CONCEPTUAL STREAMFLOW FORECASTING MODEL APPLIED TO NORTHERN NEW ENGLAND RIVERS

by

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INTRODUCTION

The techniques used by the National Weather Service (NWS) for making river and flood forecasts are in the process of being changed (Sittner, 1973). Conceptual watershed models are replacing previously used empirical procedures. In 1972 the Hydrologic Research Laboratory of the Office of Hydrology, NWS, prepared the National Weather Service River Forecast System (NWSRFS) to assist the River Forecast Centers (RFC) in the implementation of conceptual river forecasting models. The NWSRFS contains the computer programs that are needed for developing operational river forecasts based on the use of a continuously operating conceptual watershed model. A description of the computer programs contained in the original NWSRFS, as well as recommendations as to the proper use of the programs, are contained in NOAA Technical Memorandum NWS HYDRO-14. Most of the computer programs in the NWSRFS are programmed in such a way that they can be easily modified to permit changes and additions as improved techniques are developed. The initial publication describing the NWSRFS did not include techniques to model snow accumulation and snowmelt. Recently, a conceptual model of the snow accumulation and ablation process and the associated computer subroutines and programs have been added to the NWSRFS. NOAA Technical Memorandum NWS HYDRO-17 (Anderson, 1974) describes in detail the snow accumulation and ablation model and the associated computer programs, plus recommendations for determining model parameters for a given watershed.

The watershed model which is the central part of the NWSRFS consists of three main components: 1) a model of the snow cover, 2) a model of the transmission and retention of water through and over the soil (soil-moisture accounting), and 3) a model of the channel system. The current version of the NWSRFS uses Lag and K channel routing, including variable Lag and/or K where necessary (Linsley et al., 1958). It is planned that procedures for numerical channel routing by the implicit method will be added in the near future. These subroutines will allow the model to be used on basins where variable backwater conditions, extremely mild channel bottom slopes, or upstream movement of tidal waves are present. The current soil-moisture accounting model is a modified version of the Stanford Watershed Model IV (Crawford and Linsley, 1966). This soil-moisture accounting model has given reasonably good results throughout the United States, except for areas where frozen ground and other temperature related soils phenomena have a significant effect on runoff. Studies to incorporate temperature effects, as well as studies to improve other aspects of the soil-moisture accounting model, are planned. Since this paper deals with the application of the NWSRFS to watersheds where spring runoff, primarily from snowmelt, predominates and since this is a snow conference, the current NWSRFS snow cover model will be described in more detail.

SNOW ACCUMULATION AND ABLATION MODEL

Figure 1 shows a flowchart of the snow accumulation and ablation model. The flowchart shows each of the physical components which are represented in the model.

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The snow cover model uses air temperature as the only index to heat exchange across the air-snow interface. There are two basic reasons for using only air temperature data to estimate heat exchange: 1) air temperature data are readily available for model calibration and on a real time operational basis throughout the United States, and 2) comparison tests conducted by the Hydrologic Research Laboratory have shown that on two experimental watersheds the temperature index method of estimating heat exchange produced simulation results which are as good as those produced by a combination energy balance - aerodynamic method (Anderson, 1968). The Hydrologic Research Laboratory is continuing to work on an improved energy balance technique to estimate heat exchange since it is obvious that temperature is not a perfect index to snowmelt. However, the current energy balance techniques, especially when they are used with the low quality radiation data which are generally available, are not able to consistently produce estimates of snowpack heat exchange which are more accurate than those produced using temperature as the sole index to heat exchange. Thus, in addition to improved energy balance techniques, there is probably even a greater need for improved radiation measurements for operational use.

In addition to mean areal air temperature, the current NWSRFS needs mean areal precipitation data and daily evapotranspiration estimates to operate. Mean daily discharge data are required for model calibration. The basic computational interval of the NWSRFS is six hours.

Accumulation of the snowpack. The first decision which must be made is whether precipitation entering the model is in the form of rain or snow. As indicated in Fig. 1, air temperature is used as the index to the form of precipitation. The six-hour air temperature data used in the model are generally computed from max-min air temperature, and are not a perfect indicator of the form of precipitation. It is usually necessary to adjust some of the temperature data so that the form of the precipitation is correct, at least for all major storms. Errors in the form of precipitation could affect the values of certain model parameters. Three types of data which are helpful in determining whether the original estimate of the form of precipitation is in error are:

1. Continuous or frequent measurements of temperature. The most common reason for the form of precipitation being incorrect is that the maximum and minimum temperature did not occur at the assumed times.

2. Snowfall and snow-on-the-ground records.

3. The response of the hydrograph.

Operationally visual observations plus a variety of meteorological information should be available to aid in determining the form of precipitation.

In order to simulate the accumulation of the snowpack correctly, not only does the form of precipitation need to be determined, but the water-equivalent of the snowfall must be reasonably accurate. The model corrects for the deficiency in the catch of the precipitation gages during snowfall by applying a multiplication factor (SCF) to the precipitation values. In the model SCF is a mean gage catch deficiency correction factor. For an individual storm the correction may be too large or too small. However, as the number of storms contributing to the snowpack becomes large, the errors from individual storms will tend to cancel each other.

Heat exchange at the air-snow interface. The heat exchange at the air-snow interface is the most critical factor controlling the ablation of a snowpack. Table 1 summarizes the methods which are used in the model to estimate heat exchange.

TABLE 1

SNOW-AIR INTERFACE HEAT EXCHANGE SUMMARY

A. AIR TEMPERATURE > 32°F

1. No rain or light rain (< 0.1"/ 6 hr)

Heat Exchange = $(T_a - \text{MBASE}) \cdot$ Melt factor

2. Rain (≥0.1"/ 6 hr)

assume : no solar radiation
longwave equals blackbody radiation at air temperature
dew-point = air temperature
temp. of rain = air temperature

$$\text{Heat exchange} = 0.007 \cdot (T_a - 32) + 7.5 \cdot \gamma \cdot f(\mu) \cdot (T_a - 32) + 8.5 \cdot f(\mu) \cdot (e_a - 0.18) + 0.007 \cdot \text{Rain} \cdot (T_a - 32)$$

γ = psychrometric constant, e_a = vapor pressure
$f(\mu)$ = wind function

B. AIR TEMPERATURE ≤ 32 °F

Heat Exchange = $(T_{a_2} - ATI_1) \cdot$ Negative melt factor

ATI is antecedent temperature index

$ATI_2 = ATI_1 + TIPM \cdot (T_{a_2} - ATI_1)$

The model assumes melt can occur at the snow surface when the air temperature is above 32°F. During non-rain periods melt at the snow surface is assumed to be linearly related to the difference between the air temperature (T_a) and a base temperature, MBASE. The most commonly used base temperature is 32°F. Because the normal relationship between the meteorological variables which cause melt and the quantity (T_a-MBASE) changes throughout the year, the model uses a seasonally varying melt factor. The minimum melt factor is assumed to occur on December 21 and the maximum melt factor on June 21. A sine curve is used to extrapolate melt factors for other dates. During rain on snow periods, melt is computed using the combination method equation (combination of energy balance and aerodynamic equations). By making the assumptions listed in Table 1, the combination method equation can be solved for the amount of melt. The only parameter involved in the computations is the average wind function during rain on snow periods.

When the air temperature is below 32°F, the model assumes melt does not occur. In this situation, the snowpack can either gain heat or lose heat. The direction of heat flow depends on whether the air is warmer or colder than the surface layer of the snowpack. An antecedent temperature index (ATI) is used as an index of the temperature of the surface layer of the snowpack. The heat exchange during a non-melt period is assumed proportional to the temperature gradient defined by air temperature and the antecedent temperature index.

<u>Areal extent of snow cover.</u> The percent of the area which is covered by snow must be estimated to determine the area over which heat exchange is taking place and in the case of rain on snow to determine how much rain falls on bare ground. The areal depletion of snow is primarily a function of how much of the original water-equivalent of the snowpack remains. Because of a similarity in accumulation patterns and melt patterns from year to year, each area should have a reasonably unique areal depletion curve. An areal depletion curve, as used in the model, is a plot of the areal extent of snow cover versus the ratio of mean areal water-equivalent to an index value, A_i. A_i is the smaller of: 1) the maximum water-equivalent since snow began to accumulate, or 2) a preset maximum. Figure 2 shows the areal depletion curves for the Passumpsic, Ammonoosuc, and White River basins in New England.

