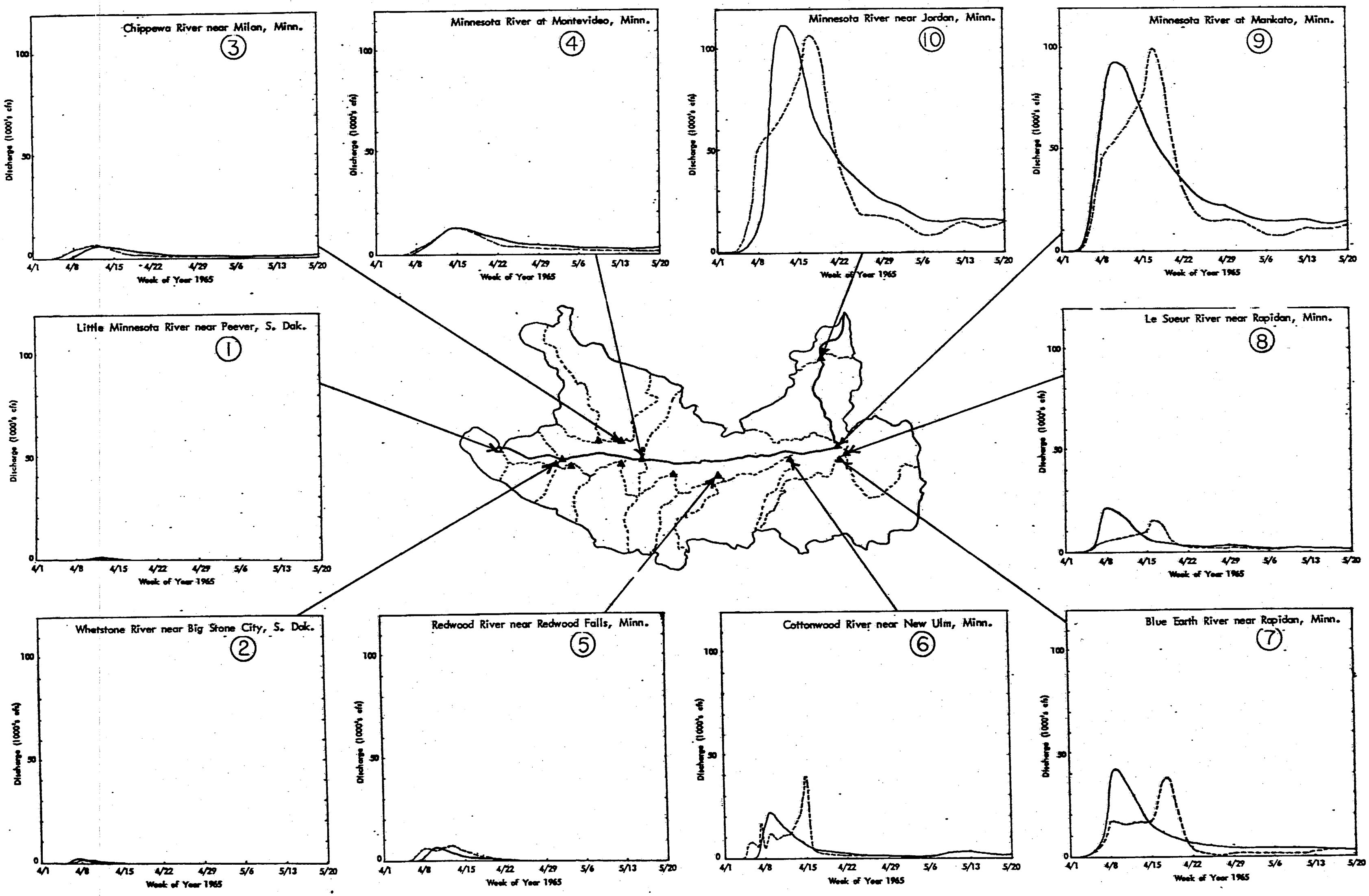

Fig. 15 Observed (solid) and computed (dotted) discharge

