COMPUTER MODEL FOR FORECASTING RUNOFF FROM MELTING SNOW

By Eric Anderson*

INTRODUCTION

For the past several years research has been carried on by Professors N. H. Crawford and R. K. Linsley[1] [2] at Stanford University in California on a digital computer model of the hydrologic cycle. Their resulting representation is called the Stanford Watershed Model and will be referred to as "the model" for simplicity throughout this paper. The model produces hourly precipitation data and has been tested on a number of watersheds with diverse climatic conditions with encouraging results. The model as developed by Crawford is designed to cope only with the effects of rainfall. This paper will describe portions of a further study[3] to incorporate the effects of snow into the model. The paper will deal with that portion of the study which uses ambient air temperature as the only meteorological input in addition to that required by the model. The representation of the snow accumulation and melt processes developed is a subroutine of the model and will be referred to as "the melt-factor subroutine" or "the subroutine."

Figure 1 shows a flowchart of the overall watershed model. Incoming precipitation enters the melt-factor subroutine where an accounting takes place depending on the form of the precipitation and the amount of snowpack existing in the watershed. Water which leaves the bottom of the snowpack can become runoff from impervious areas or can enter a variable capacity upper zone which in turn controls the inflow to a constant capacity lower zone. The amount of water stored in the lower zone is determined by an infiltration curve which is a function of existing lower zone storage to the maximum permissible lower zone storage. Water in excess of that infiltrated is separated into surface runoff and interflow, and appropriate routings applied. Water in the lower zone storage can percolate into groundwater storage and then the groundwater flow, which is a function of the size of groundwater storage, is determined and added to surface runoff and interflow to produce the synthesized hydrograph for the watershed. Evaporation from the snowpack is calculated separately while evapotranspiration from the soil is assumed to be equal to the potential rate as long as there is water available in the upper zone and at a rate which is a function of lower zone storage if there is not.

In the remaining portions of this paper I will briefly describe the melt-factor subroutine, the results obtained on two western mountain watersheds, and the conclusions drawn.

DESCRIPTION OF THE MELT-FACTOR SUBROUTINE

The melt-factor subroutine is designed to represent the snow accumulation and runoff process for a general subarea or watershed. The subroutine contains parameters which will differ from one subarea or watershed to the

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WATERSHED MODEL FLOWCHART

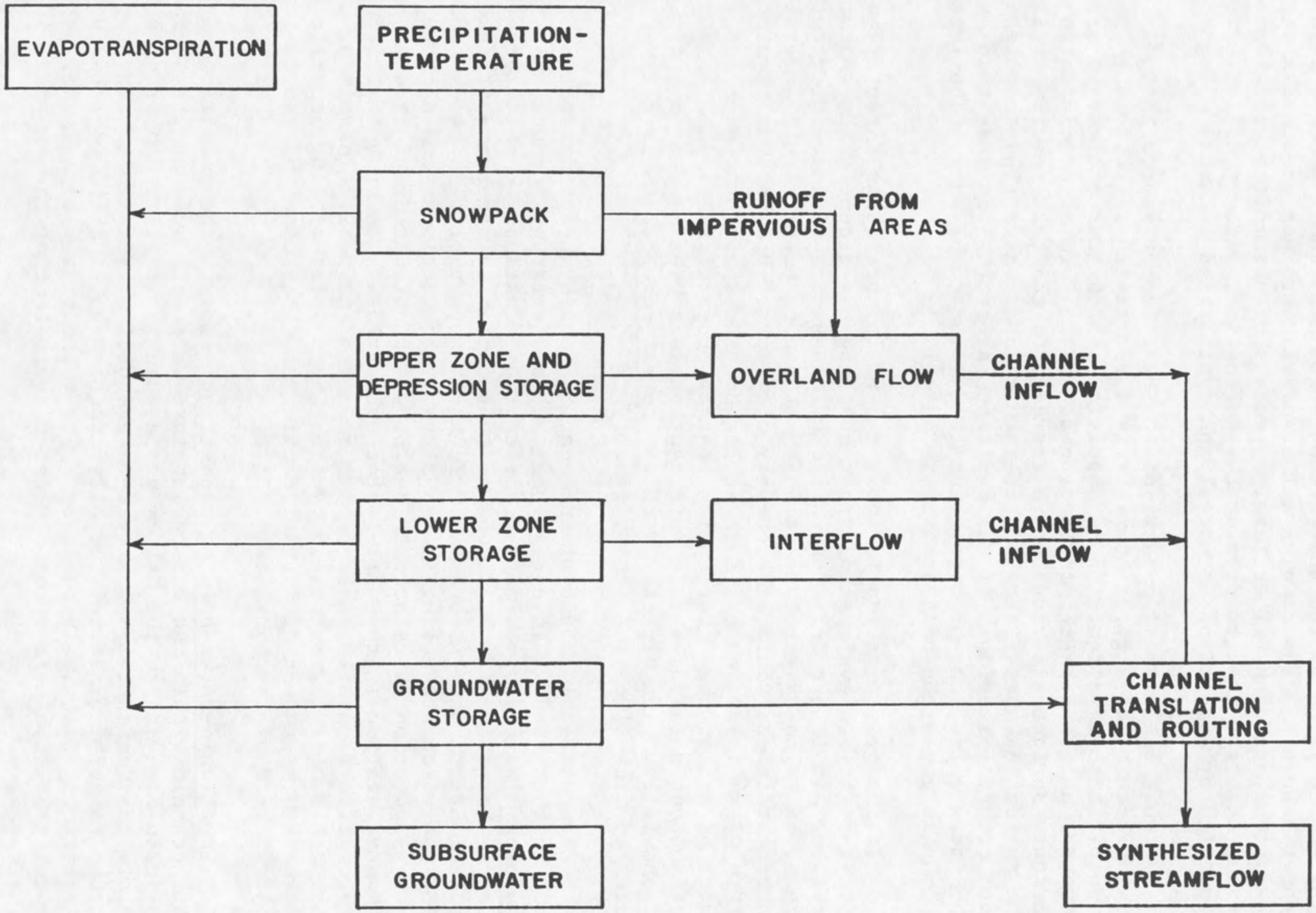

FIGURE I

next and the process of finding these parameters must be distinguished from the development of the general subroutine. The subroutine attempts to represent each segment of the snow accumulation and runoff process in a rational manner. However, the complex nature of this process prevents a strictly analytical approach. Therefore, a process of assumption, trial and modification has been used to develop the subroutine, with specific improvements suggested by comparison of actual and synthesized records.

Figure 2 shows a flowchart of the melt-factor subroutine. If precipitation occurs for a given hour, it is first tested as to form. The form of precipitation is a function of conditions throughout the entire air mass. However, unless a better indication as to the form of precipitation is present, surface air temperature seems to be the best readily available index. The subroutine uses a single temperature index value (T_p) to determine the form of precipitation. If the air temperature (T_a) is less than or equal to the index value, the precipitation is assumed to be snow. The index value which has given the best results to date is 33°F.

If the precipitation is snow, a certain portion is intercepted by the forest cover and evaporated, never reaching the ground. The amount of interception loss is not only controlled by the amount of snow intercepted by the trees, but also by the rate at which it can be evaporated. An evaluation of these conditions would be extremely difficult. However, as reported in Snow Hydrology,[4] investigators such as Ingebo have shown that over the snow accumulation season the interception loss is proportional to the canopy density. The subroutine assumes that interception loss over a watershed for each hour of snowfall varies directly with net forest cover which is defined as the forested area times the canopy density.

An additional amount of snow can be lost by evaporation from the snowpack on the ground. Investigators such as Sverdrup,[5] de Quervain[6] and Snow Hydrology[4] have derived mass-transfer type equations to calculate this factor. West[7] [8] has shown the magnitude of this factor in measurements taken at the Central Sierra Snow Laboratory. In another part of this study[3] snow evaporation was calculated using the mass-transfer equations, and a curve of mean snow-evaporation as related to season was constructed and used to estimate snow-evaporation in the melt-factor subroutine. The snow that is not lost by evaporation is available as runoff from the snowpack. The timing of this snowpack runoff is controlled by the liquid-water-holding capacity of the snowpack, the amount of "negative melt" and the amount of snowmelt in the upper layers of the snowpack.

The liquid-water-holding capacity of snow is the amount of water which will be held within the snowpack before water produced at the surface is able to drain downward to the bottom of the pack. It is common practice to relate the variability in liquid-water-holding capacity to density, although in the range of densities normally experienced, the liquid-water-holding capacity is effectively constant. The subroutine uses a liquid-water-holding capacity of five percent of the water equivalent of the snowpack in this density range.