<u>Snowpack heat storage.</u> The model keeps a continuous accounting of the heat storage of the snowpack. When the snowpack is isothermal at 32°F, the snowpack heat storage is assumed to be zero. When heat is transferred from the snow to the air a heat deficit is produced. Enough heat must be added later to bring this heat deficit back to zero before surface melt water or rain water can contribute to liquid-water storage or snowpack outflow.

<u>Liquid-water retention and transmission.</u> In the model, liquid-water retention and transmission characteristics are assumed to be the same for all snowpack conditions. In reality, retention and transmission for fresh snow or for a snowpack with thick ice lenses are undoubtedly different than that for a "ripe" snowpack. The equations used in the model only apply to a "ripe" snowpack.

<u>Heat exchange at the soil-snow interface.</u> The model assumes that a constant amount of melt takes place at the soil-snow interface.

RESULTS

The NWSRFS has been applied to basins throughout the United States representing a wide range of geographic conditions. The NWSRFS with the snow cover model included has been tested on watersheds in California, Montana, Arizona, Alaska, and Minnesota, as well as on watersheds in New England. Since this is the Eastern Snow Conference, this paper presents the results of applying the NWSRFS to three northern New England watersheds. These watersheds are: 1) the Passumpsic River at Passumpsic, Vermont, 2) the Ammonoosuc River near Bath, New Hampshire, and 3) the White River at West Hartford, Vermont. Table 2 gives some background information for each watershed. The period of record used for the tests is from October 1963 through September 1971. Although these watersheds are reasonably large in size, the response time of each is quite fast. The unit hydrograph for each watershed peaks in about 12 to 18 hours.

Table 2 - Background Information
for the Test Watersheds

	Watersheds		
	Passumpsic	Ammonoosuc	White
Area - square miles	436	395	690
Mean Elevation - feet	1445	1728	1471
Elevation range - feet	490'-3400'	454'-6288'	375'-3550'
Number of stations and elevation range to compute: 1. Mean Precipitation	4 stations 699'-1140'	7 stations 480'-4000'	12 stations 463'-1000'
2. Mean Temperature	3 stations 699'-1140'	6 stations 480'-6262'	6 stations 562'-1126'
Mean annual value for the test period: 1. Discharge - inches 2. Precipitation - inches 3. Snowfall - inches water-equivalent	 20.3 40.4 12.8	 19.7 43.0 14.0	 19.2 40.4 12.9

The recommended calibration procedure for the NWSRFS involves the use of trial-and-error and automatic optimization. Trial-and-error calibration consists of making subjective manual adjustments to model parameters based on specific characteristics of previous simulation results. In automatic parameter optimization, the computer adjusts parameters in a semi-random manner based on changes in the value of a single numerical evaluation criterion. The evaluation criterion used in the NWSRFS for automatic parameter optimization is the root-mean-square (RMS) error computed from mean daily observed and simulated discharges. The reason for using a combination of two calibration methods is so that the advantages of each method will minimize the disadvantages of the other. The resulting calibration procedure can be used to calibrate a large number of watersheds in a reasonable length of time.

Experience has shown that no single numerical value can be used to completely judge model performance. This is one of the disadvantages of automatic optimization. In order to get a true picture of model accuracy, as much information as possible should be examined. Table 3 shows several statistics which partly summarize model performance on the Passumpsic, Ammonoosuc, and White River basins.

Table 3 - Statistical Summary of Model Performance

Statistic [2]	Passumpsic	Ammonoosuc	White
Percent Bias	0.8%	1.3%	-0.3%
RMS Error	316. CFSD	352. CFSD	456. CFSD
RMS Error divided by Mean Discharge	0.48	0.61	0.47
Best fit line			
intercept	77. CFSD	49. CFSD	35. CFSD
slope	0.88	0.90	0.97
Correlation Coefficient	0.937	0.901	0.954

The best summary of model performance is a plot of the simulated and observed discharges. Figures 3 through 7 show mean daily flow plots during the spring snowmelt period for the Passumpsic, White, and Ammonoosuc Rivers.

DISCUSSION

Prior to the application to the Passumpsic, Ammonoosuc, and White Rivers, the NWSRFS had been applied to five years of data from the Sleepers River Research Watershed of the Agricultural Research Service. The Sleepers River is a tributary of the Passumpsic River and is located in the southwestern corner of the Passumpsic basin. The Sleepers River results (which were reasonably good) gave some idea of the type of accuracy that could be expected on other watersheds in northern New England. The White and Passumpsic Rivers lived up to expectations. The Ammonoosuc River results did not.

The results for the Passumpsic River, however, were not quite as good as those for the White River. This is to be expected since the number of precipitation stations is greater and the spatial distribution is better for the White River than for the Passumpsic River.

As far as the Ammonoosuc basin is concerned, there are no biases which would indicate that the model itself is a major factor causing the results to be less accurate than those for the Passumpsic and White River basins. An examination of the simulation results indicates that an increased variability between simulated and observed runoff volumes from individual rain periods is the major reason for the lesser accuracy of the Ammonoosuc River results. There is only a slight increase in the variability during snowmelt periods and only a slight increase in the variability between simulated and observed total spring runoff (note the top portions of Figs. 10 and 11).

In order to obtain some insight into why runoff from rain was more variable in the Ammonoosuc basin, simulation runs were made with two different gage configurations.

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[2] All statistics are based on mean daily discharges.

These were: 1) a network using all available stations, and 2) a network using only low elevation stations (two high elevation stations were removed). Adjustments were made to insure that the precipitation total and mean temperature for the eight-year period for each network were the same. Table 4 shows the effect of each network on the summary error statistics. The percent bias remained about the same for each network.

Table 4 - Effect of the Data Network on Ammonoosuc River Results

Precipitation Network	Temperature Network	RMS error CFSD	Best fit line intercept CFSD	Best fit line slope	Correlation coefficient
All stations	All stations	352.	49.	.90	.901
All stations	Low elevation stations	350.	49.	.90	.903
Low elevation stations	Low elevation stations	501.	142.	.75	.822

Figure 8 shows the simulated hydrograph for each network plus the observed hydrograph for the 1964 spring snowmelt period. Figure 8 also contains the simulated hydrograph for a network consisting of one centrally located station (Bethlehem, N.H.). Table 4 shows that in the Ammonoosuc basin the use of only low elevation stations increases the variability and, in addition, significantly changes the slope of the best fit line. The primary reason is that during several rain events the use of the low elevation stations causes a significant overestimation of the mean basin precipitation amount. In the White and Passumpsic basins, where only low elevation station data were available, such overestimations were far fewer in number and much less in magnitude. In the Ammonoosuc basin, high and low elevations are in two distinct locations. In the White and Passumpsic basins, areas of different elevations are scattered throughout.

Another factor which should be noted is the distribution of runoff with elevation. The streamgage on the Ammonoosuc River at Bethlehem Junction which represents about the upper third of the basin, had an average of 30.4" of runoff for water years 1964 through 1971. Thus, the runoff from the remainder of the basin was only about 15 inches.

The preceding information suggests that basins like the Ammonoosuc which have areas with significant elevation differences located in completely separate parts of the basin should be subdivided for modeling purposes. The Ammonoosuc should probably be divided into two parts: the high elevation, high runoff producing area and the low elevation, low runoff producing area.

In general, the snow cover model gives good results in northern New England. However, during some periods, discussed below, model accuracy was unsatisfactory. For the sake of future research considerations, these periods are documented in some detail.

Snowmelt estimates from air temperature. Air temperature is a good index to snowmelt. However, there are periods when it is obvious that the estimate of snowmelt is in error. Two such periods which had a considerable effect upon simulation results were:

1. April 2-3, 1967. Figure 5 shows that there was a very significant rise in the hydrograph near the beginning of the snowmelt period in early April 1967. This rise was almost entirely caused by snowmelt (about 0.25 inches of rain occurred on the 2nd). On all three watersheds simulated discharge was considerably less than observed. The model estimated melt with reasonable accuracy on the 1st of April. On the 2nd of April, temperatures were similar to those on the 1st; however, it is obvious that the melt rate was greater. Meteorological data show that April 2nd was a mostly sunny, warm day with a dew point in excess of 50°F during the later portion of the day and during the pre-dawn hours of the 3rd. In addition, the rise in dew point occurred simultaneously with an increase in wind speed. The high melt rate ceased with the passage of a cold front on the 3rd of April.