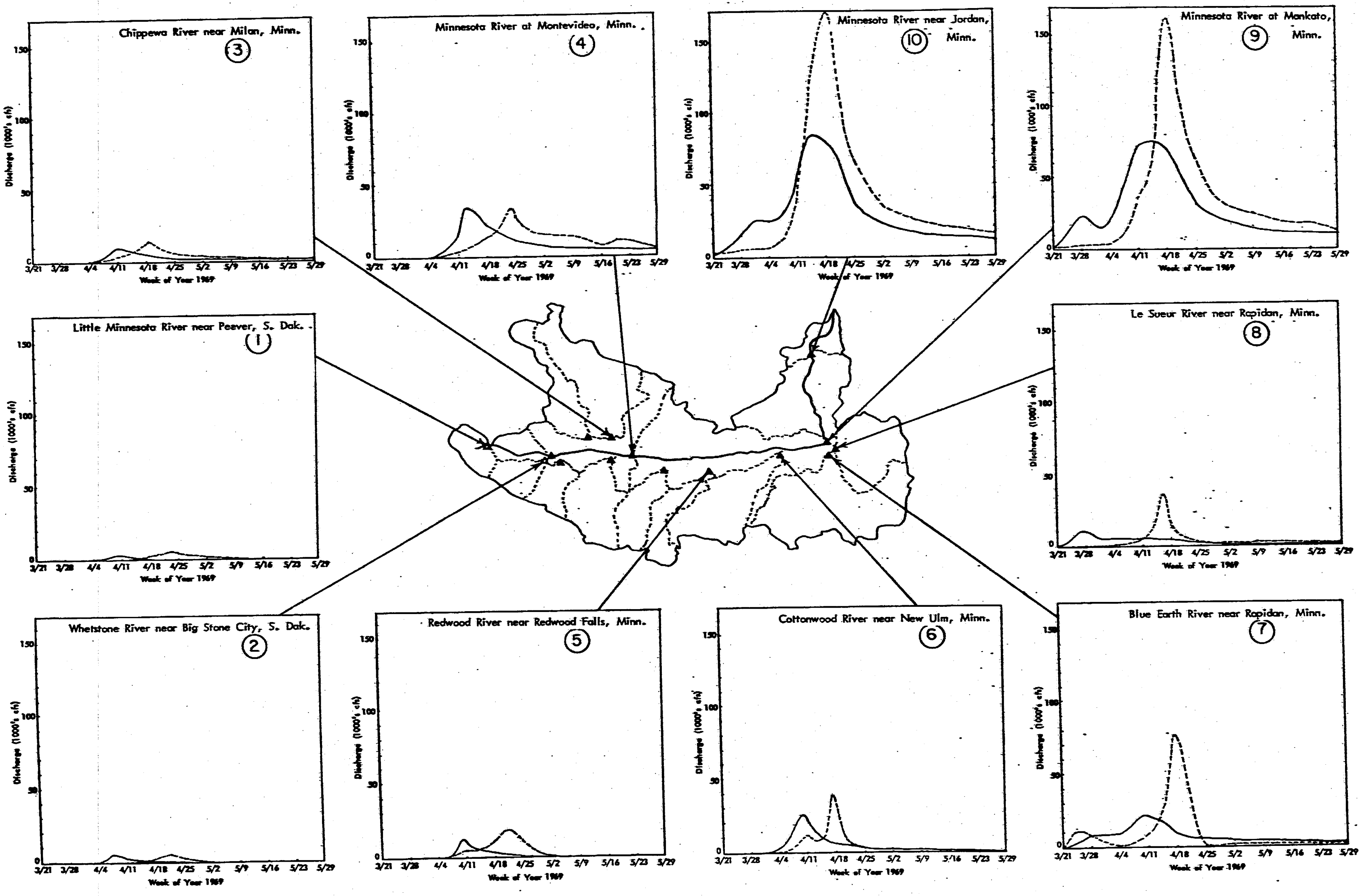

Fig. 16 Observed (solid) and computed (dotted) discharge from SSARR model for 1969.