FLOWCHART OF SNOWMELT SUBROUTINE

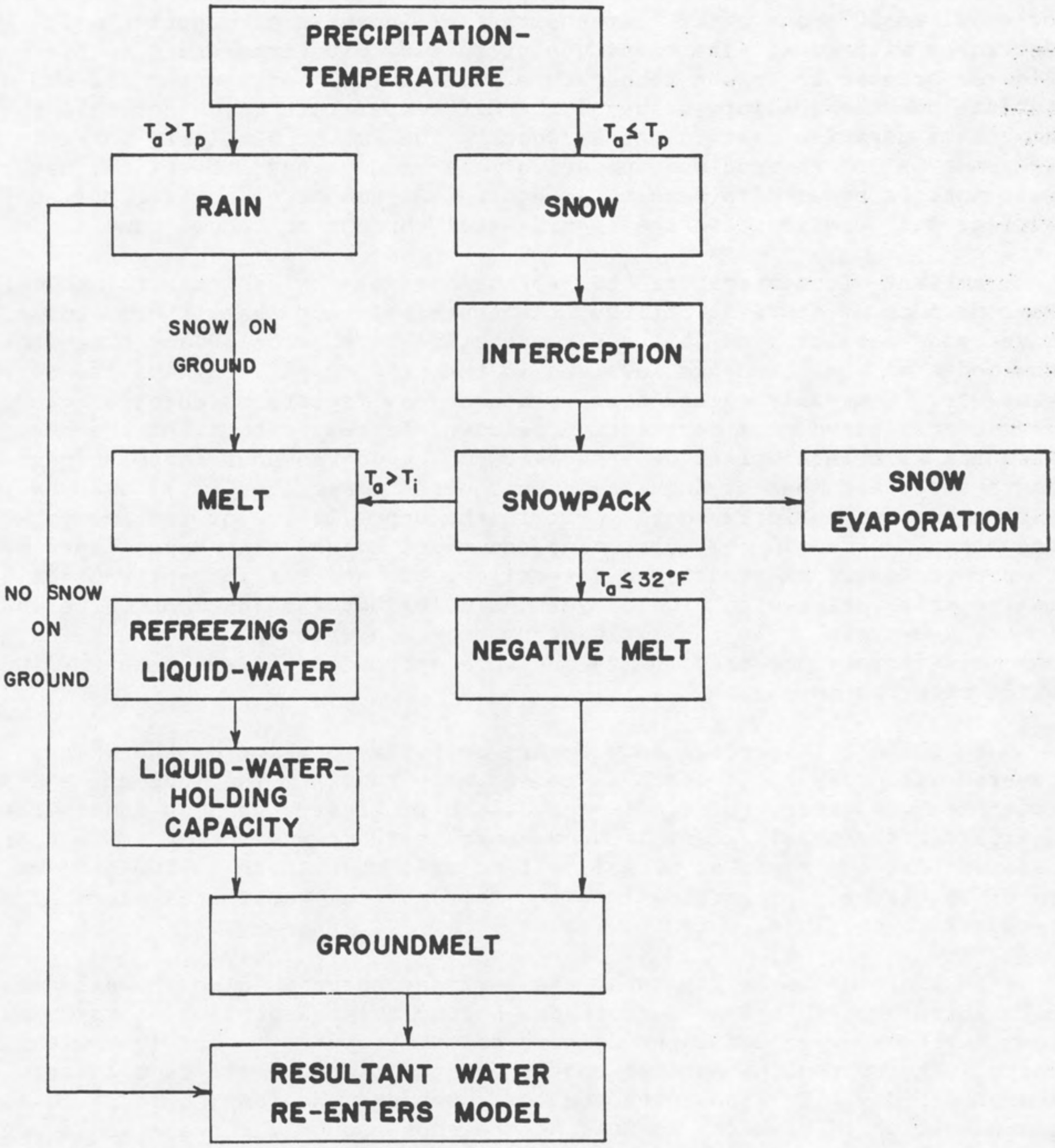

FIGURE 2

Negative melt is defined as the net heat sink which must be satisfied before surface melt water can add to the liquid-water content of the snowpack or become snowpack runoff. An empirical relationship was used to calculate negative melt. It was assumed that this heat sink accumulates at a constant rate during the first twelve hours the air temperature is less than or equal to 32°F and after that the rate of increase of negative melt decreases with time. The magnitude of surface air temperature is not considered because it is the temperature differential between the air and snow surface not the absolute value of the air temperature which controls the amount of negative melt in the snowpack. The amount of liquid-water in the snowpack is not reduced when negative melt accumulates; therefore, negative melt must be reduced to zero by an equivalent amount of surface melt before surface melt can increase the liquid-water content or become runoff.

Ambient air temperature has been used widely as an index to snowmelt. Reasons such as its availability, the empirical fact that it has generally given good results, and that air temperature is physically an integrator of the modes of heat exchange involved in the melting of snow have led to this wide use. Generally degree-hour or degree-day factors which have been derived are based on a correlation between air temperature and the change in snowpack water-equivalent or streamflow. The degree-hour factors [degree-hours are the number of degrees above a base temperature (T_i)] used by the subroutine are an index to the melt in the upper layers of the snowpack, and the other factors in the subroutine and model adjust this upper layer melt to produce snowpack runoff and streamflow. To account for any variability in the melt-factor with time of year, a melt-factor adjustment curve is used in the subroutine. In the two western mountain watersheds tested, the maximum melt-factors occurred in May and were approximately twice the minimums which occurred in January.

When there is partial snow cover, only that portion of the watershed covered with snow can contribute to snowmelt runoff. The subroutine assumes that when the water equivalent of the snow is greater than an index water equivalent the areal extent of snow cover is 100 percent. It is further assumed that the ratio of actual melt to melt when there is 100 percent snow cover is directly proportional to the ratio of the water equivalent of the snowpack to the index water equivalent.

In addition to melting near the surface, there is also a small amount of melt which occurs in some watersheds, during a large portion of the snow season, at the snow-ground interface due to the release of heat from within the earth. The subroutine assumes that the rate of groundmelt is a constant amount per day. In areas with shallow snowpacks and long, cold periods, groundmelt would be zero, as melt at the snow-ground interface would not be a continuous process. However, in areas of deep snow accumulation, a groundmelt value greater than zero would probably be warranted. A value in the range of 0.02 inch per day is sufficient to raise soil moisture slightly and maintain flow in the stream throughout the winter.

RESULTS OF STREAMFLOW SYNTHESIS FOR TWO WATERSHEDS

The melt-factor subroutine was tested extensively on two western mountain watersheds: Upper Castle Creek, Central Sierra Snow Laboratory, California and Skyland Creek, Upper Columbia Snow Laboratory, Montana. The general procedure for the testing of the watersheds and the development of procedures was as follows: First, a subroutine was devised which attempted to represent the snow accumulation and runoff process in a rational manner. Then one or two years of data were tested and basin and snowmelt parameters developed so that the synthetic outflow hydrograph reasonably approximated the actual. Where discrepancies existed between the hydrographs, the situation was examined more closely to determine the cause. The determination of the causes of these discrepancies led either to ways of improving the procedure or pointed out situations where air temperature alone was not a good index to the volume of snowmelt or the form of precipitation. After these first years of data were matched as reasonably as was felt possible, additional years were tested to make sure that the procedure and parameters would work in general and not just for selected years. The results presented here were computed using the same set of watershed and snowmelt parameters on all years of data for each watershed.

UPPER CASTLE CREEK

Upper Castle Creek, shown in figure 3, is a tributary of the Yuba River, near Donner Summit, California. It has an elevation range of 6891 to 9104 feet above mean sea level and a watershed drainage area of 3.96 square miles. The average annual watershed precipitation is approximately 75 inches of which about 80 percent is in the form of snow. The average annual runoff for the watershed during the period 1947-1951 is 46.0 inches.

Table 1 shows a comparison of actual and synthetic runoff volumes on a monthly and yearly basis. The percent error of the yearly synthetic volumes is random with five of the years showing positive departures and four years, negative. Figures 4 through 12 show a comparison of actual and synthetic mean daily flows during each of the snowmelt periods. Water years 1947-1951 from which data were gathered during the Snow Investigations of the Corps of Engineers and the U. S. Weather Bureau were used to determine the watershed and snowmelt parameters; water years 1959-1962 for which data were gathered by the U. S. Forest Service were used as an independent test. The degree-hour factor used on Upper Castle Creek was 0.0054 inch per °F in combination with a base temperature of 35°F. Table 2 shows a summary of the daily flow estimates and daily correlation coefficients. Daily correlation coefficients were all in excess of 0.90.