2. April 6-12, 1969. During this period, snowmelt was underestimated on all three watersheds. The effect on the White River can be seen in Figure 6. Underestimation of melt for a period this long not only caused the discharge estimates to be too low during the first part of April, but also resulted in simulated discharges being too high later in April because snow that should have been melted from the 6th to the 12th was not melted until later in the month. This period decreased the overall model accuracy since it affected simulation results during the month which has the highest discharges during the eight-year period. Figure 9 shows the same under-estimation of melt when the snow cover model was applied to a point location - the NOAA-ARS Cooperative Snow Research STation near Danville, Vermont. Meteorological data collected at the research station indicates that, except for the 10th, this was a cool period with very clear skies, thus maximum amounts of solar radiation. Therefore, there was enough energy available to cause more melt than was indicated by the air tempera-ture.

<u>Liquid-water retention and transmission</u>. As mentioned earlier, the equations used in the model to estimate the retention and transmission of liquid water, apply only to a "ripe" snowpack. This can result in simulation errors during events when rain is falling on fresh snow or on a snowpack which contains thick ice lenses. There are two such cases during the eight years:

1. March 17-24, 1968. This period caused simulation problems on all three basins. About one inch of rain fell on the 17th and 18th, followed by about 1.5 inches of rain on the 22nd and 23rd. The intervening period was warm with about 2 inches of snowmelt. The responses of the simulated hydrographs during this period on the Passumpsic and Ammonoosuc Rivers are shown on Figs. 3 and 7. The station diary from the NOAA-ARS snow research station helps explain what actually occurred. Because of a cold fall and winter, plus a shallow snowpack, a 1/2-inch thick ice layer remained at the bottom of the snowpack. The rain on the 17th and 18th was retained in the snowpack by this ice layer. During the next few days, this rain water plus the added melt water slow began to percolate out of the snowpack. The hydrographs did not peak until March 22nd on the White River and not until the 24th on the Passumpsic and Ammonoosuc Rivers.

2. December 26-28, 1970. This storm started as snowfall and then changed to freezing rain. The storm ended as freezing rain in Vermont. However, over the Ammonoosuc basin the precipitation changed to rain at the end. About 1.5 inches of rain fell on top of the ice layer which had formed. Total simulated and observed runoff were nearly equal. However, the maxi-mum simulated flow was 7500 CFSD on the 27th while the maximum observed flow was 4500 CFSD on the 28th.

The NWSRFS can be used for both short term river forecasting and for water supply forecasting. In either case, it may be possible to improve the forecast by periodically correcting the model variables to conform to observed conditions. One variable which could be corrected is areal water-equivalent. The correction would be based on measured values of snowpack water-equivalent. Figures 10 and 11 give some indication as to whether presently available snow course measurements could be used to improve model accuracy. The upper plot in each figure shows spring runoff (March through May) from the continuous simulation plotted against observed spring runoff. The bottom plot shows simulated basin water-equivalent plotted against snow course water-equivalent. The plotted snow course measurements were made in early or mid March prior to the spring runoff period. In order to indicate a possible improvement in the simulation of total runoff, the symbol for a given year should be on the same side of the line in each plot. For example, on Figure 10 simulated runoff for the year 1969 is low. Thus, to improve the estimation of runoff, basin water-equivalent should be increased. On the bottom plot, the Cannon Mountain (base) snow course indicates that basin water-equivalent for 1969 is low and should be increased. The Bethlehem Junction snow course indicates that basin water-equivalent should be decreased. Thus, using the Cannon Mountain (base) snow course, the estimation of total runoff for 1969 would be improved, whereas the Bethlehem Junction snow course would make the estimate worse. Examining the other years on Figure 10 indicates that using the Cannon Mountain (base) snow course to correct the model would improve total runoff estimates for most years. Use of the Bethlehem Junction snow course would make the estimate worse for most years. For the White River (Fig. 11) the difference between simulated and observed total runoff is so slight that further improvement would be difficult. For the White River there is also a good relationship between simulated basin water-equivalent and the snow course data. It should be noted that in New England much of the March-May runoff is generated by precipitation which falls during those months. For example, for the White River March 1st water-equivalent accounts for only 30 to 55 percent of the total March-May input to the soil-moisture accounting procedure during this eight-year period. Thus, diagrams like Figs. 10 and 11 may not reveal the value of water-equivalent measurements, since an improvement in the estimate of basin water-equivalent could be offset by a later error in estimating storm precipitation.

SUMMARY

The National Weather Service River Forecast System gives good simulation results when applied to northern New England watersheds. The reproduction of the mean daily flow hydrograph is quite reasonable and the simulation of total spring runoff is very good. Simulation accuracy is unsatisfactory during a few periods when air temperature is not a good index to snowmelt and when thick ice lenses have an excessive influence on the transmission of liquid-water through the snowpack.

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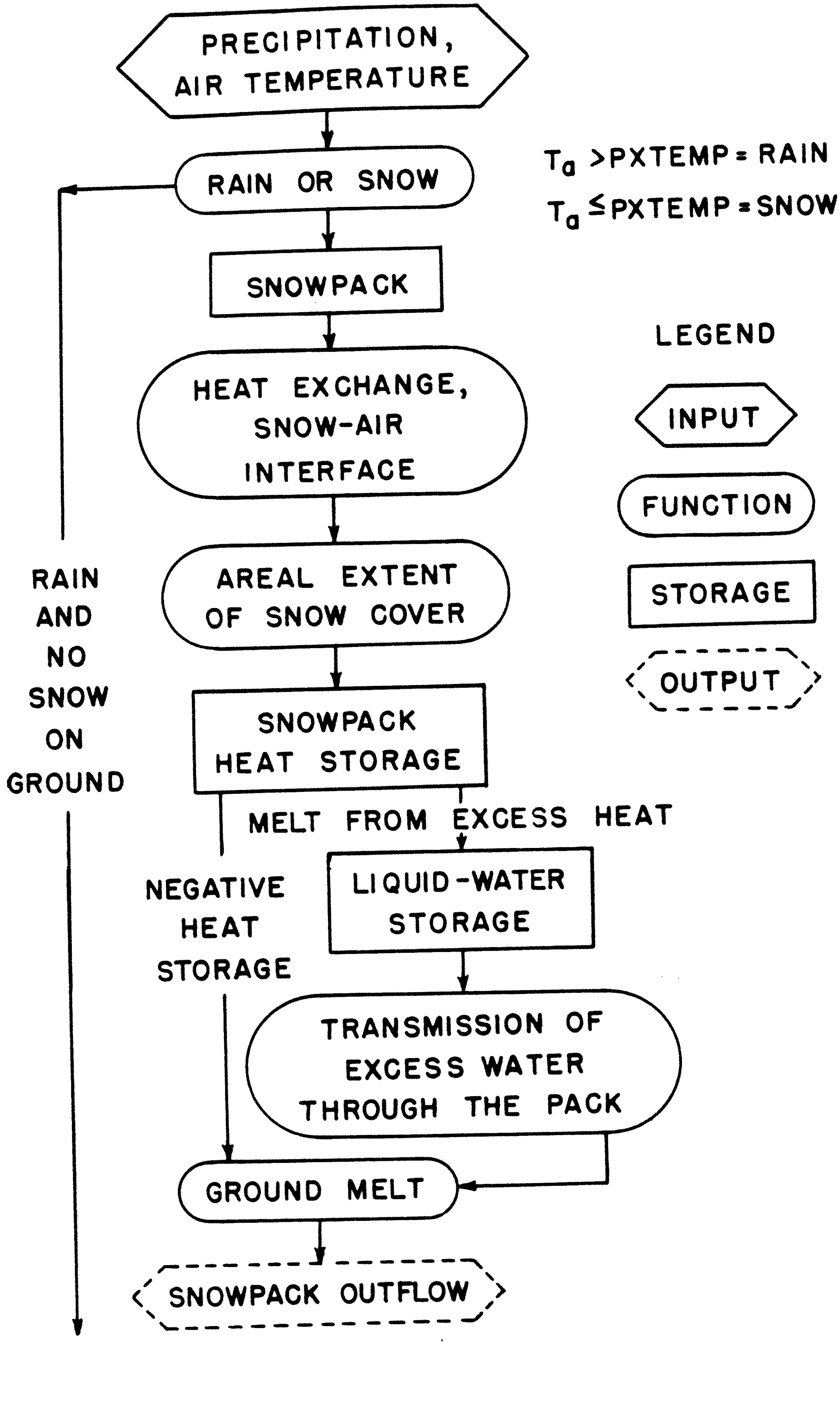


Figure 1. - Flow chart of snow accumulation and ablation model.