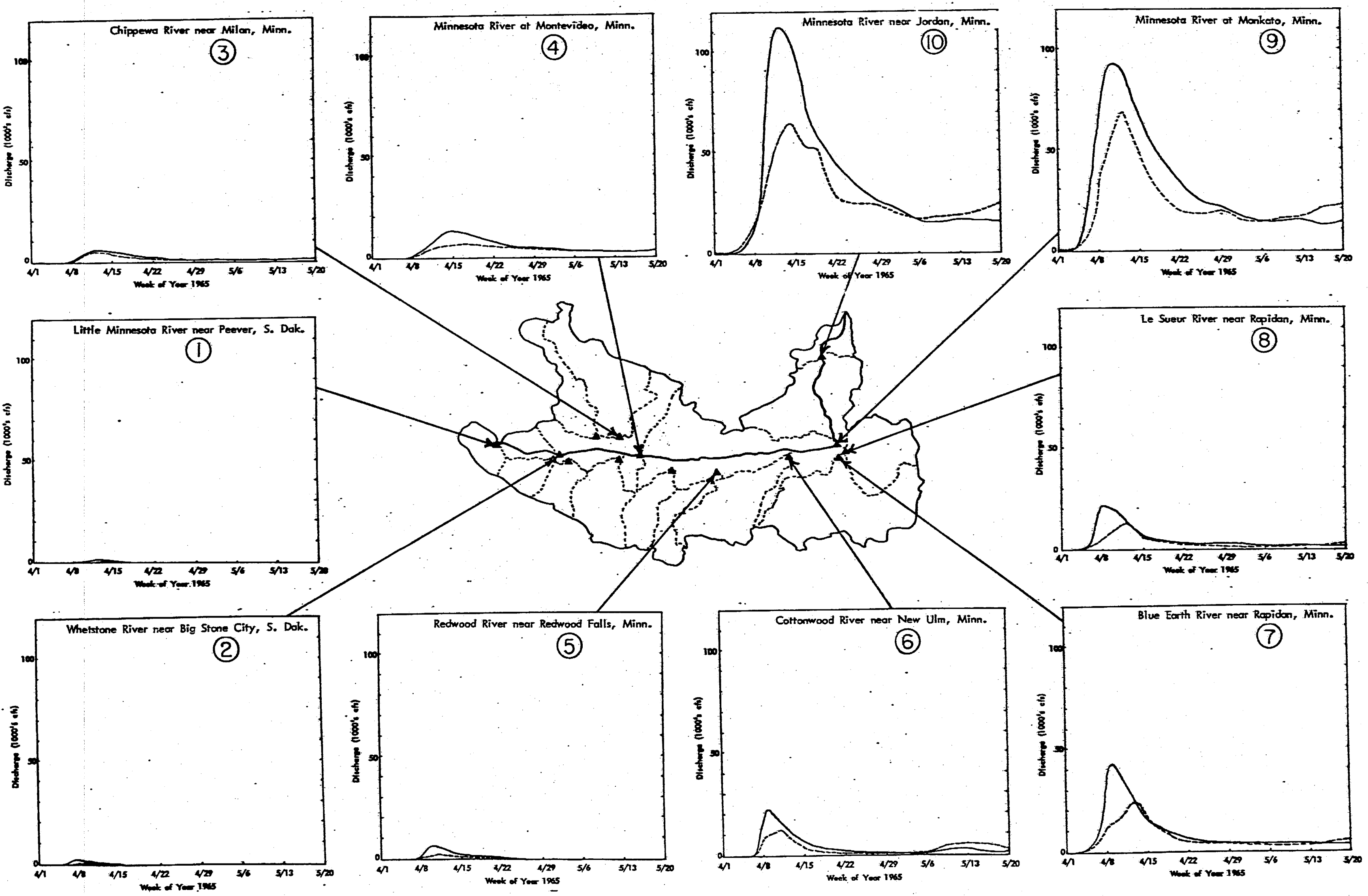

Fig. 17 Observed (solid) and computed (dotted) discharge from HEC-1 model for 1965.