SKYLAND CREEK

Skyland Creek, shown in figure 13, is located at the extreme headwaters of the Columbia-Clark Fork-Flathead river system near Marias Pass, Montana. It has an elevation range of 4800 to 7610 feet above mean sea level and a watershed drainage area of 8.09 square miles. The average annual watershed precipitation is approximately 60 inches, of which about 60 percent is snow. The average annual runoff for the period 1947-1951 is 33.3 inches.

Table 3 shows a comparison of actual and synthetic monthly and yearly flow volumes for the four years of data for which hourly precipitation records were available. Two years show plus percent errors on yearly volume and the other two years, negative. Figures 14 through 17 show the actual

UPPER CASTLE CREEK WATERSHED

DRAINAGE AREA: 3.96 SQ. MI.

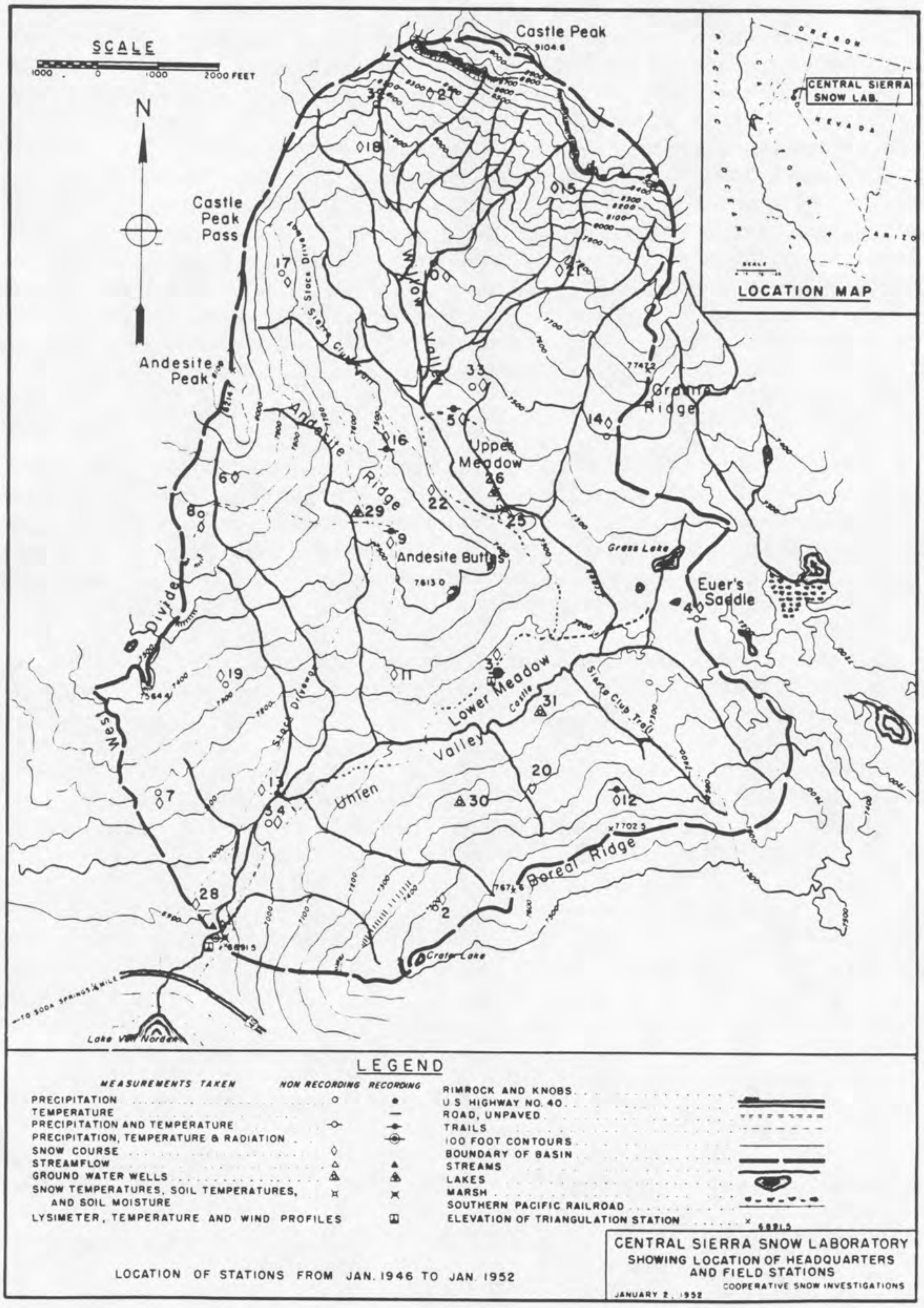

FIGURE 3

Table 1

Comparison of Monthly Flow--Upper Castle Creek
(all values in inches depth on the drainage area)

Year		1946-47	1947-48	1948-49	1949-50	1950-51	1958-59	1959-60	1960-61	1961-62
Oct.	Est.	0.09	2.21	0.02	0.03	0.87	0.03	0.09	0.08	0.23
	Act.	0.00	0.58	0.00	0.00	0.13	0.01	0.00	0.00	0.04
Nov.	Est.	0.03	0.35	0.97	0.09	16.2	0.14	0.02	0.38	0.23
	Act.	0.09	0.50	0.32	0.11	19.6	0.07	0.00	0.01	0.06
Dec.	Est.	0.39	0.36	0.14	0.10	12.5	0.13	0.03	0.09	0.12
	Act.	0.16	0.33	0.12	0.09	12.3	0.05	0.00	0.06	0.22
Jan.	Est.	0.22	1.72	0.13	0.82	1.13	0.39	0.04	0.12	0.33
	Act.	0.22	1.95	0.14	0.65	1.63	0.69	0.00	0.13	0.37
Feb.	Est.	0.76	0.57	0.13	0.37	0.66	0.18	1.06	0.39	0.75
	Act.	0.88	0.73	0.13	0.72	1.54	0.46	0.63	0.70	0.51
Mar.	Est.	4.67	0.48	0.15	1.67	2.49	1.84	4.99	0.20	0.33
	Act.	2.38	0.76	0.22	1.70	2.48	2.22	3.50	0.77	0.53
Apr.	Est.	9.63	3.06	14.0	9.47	14.8	12.5	5.98	6.81	13.6
	Act.	9.03	4.28	9.61	9.57	11.4	10.0	9.60	7.06	11.5
May	Est.	11.0	15.3	18.1	24.8	16.8	10.1	14.7	12.9	13.1
	Act.	14.2	15.1	18.2	23.4	15.8	10.3	14.4	13.3	15.3
June	Est.	2.30	19.7	3.01	13.3	3.22	2.41	6.95	7.00	8.72
	Act.	2.84	18.8	3.72	15.8	4.45	3.28	5.68	5.10	11.1
July	Est.	0.35	2.20	0.41	1.35	0.43	0.39	0.55	0.73	0.87
	Act.	0.13	1.42	0.15	1.53	0.26	0.16	0.15	0.15	0.76
Aug.	Est.	0.08	0.23	0.13	0.16	0.09	0.09	0.11	0.16	0.15
	Act.	0.00	0.08	0.00	0.06	0.00	0.00	0.00	0.00	0.05
Sept.	Est.	0.02	0.05	0.04	0.06	0.03	0.47	0.03	0.08	0.04
	Act.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	Est.	29.57	46.18	37.15	52.30	69.19	28.75	34.53	28.91	38.53
	Act.	29.98	44.46	32.73	53.97	69.47	27.32	34.01	27.26	39.39
Water Year % Error		-1.4	+3.9	+13.5	-3.1	-0.4	+5.2	+1.5	+6.0	-2.2