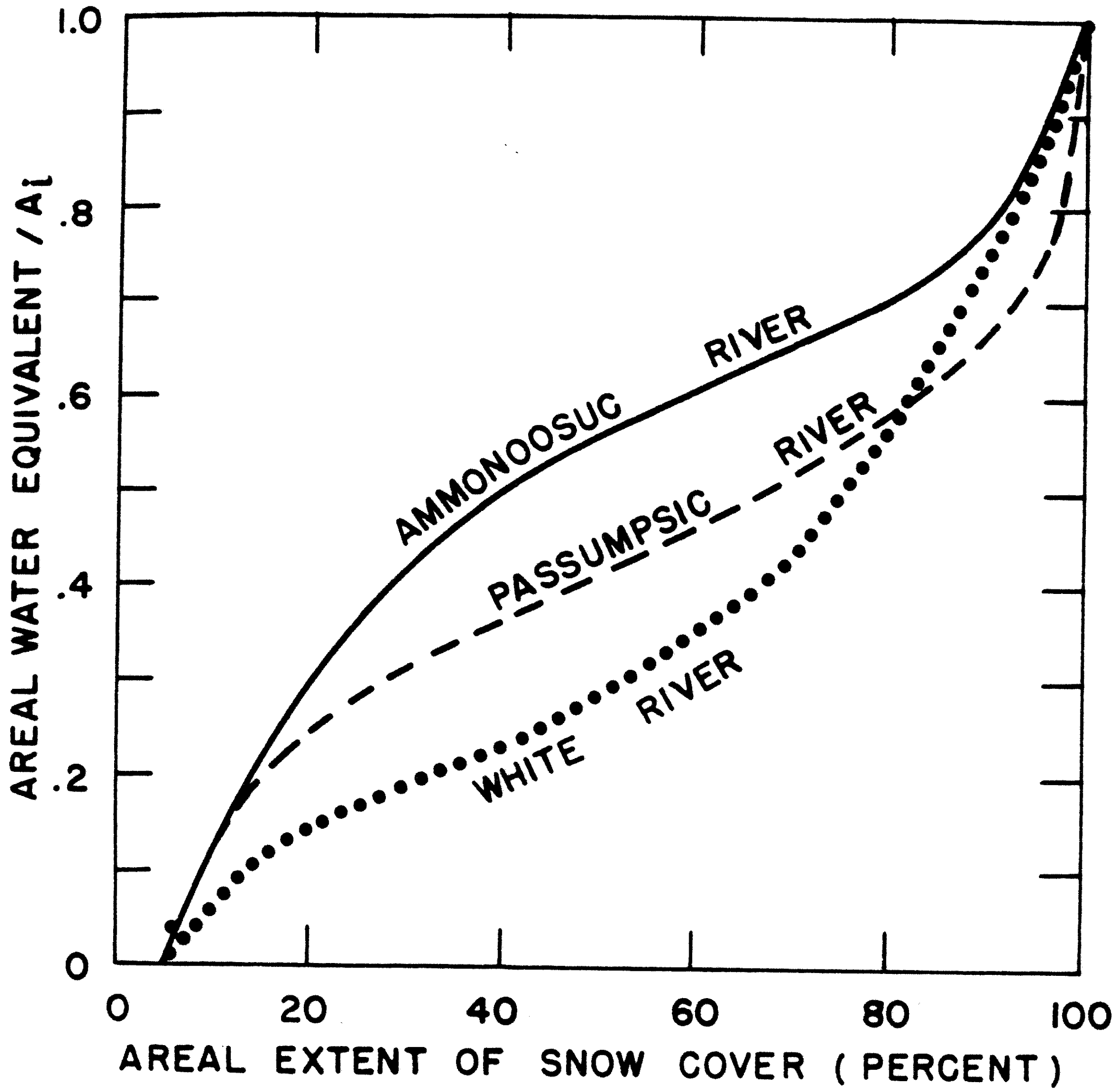


Figure 2 – Snow cover areal depletion curves.