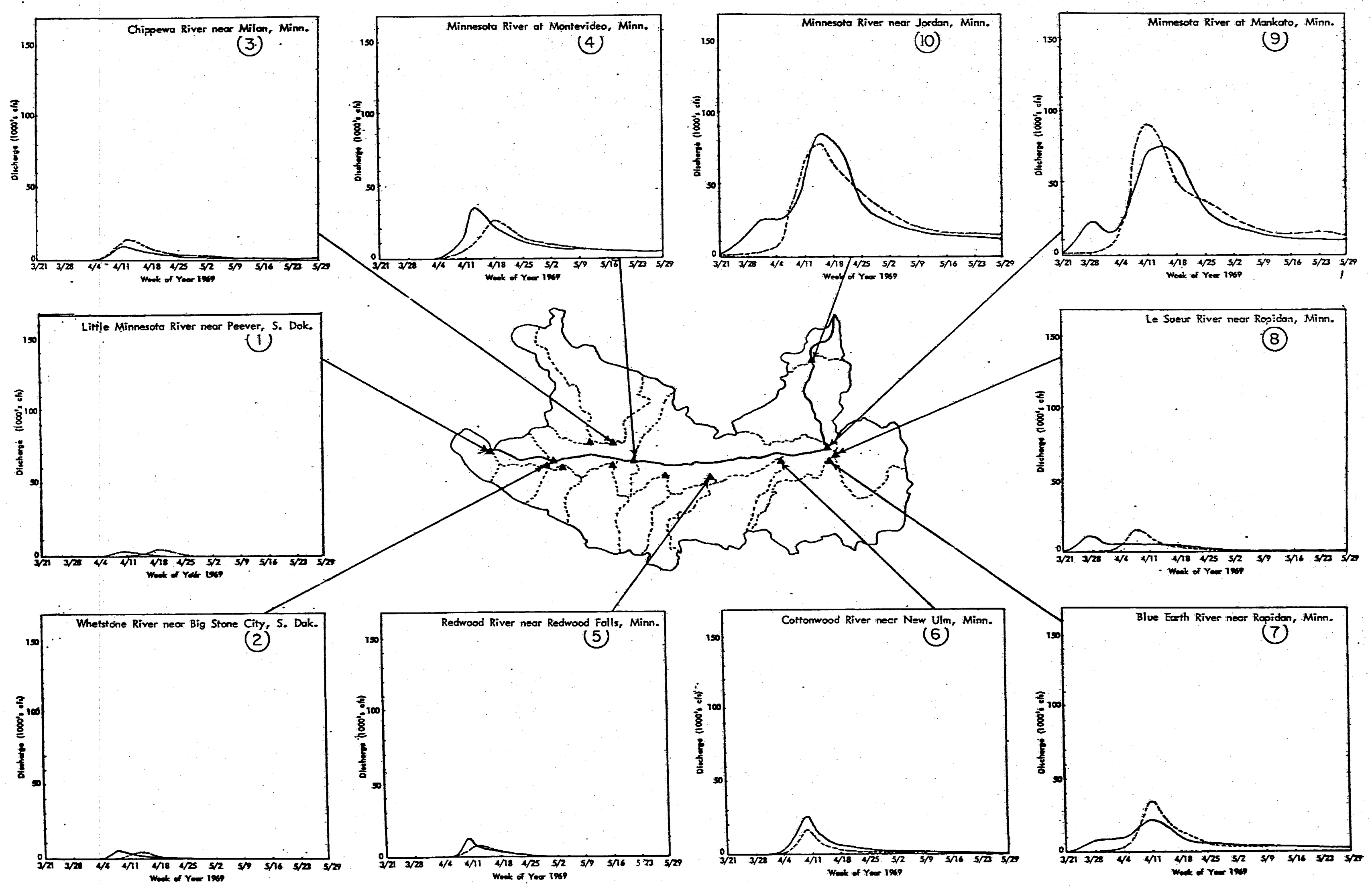

Fig. 18 Observed (solid) and computed (dotted) discharge from HEC-1 model for 1969.