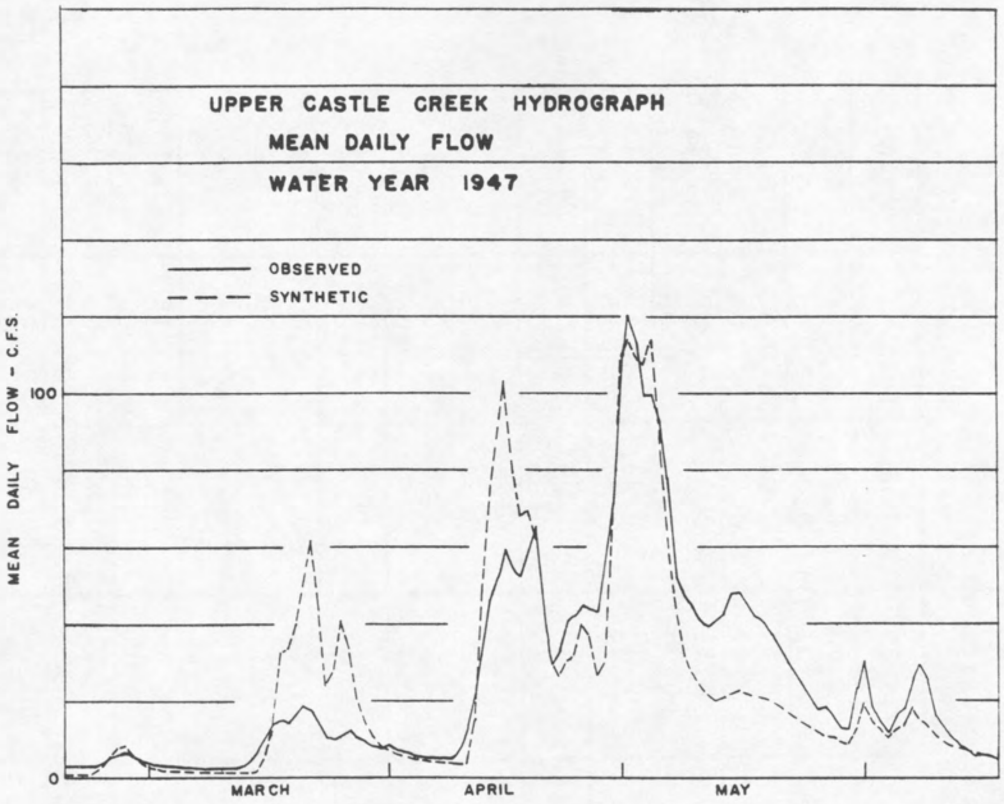

FIGURE 4

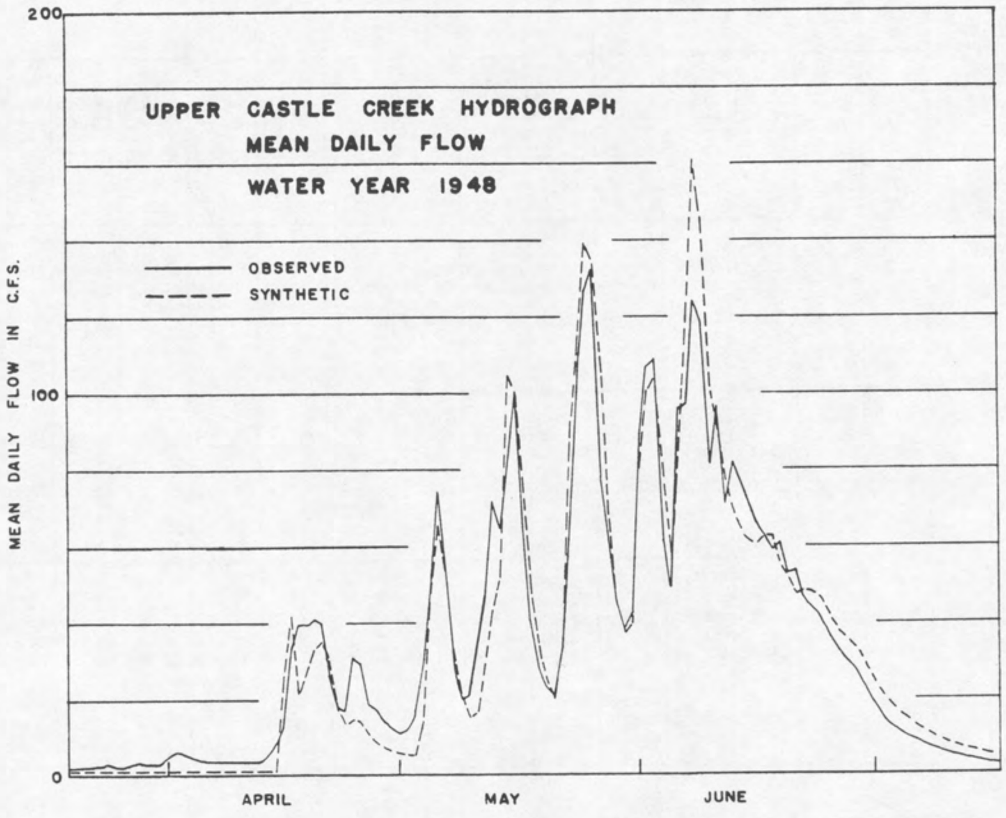

FIGURE 5

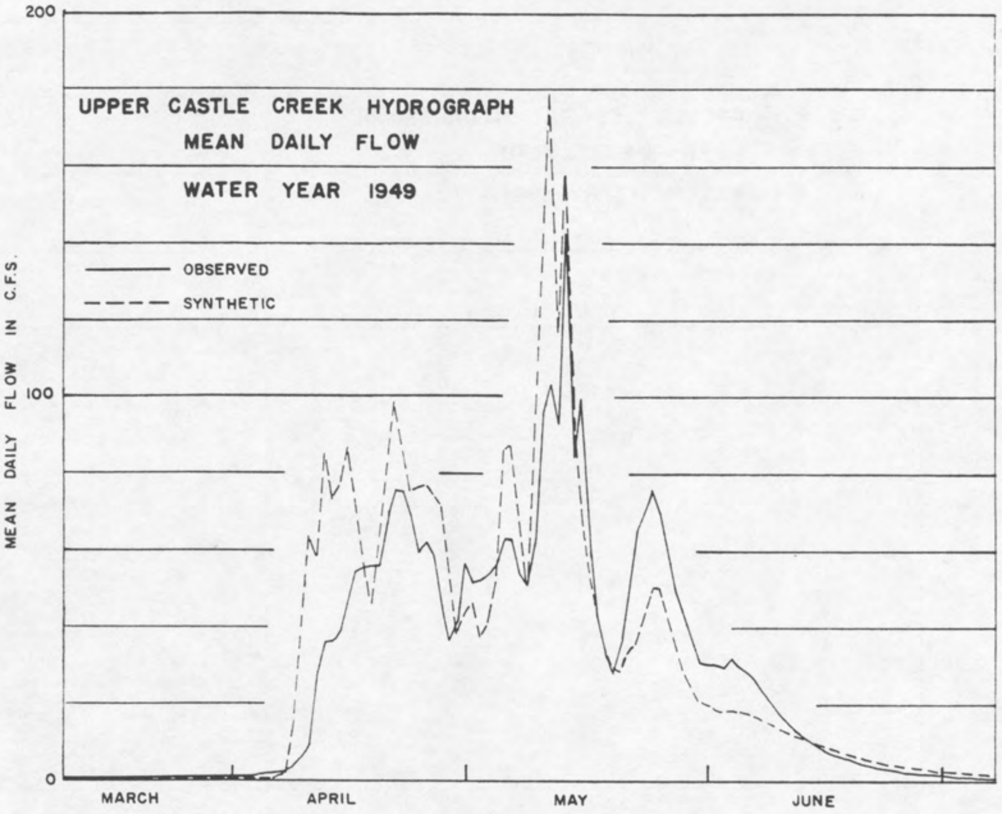

FIGURE 6

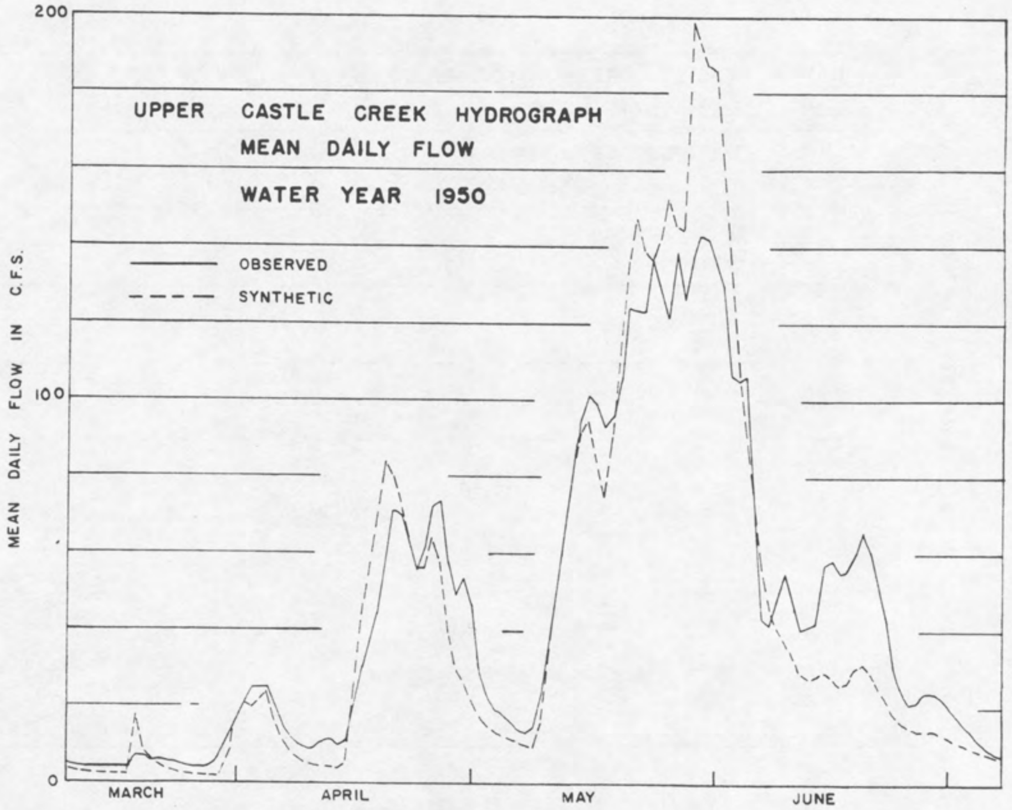

FIGURE 7

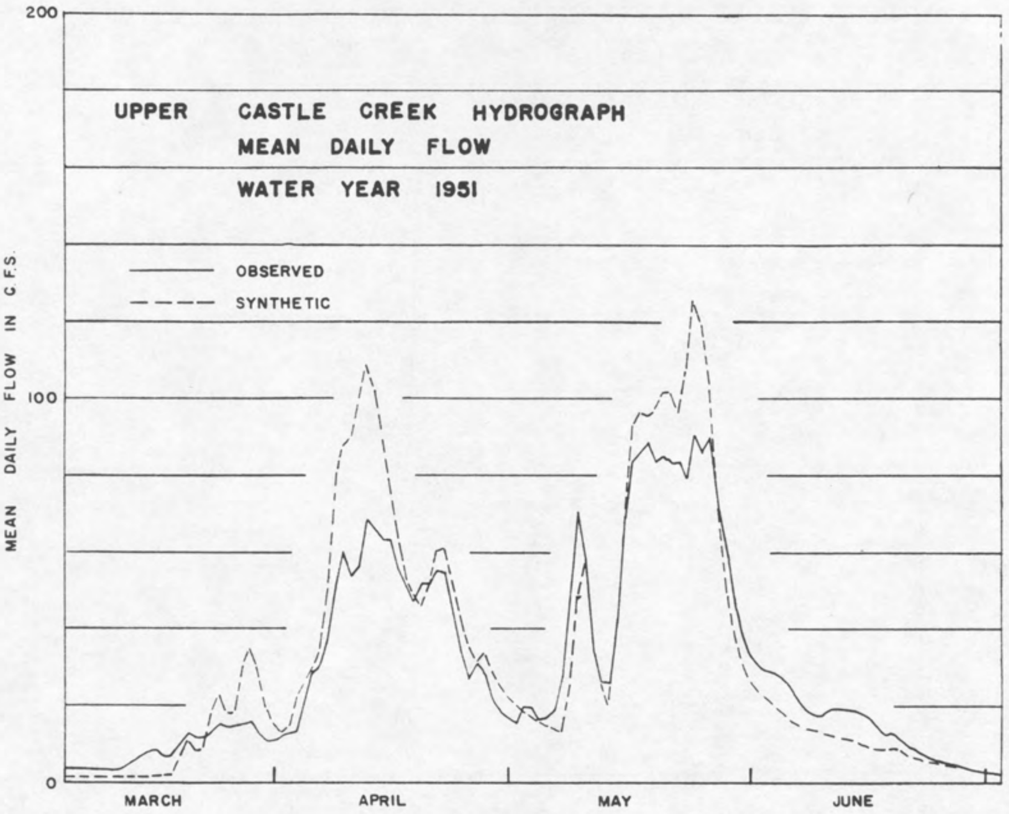

FIGURE 8

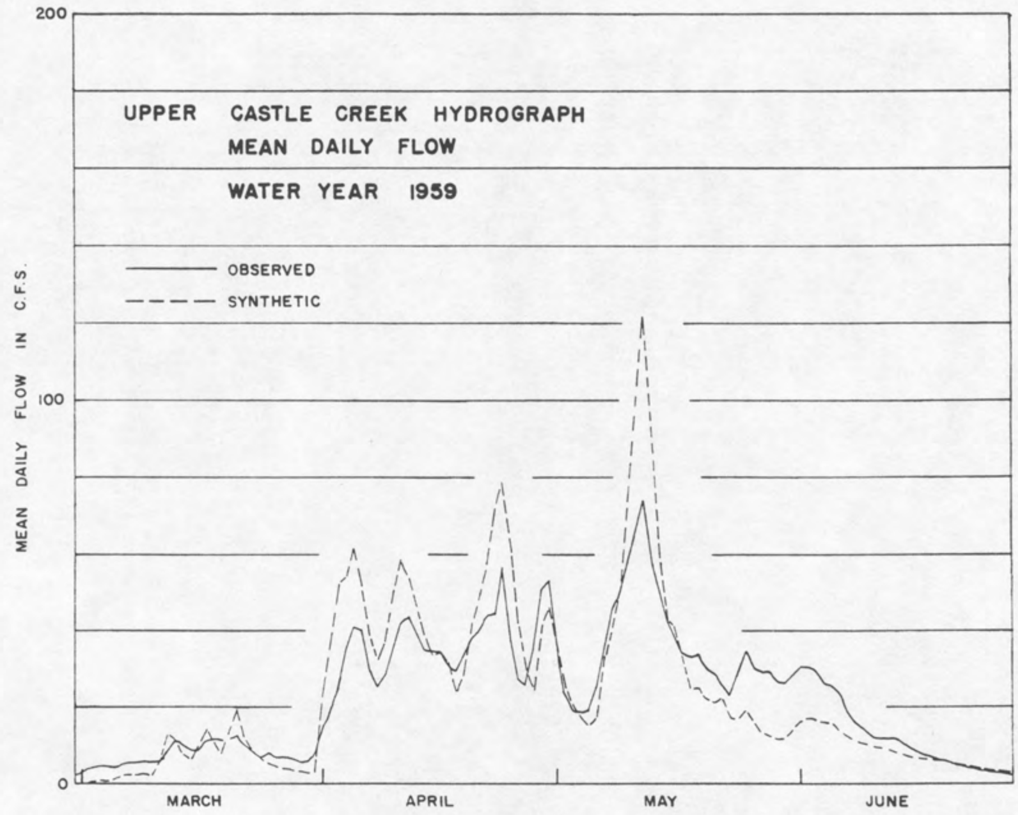

FIGURE 9

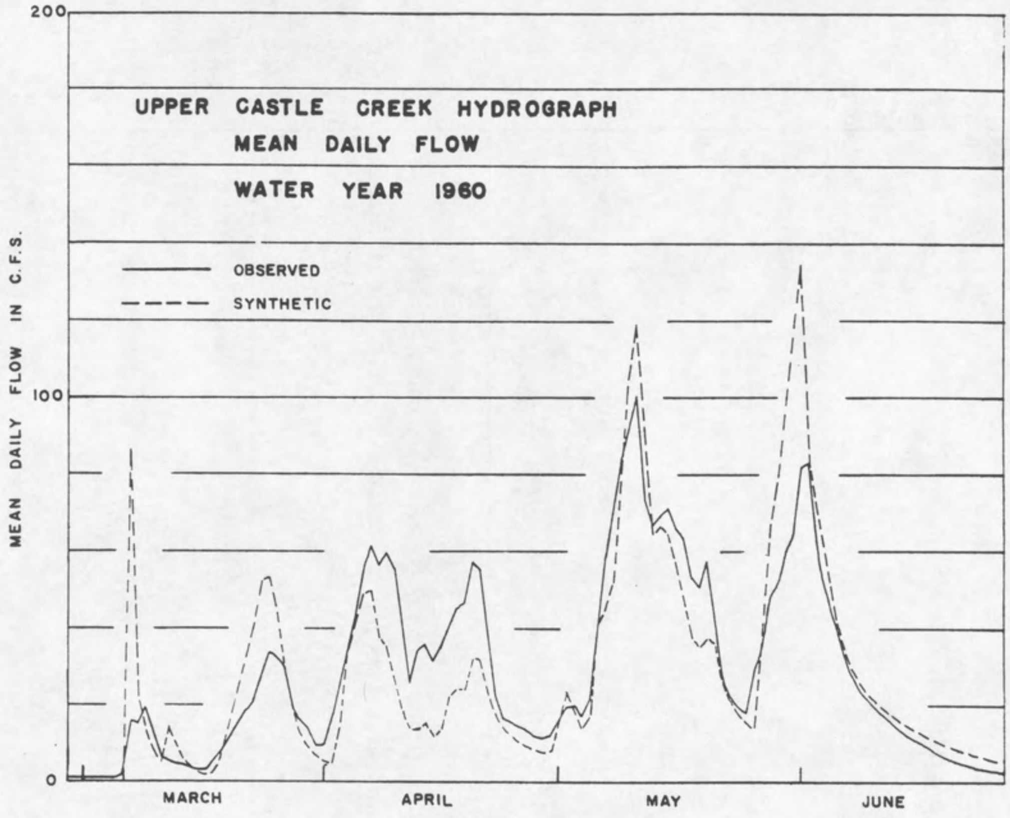

FIGURE 10

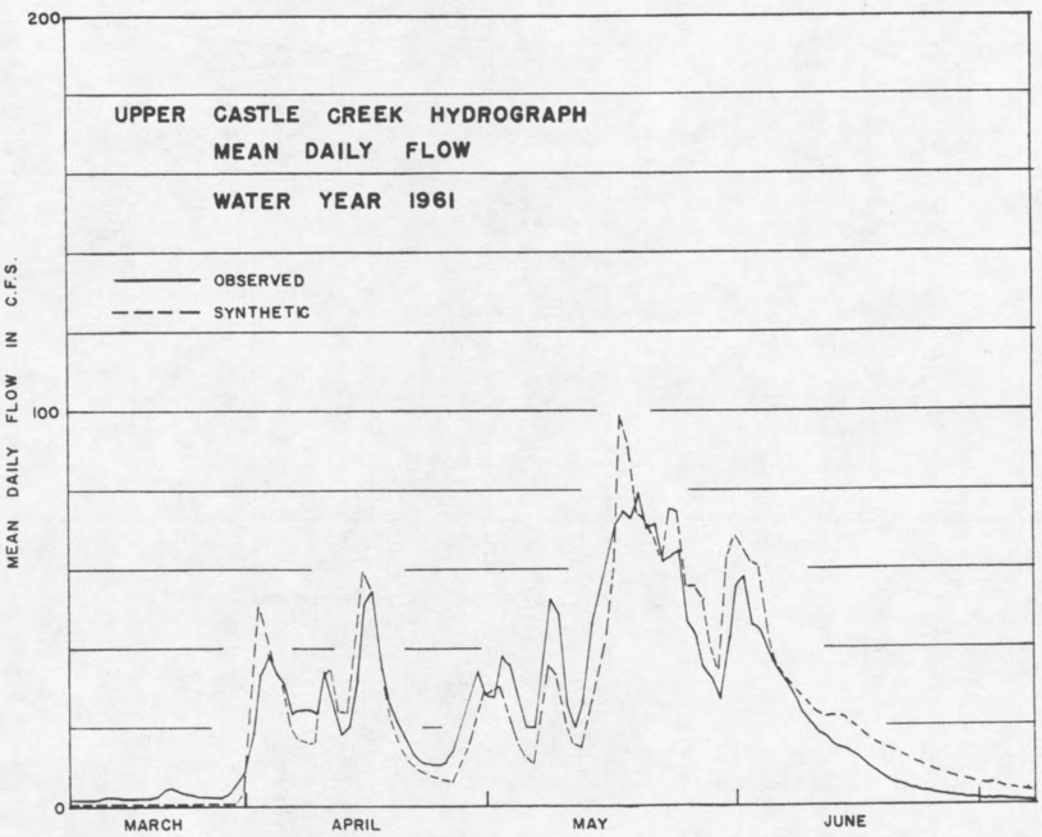

FIGURE 11

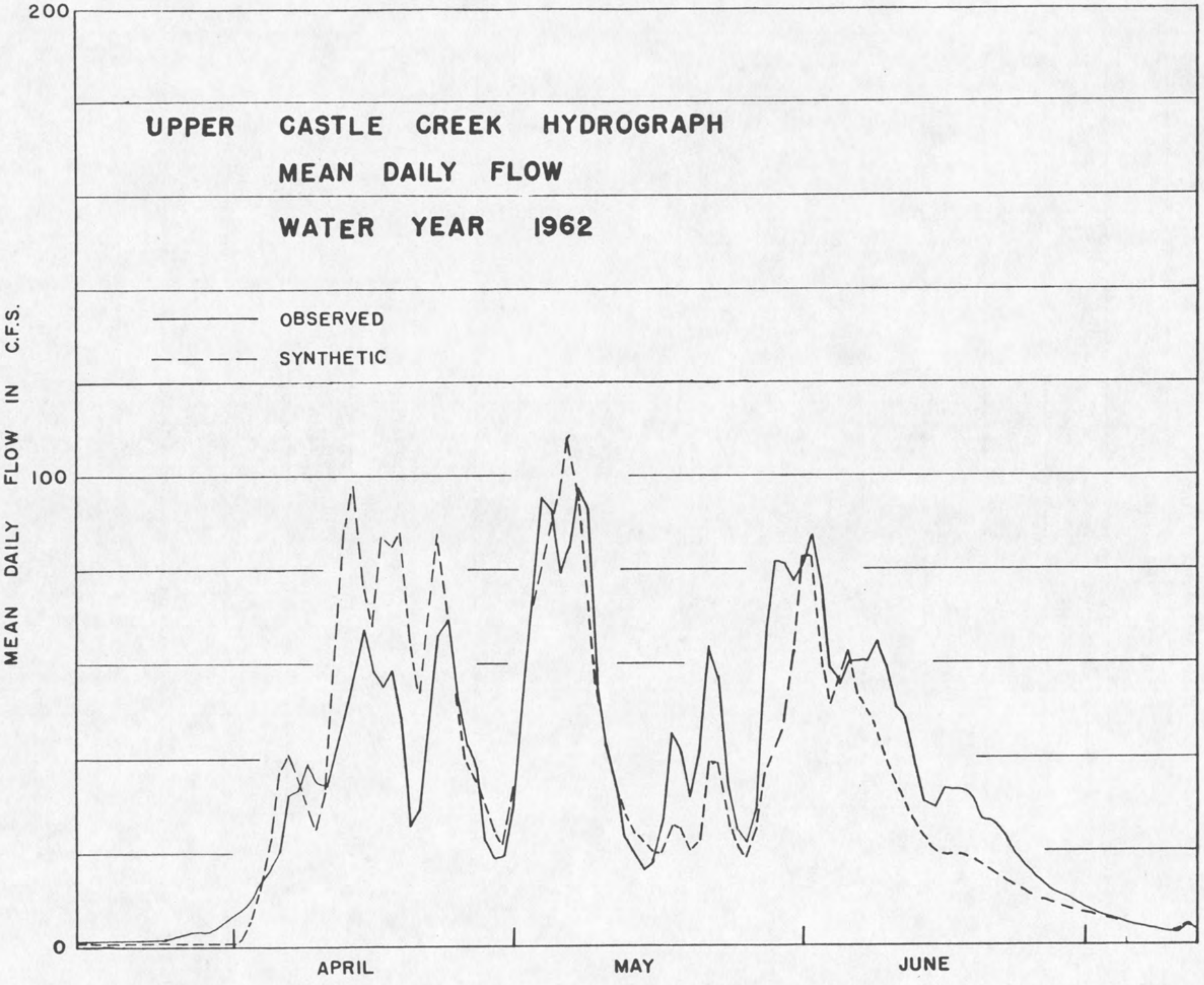