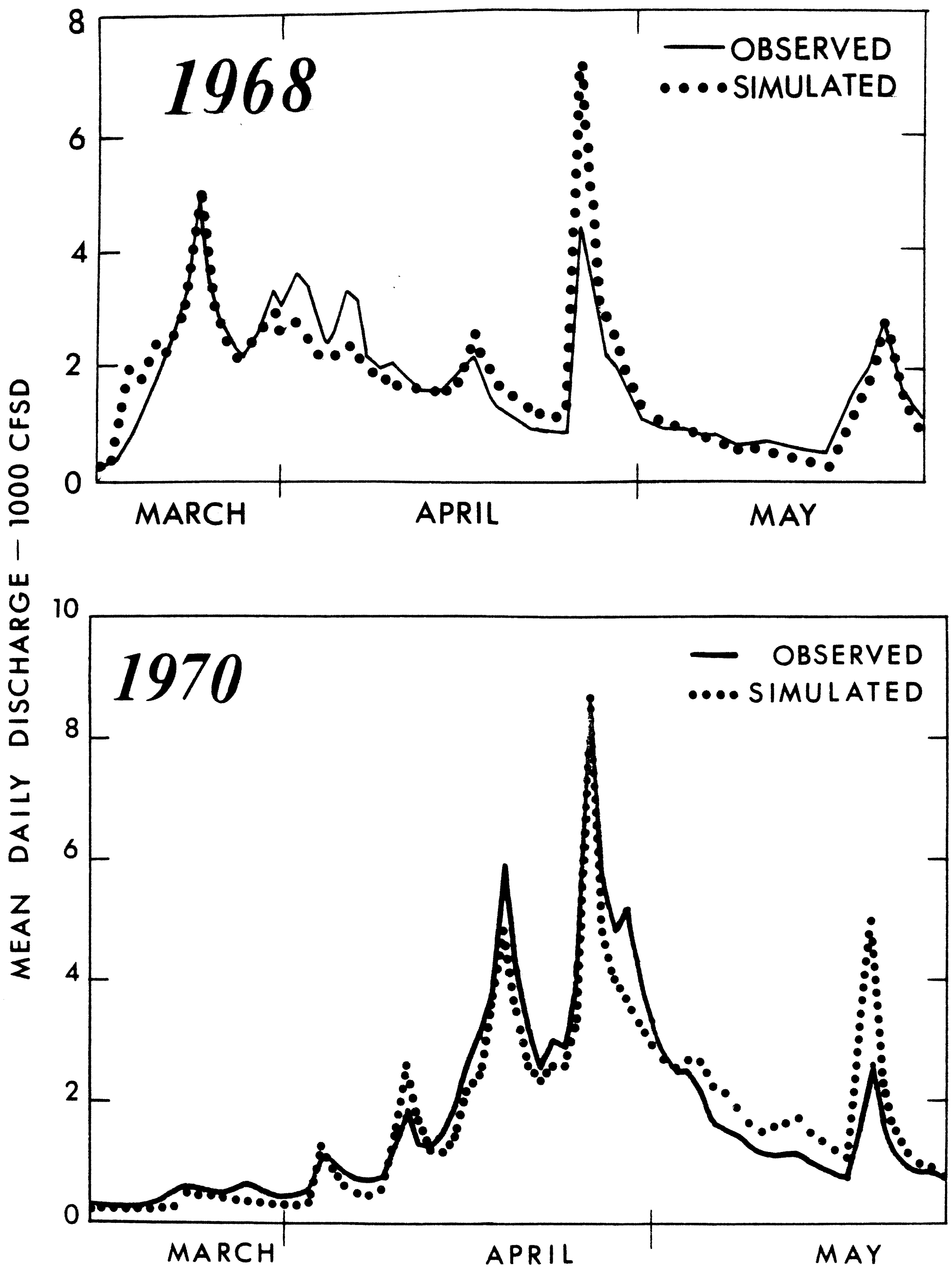


FIGURE 3 — PASSUMPSIC RIVER HYDROGRAPHS

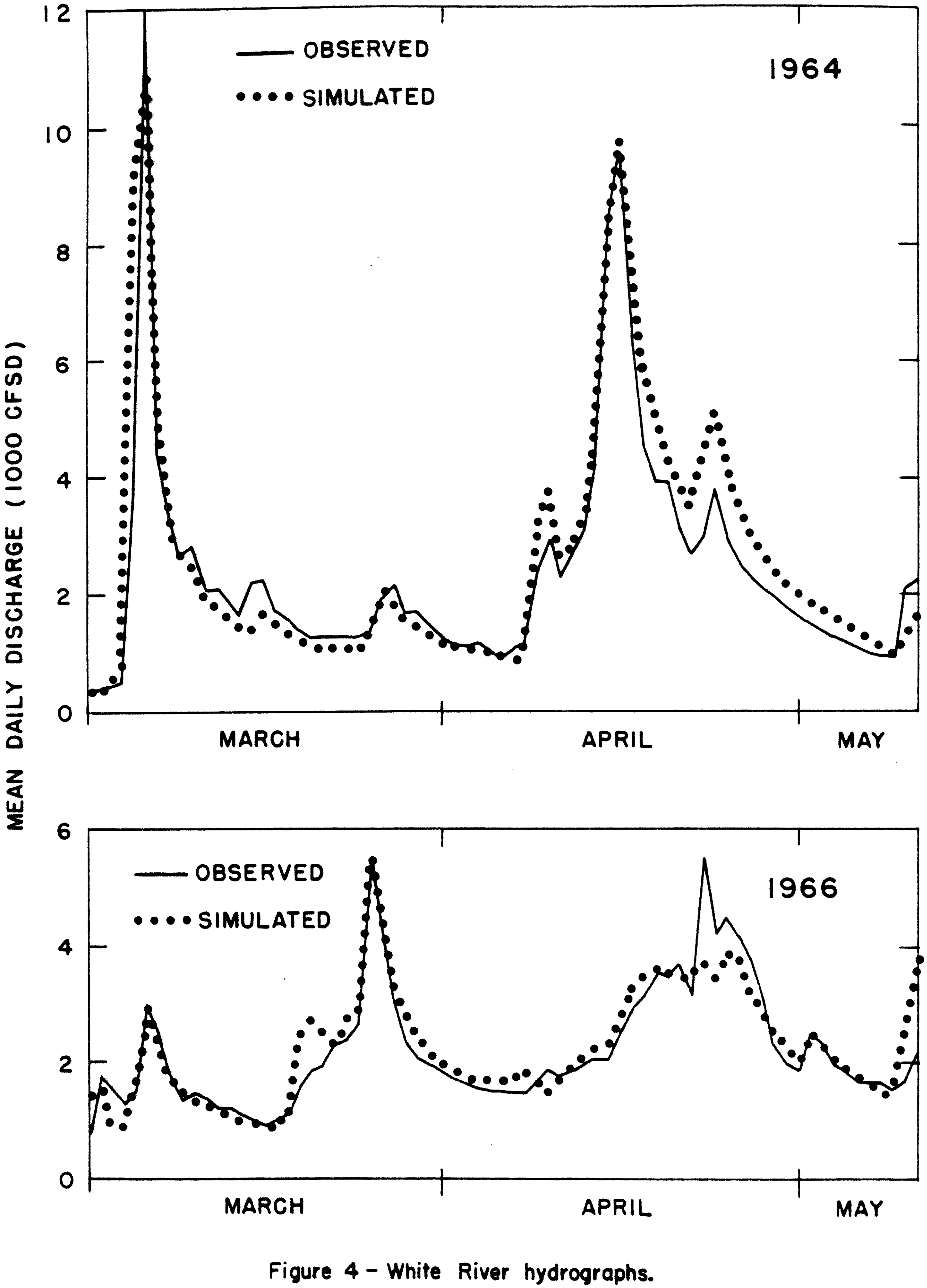


Figure 4 - White River hydrographs.

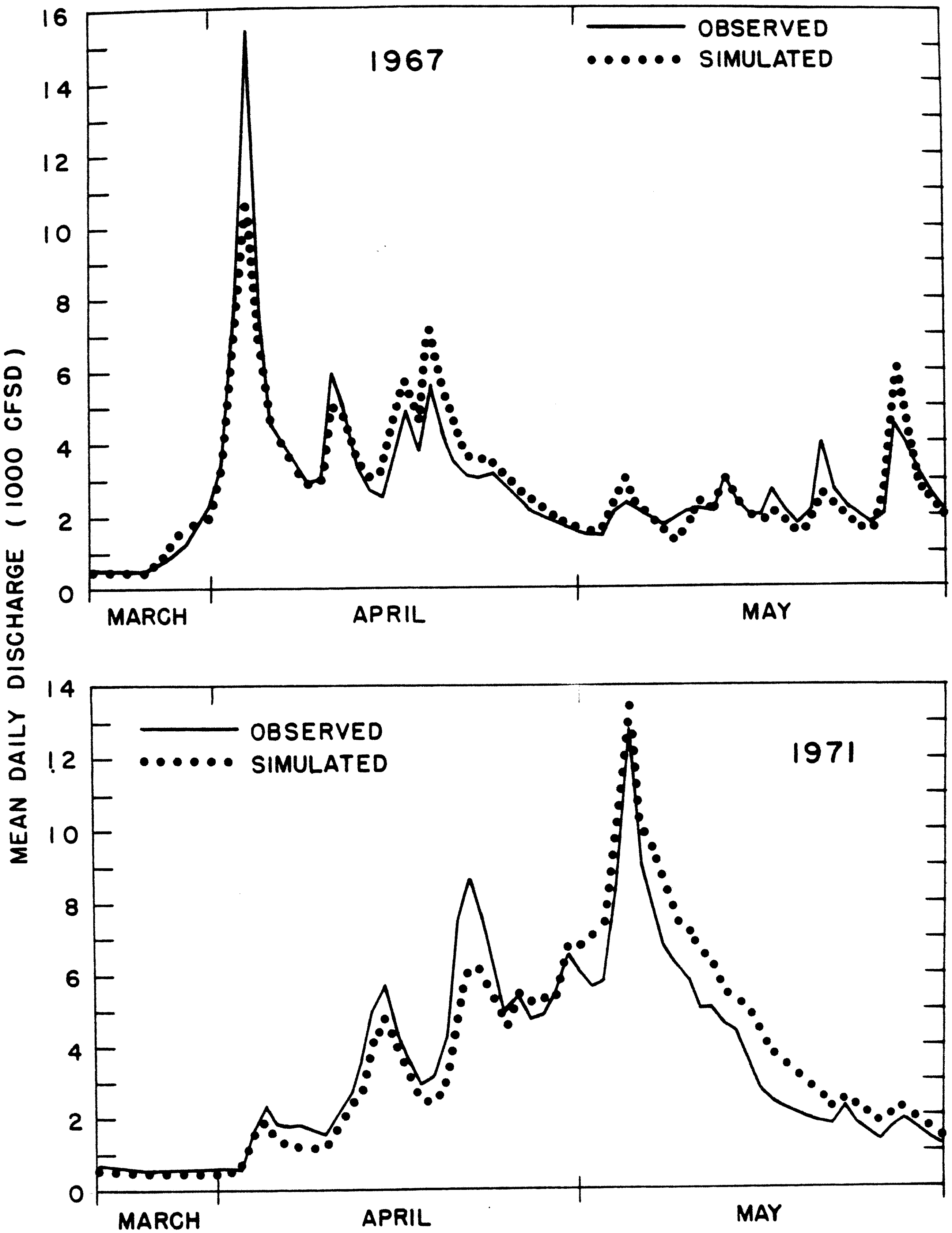


Figure 5 - White River hydrographs

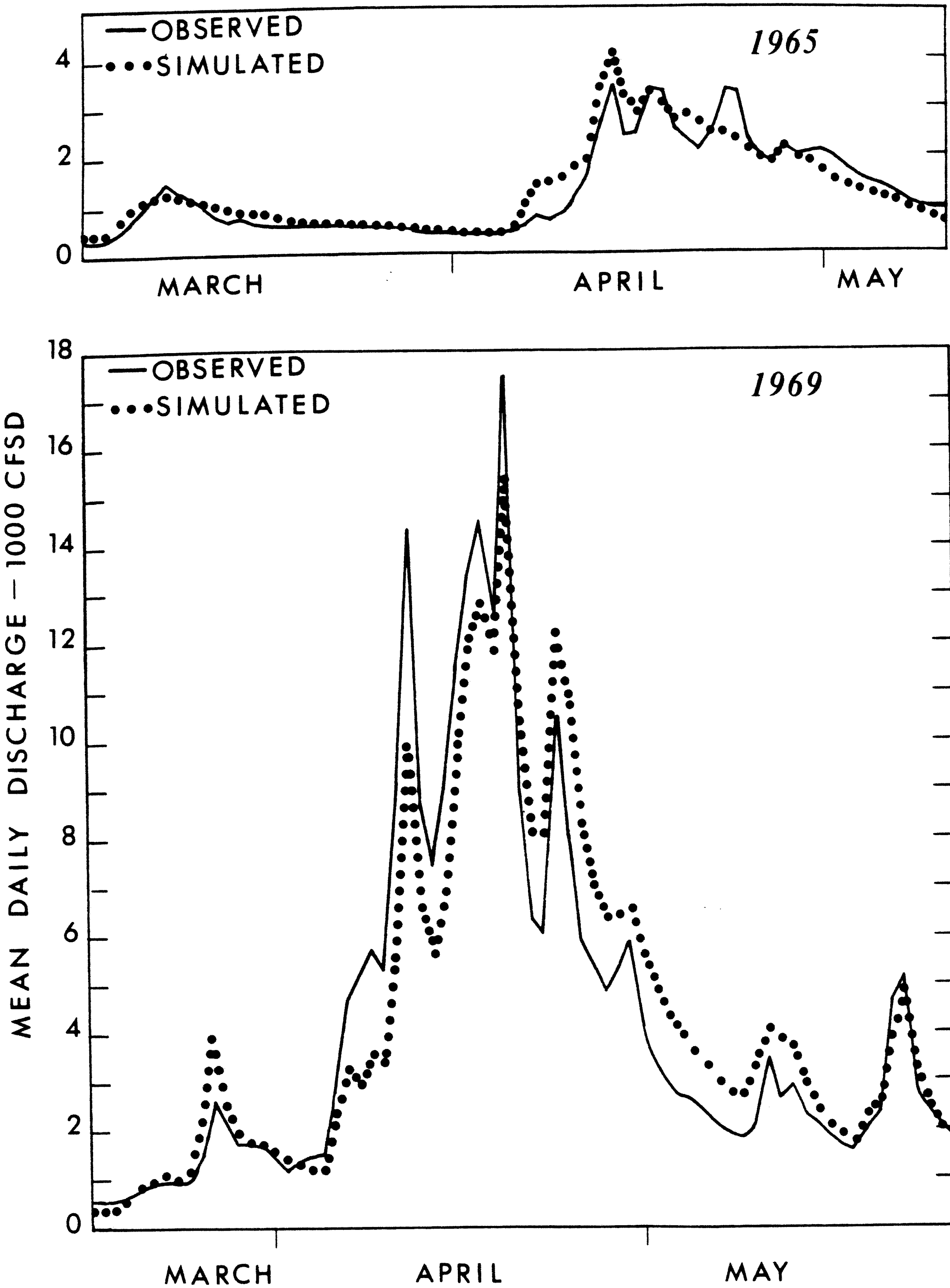


FIGURE 6 — WHITE RIVER HYDROGRAPHS.

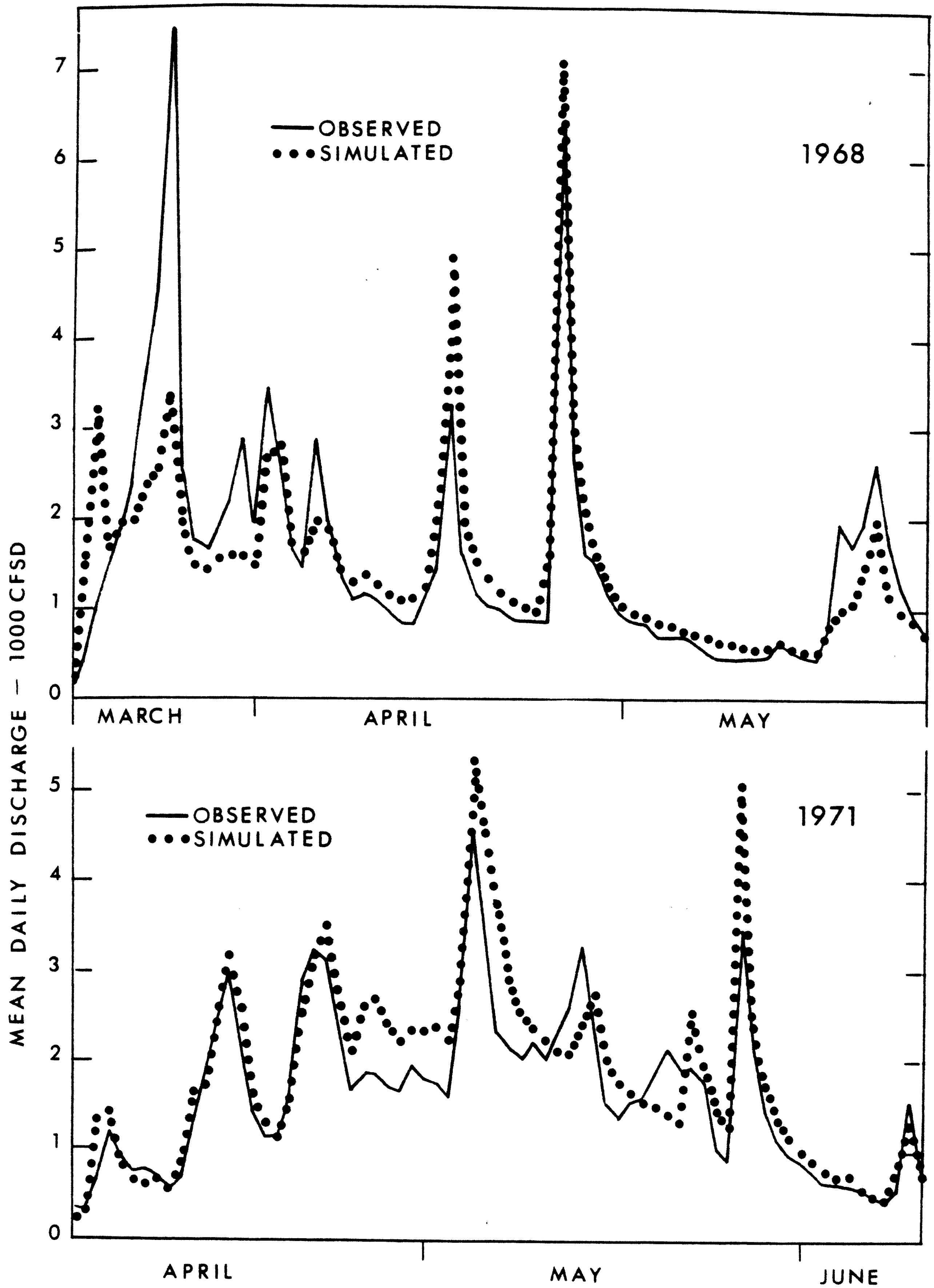


FIGURE 7 — AMMONOOSUC RIVER HYDROGRAPHS.