UPPER CASTLE CREEK HYDROGRAPH
MEAN DAILY FLOW
WATER YEAR 1962
OBSERVED
SYNTHETIC
MEAN DAILY FLOW IN C.F.S.
200
100
0
APRIL
MAY
JUNE

FIGURE 12

Table 2
Summary of Daily Flow Estimates
Upper Castle Creek
Water Years 1947-1951 and 1959-1962

Flow Interval CFS	Number of Days		Av. Error
	Observed	Synthetic	CFS
0.0- 0.99	1612	1555	0.37
1.0- 1.59	216	282	0.73
1.6- 2.69	227	274	0.02
2.7- 4.49	201	179	-0.72
4.5- 7.39	165	140	-0.14
7.4- 12.19	125	133	-0.47
12.2- 19.99	154	169	0.97
20.0- 33.09	171	169	-2.30
33.1- 54.59	196	167	-0.51
54.6- 89.99	161	134	2.11
90.0- 148.39	53	74	9.85
148.4- 244.69	2	7	-3.4
244.7- 403.39	3	2	-23.9
403.4- 665.09	0	2	---
665.1-1096.59	1	0	-286.8

Daily Correlation Coefficients

Water Year	Correlation Coefficient	Water Year	Correlation Coefficient
1946-47	0.920	1958-59	0.934
1947-48	0.965	1959-60	0.902
1948-49	0.932	1960-61	0-957
1949-50	0.965	1961-62	0.937
1950-51	0.953		

SKYLAND CREEK WATERSHED

DRAINAGE AREA: 8.09 SQ.MI.