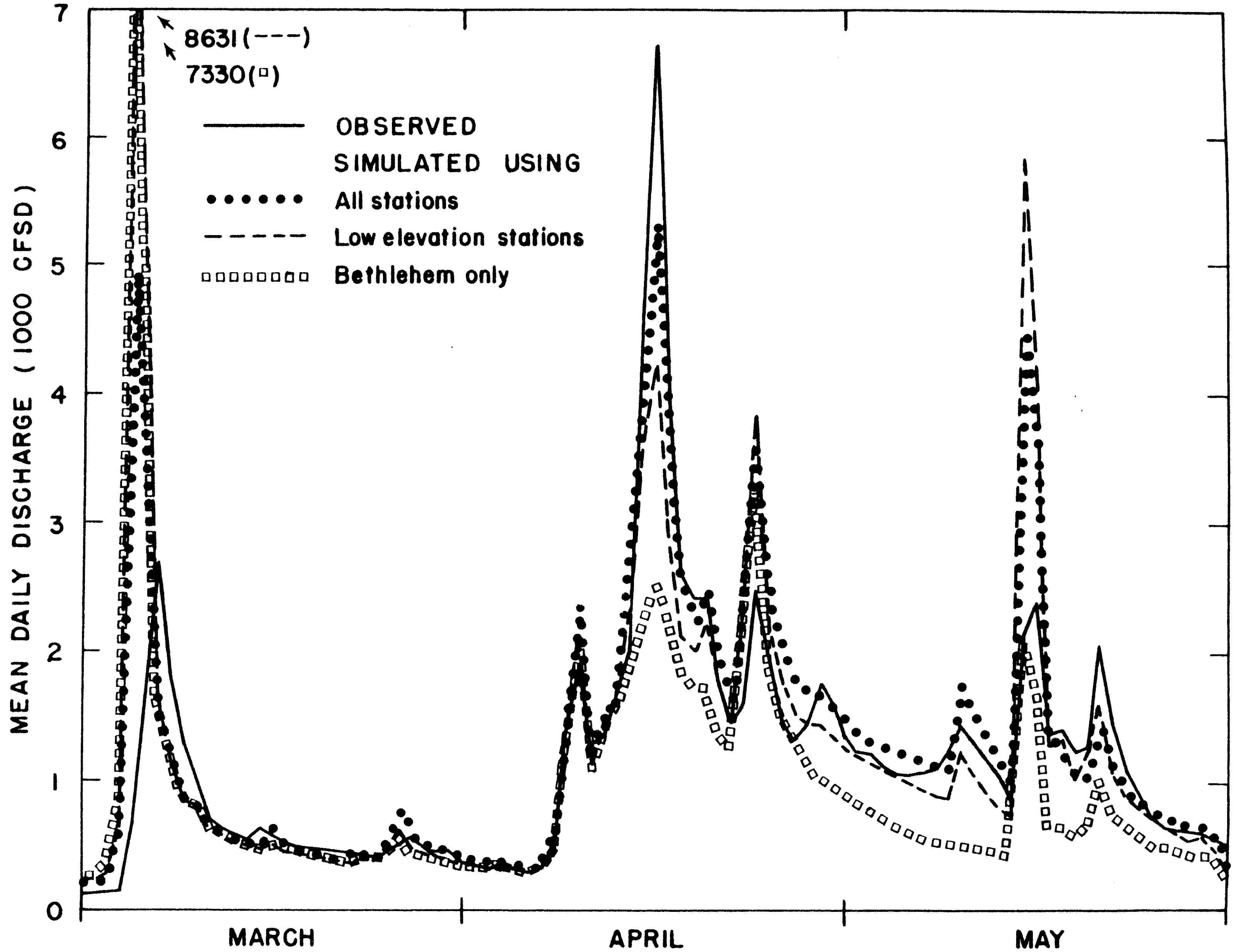


Figure 8 - Hydrograph comparisons using various precipitation and temperature networks, Ammonoosuc River, 1964

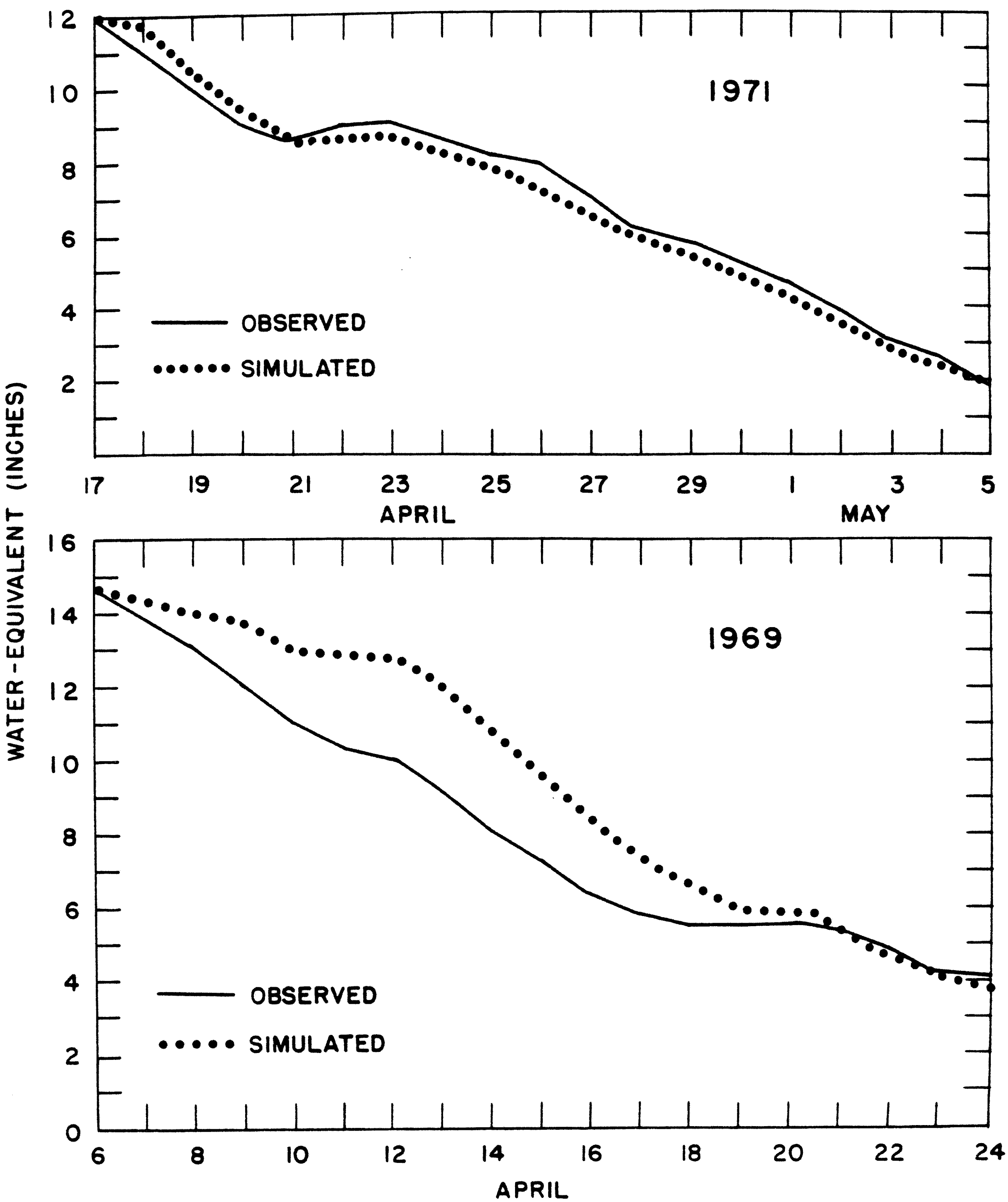
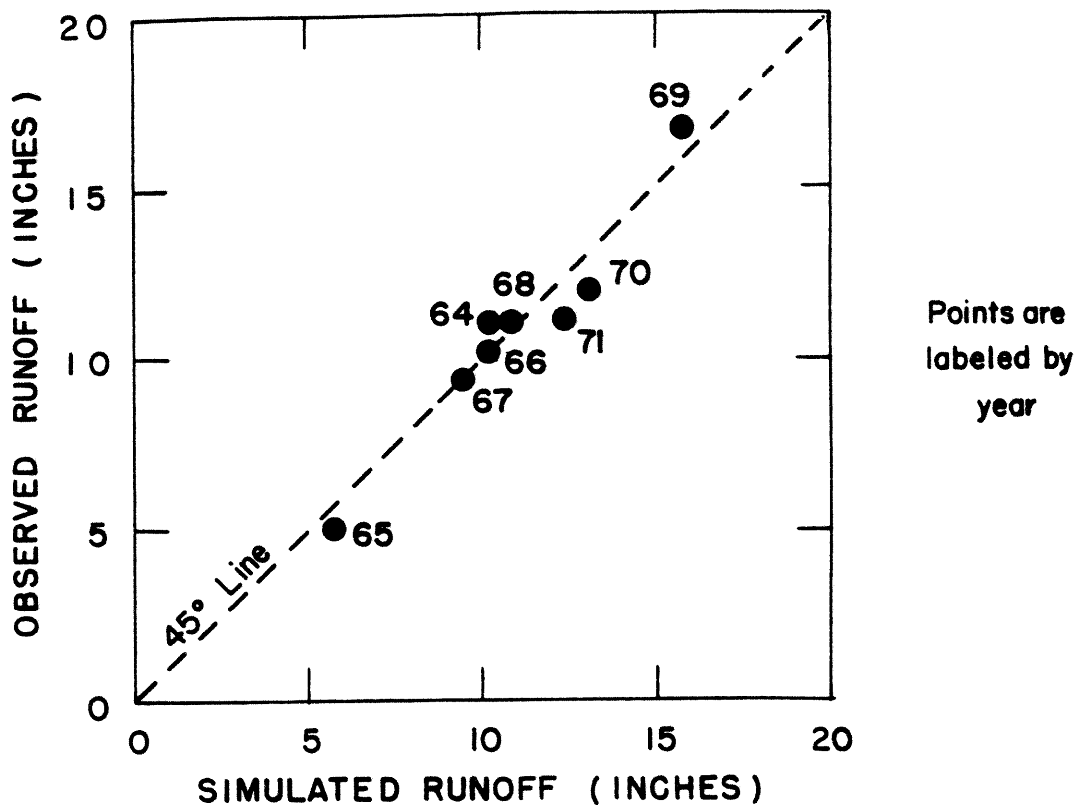


Figure 9 - Simulation of snow pillow data-NOAA-ARS Cooperative Snow Research Station, Danville, Vt.



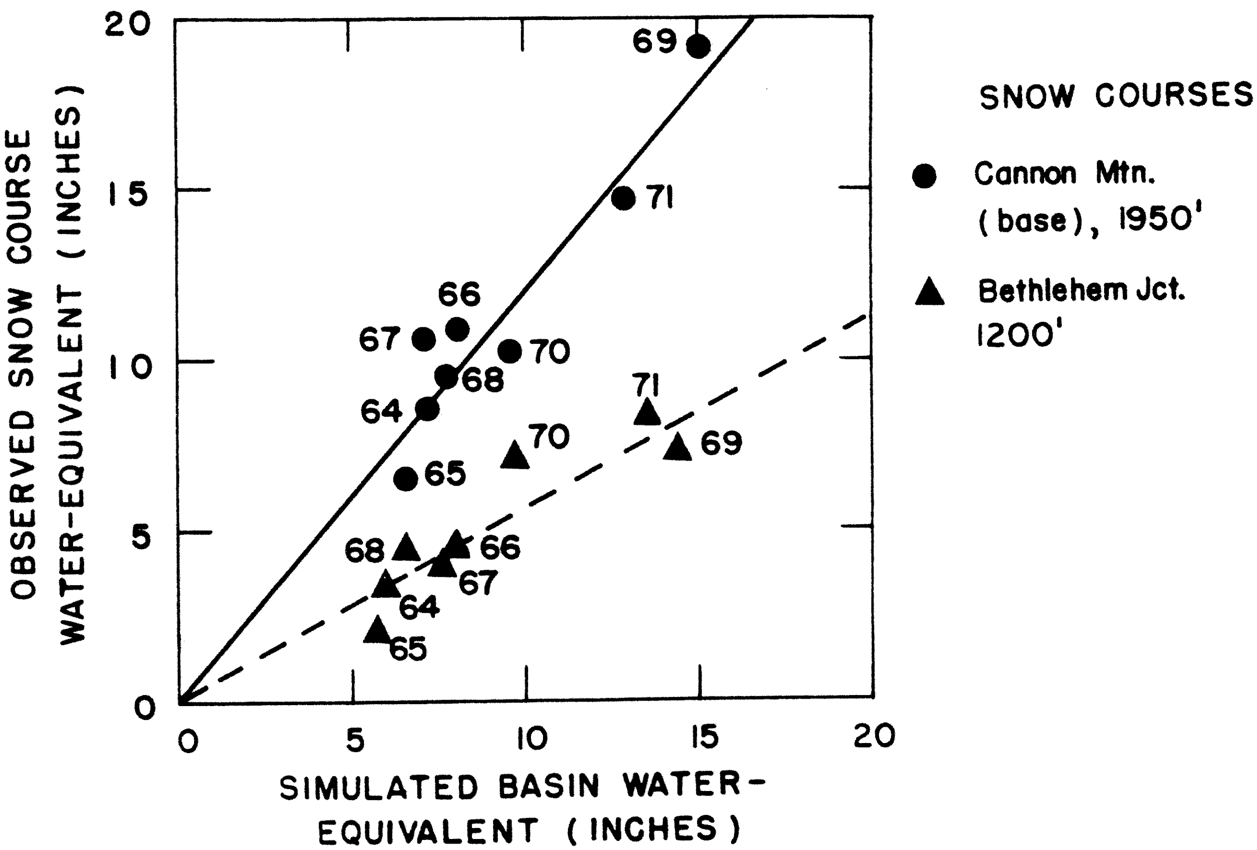
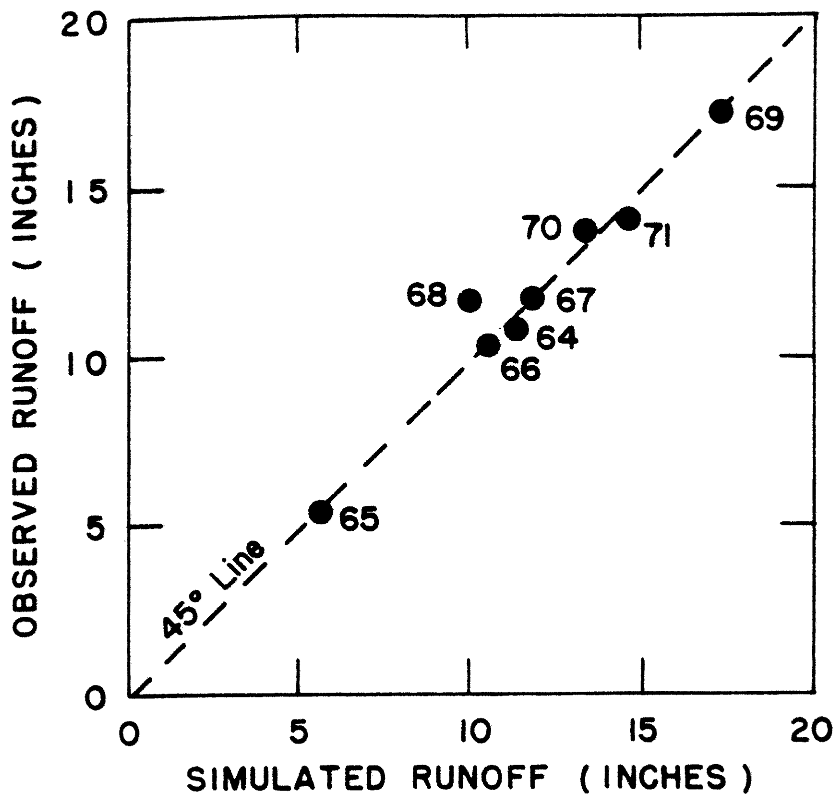
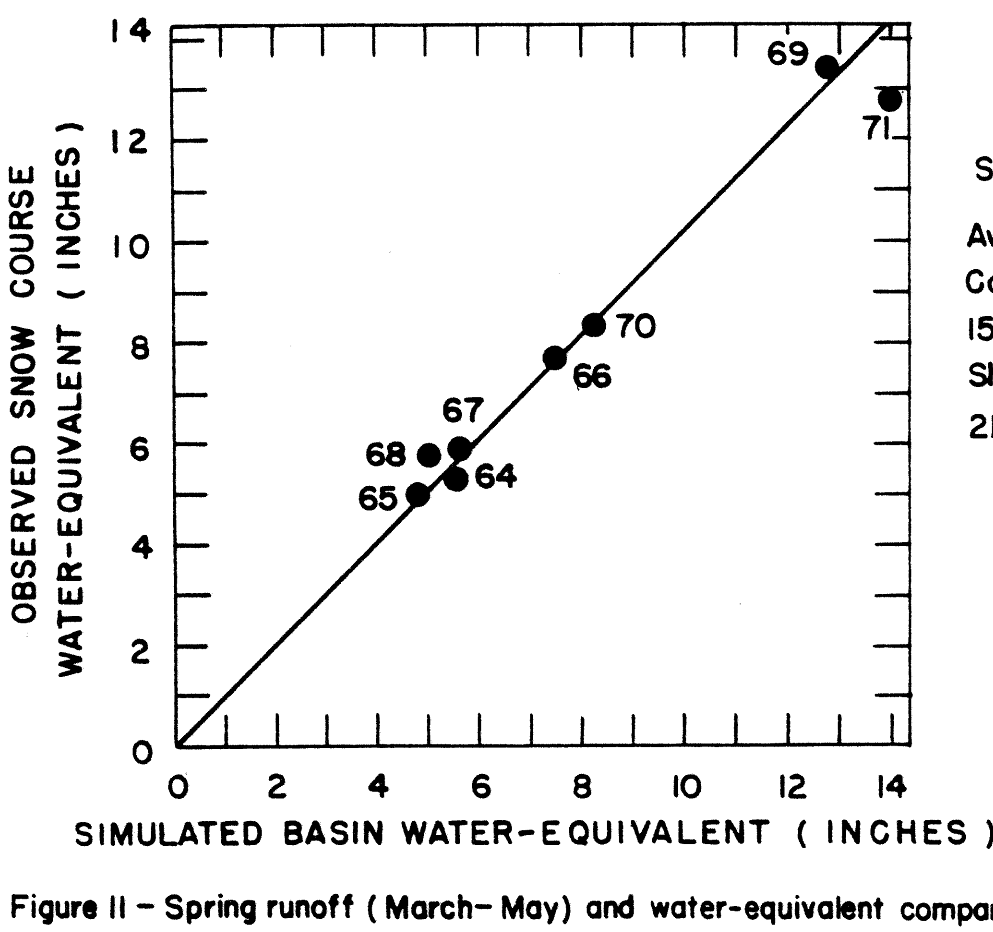


Figure 10 – Spring runoff (March-May) and water-equivalent comparisons, Ammonoosuc River



Points are labeled by year



SNOW COURSES

Average of County Line, Vt. 1590' and Sherburne Pass, Vt. 2150'

Figure II – Spring runoff (March– May) and water-equivalent comparisons, White River