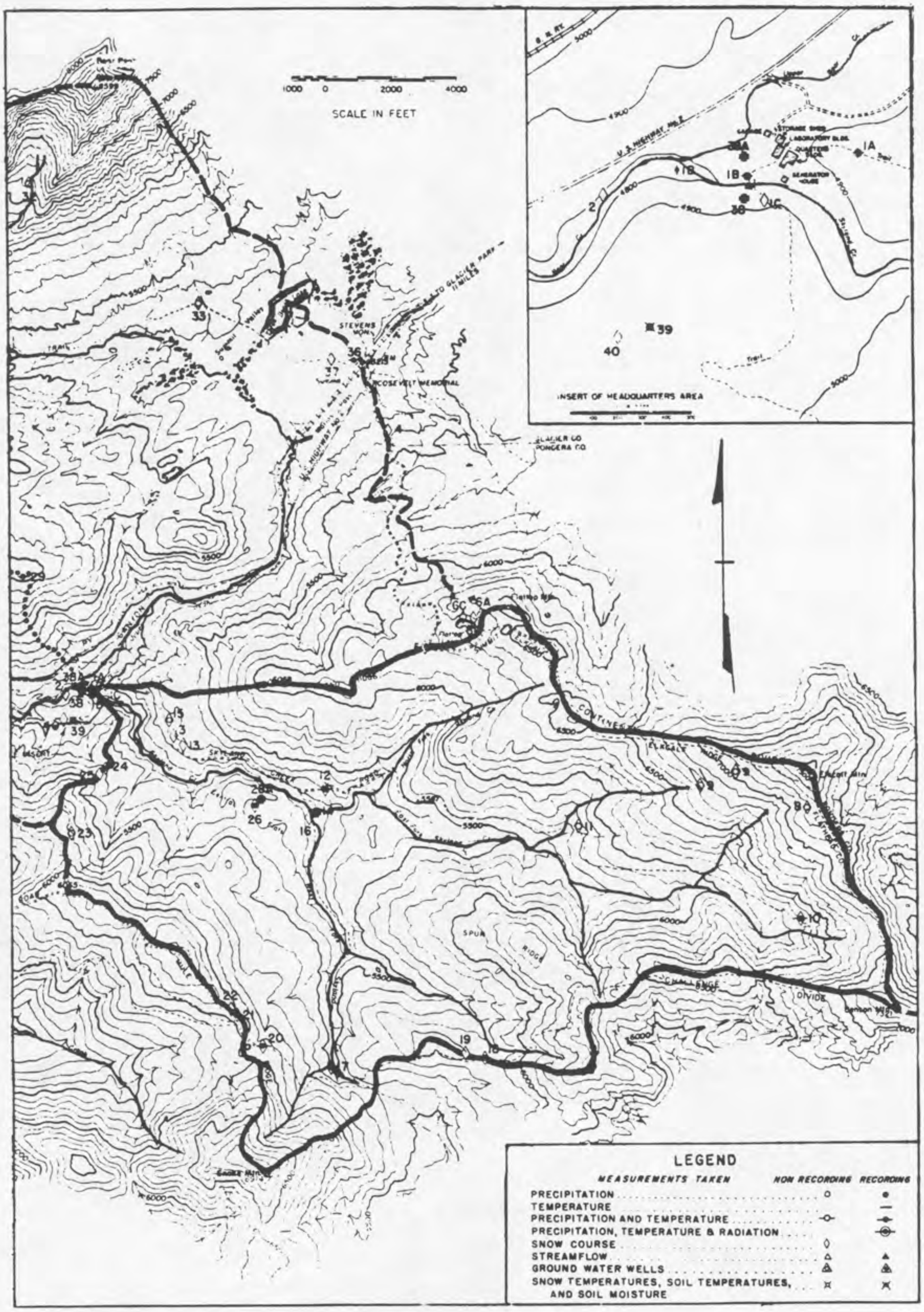

FIGURE 13

Table 3
Comparison of Monthly Flow
Skyland Creek
(all values in inches depth on the drainage area)

Year		1946-47	1948-49	1949-50	1950-51
Oct.	Est.	1.20	0.28	0.75	2.21
	Act.	0.92	0.82	0.67	1.22
Nov.	Est.	0.97	0.22	1.06	2.31
	Act.	0.67	0.58	0.73	1.17
Dec.	Est.	0.63	0.18	0.84	1.80
	Act.	0.65	0.58	0.67	1.21
Jan.	Est.	0.48	0.15	0.56	1.00
	Act.	0.55	0.51	0.42	0.96
Feb.	Est.	0.37	0.11	0.41	0.62
	Act.	0.44	0.44	0.39	0.82
Mar.	Est.	0.74	0.10	0.39	0.57
	Act.	0.45	0.45	0.43	0.66
Apr.	Est.	2.44	0.82	0.47	0.86
	Act.	1.75	1.26	0.66	1.40
May	Est.	12.9	9.31	5.80	10.8
	Act.	12.8	9.62	6.38	11.5
June	Est.	6.78	5.01	20.9	12.5
	Act.	7.27	4.62	21.4	11.6
July	Est.	1.82	1.46	8.27	5.58
	Act.	1.84	1.31	7.28	6.03
Aug.	Est.	0.84	0.62	1.41	1.26
	Act.	1.21	0.87	1.77	1.96
Sept.	Est.	0.69	0.46	0.53	1.08
	Act.	1.04	0.74	1.13	1.49
Total	Est.	29.87	18.72	41.42	40.63
	Act.	29.68	21.89	42.01	40.10
Water Year % Error		+0.6	-14.4	-1.4	+1.3

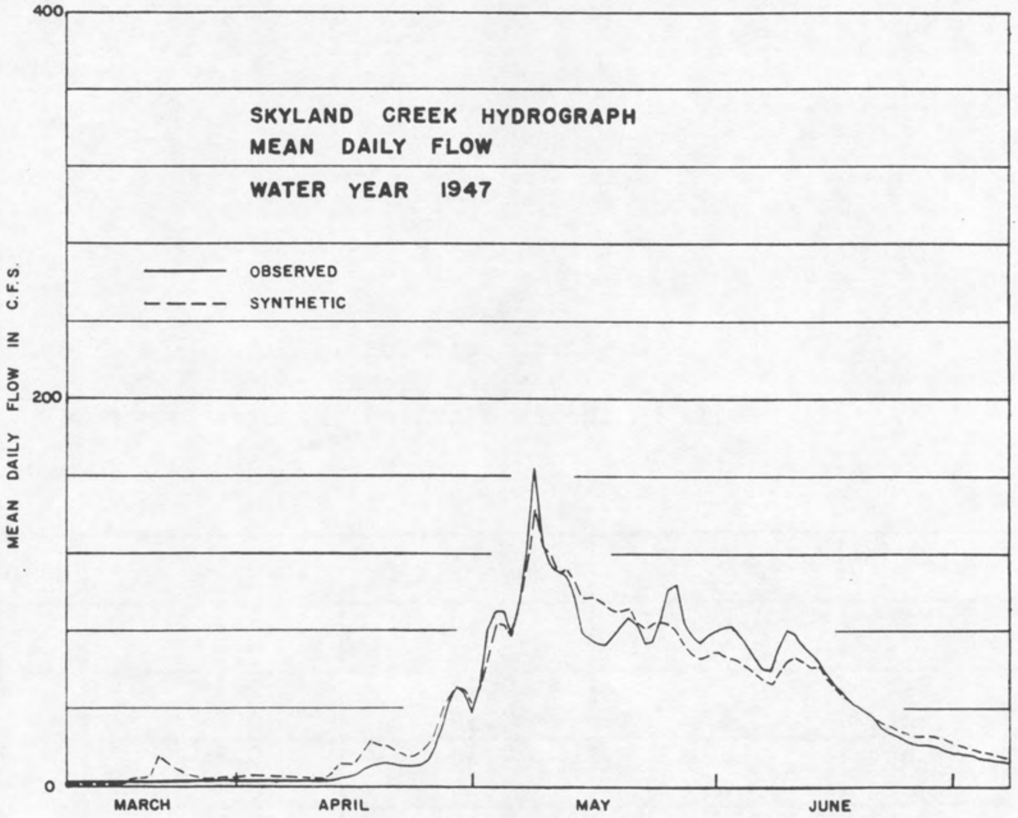

FIGURE 14

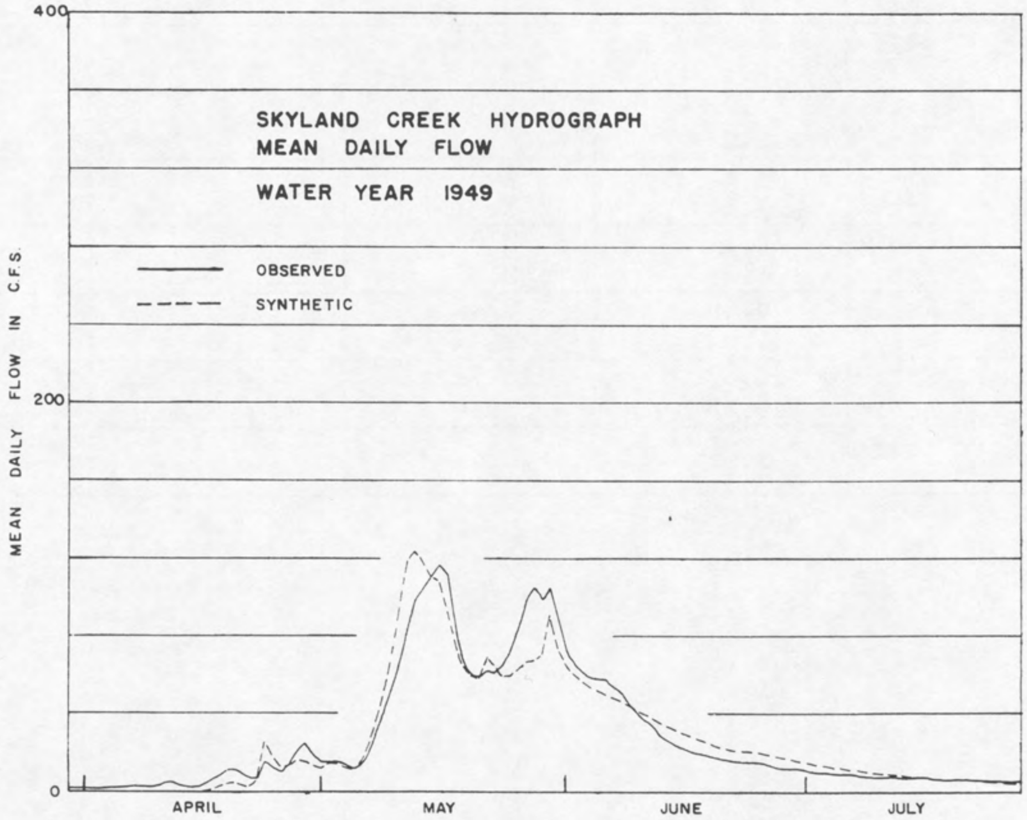

FIGURE 15

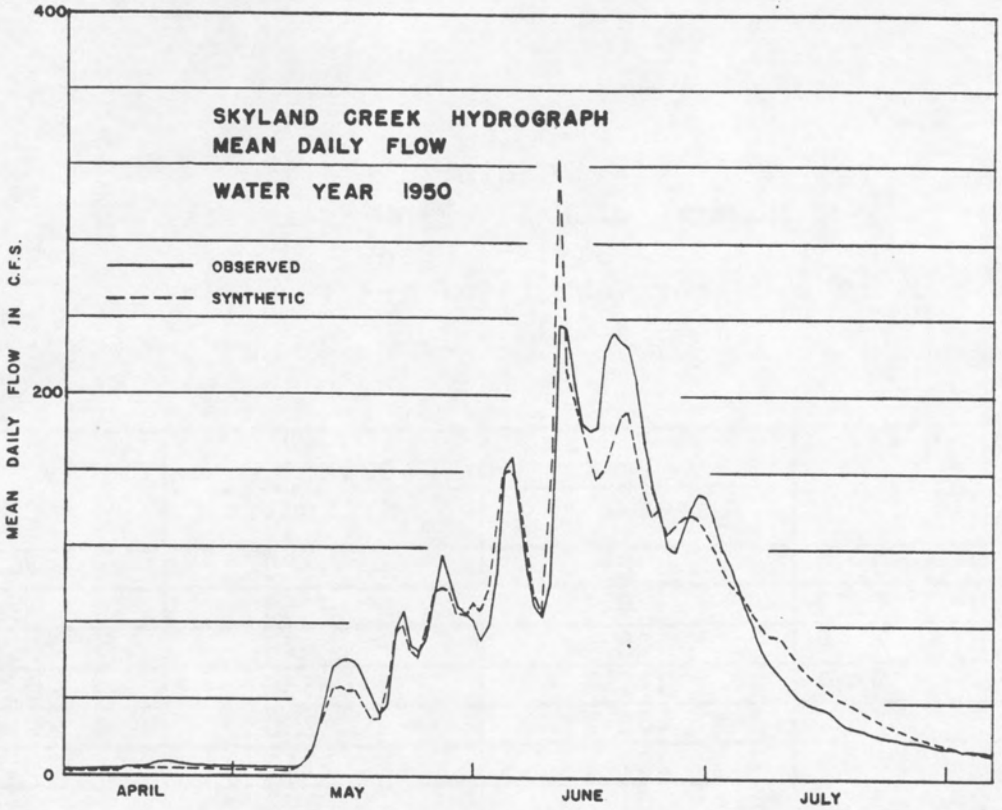

FIGURE 16

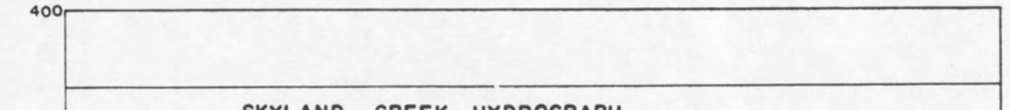

FIGURE 17

Table 4
Summary of Daily Flow Estimates
Skyland Creek
Water Years 1947 and 1949-51

Flow Interval CFS	Number of Days		Av. Error CFS
	Observed	Synthetic	
0.0- 0.99	0	80	---
1.0- 1.59	0	69	---
1.6- 2.69	28	78	0.90
2.7- 4.49	372	366	-0.72
4.5- 7.39	402	290	-0.63
7.4- 12.19	282	145	0.00
12.2- 20.09	101	121	0.59
20.1- 33.09	47	74	2.41
33.1- 54.59	46	58	5.20
54.6- 89.99	100	95	-0.89
90.0- 148.39	62	66	-1.65
148.4- 244.69	20	18	-18.3
244.7- 403.39	0	0	---

Daily Correlation Coefficients

Water Year	1946-47	1948-49	1949-50	1950-51
Correlation Coefficient	0.982	0.970	0.980	0.952

and synthetic hydrographs of the snowmelt season for this watershed. A degree-hour factor of 0.0037 inch per °F in conjunction with a base temperature of 32°F was used. The daily flow estimates are summarized in table 4 along with the daily correlation coefficients. The general improvement in the synthesis of the snowmelt hydrographs for Skyland Creek over those for Upper Castle Creek can most likely be attributed to the increased importance of longwave radiation, which is closely related to air temperature, in the snowmelt process due to the relatively dense forest cover in this watershed. The net forest cover of the Skyland Creek drainage is approximately 70 percent while the Upper Castle Creek drainage has a net forest cover of 28 percent.

CONCLUSIONS

The basic purpose of this study is to determine the feasibility of modeling the snow accumulation and runoff process of a watershed on a digital computer. On the basis of the results obtained on Upper Castle Creek and Skyland Creek, the following conclusions concerning the success of the subroutine to reproduce observed snowmelt runoff hydrographs are warranted:

1. Ambient air temperature is a relatively good indicator of upper layer snowmelt. There are some periods when air temperature does not provide a reasonable index to the snowmelt process; however, in general, a satisfactory estimate of upper layer melt can be made. It can also be concluded that the ability of an air temperature index to calculate upper layer melt improves with an increased amount of forest cover.
2. The subroutine can reproduce annual and monthly snowmelt runoff volumes with reasonable accuracy.
3. The frequency distribution of daily flows produced by the subroutine is quite good. Errors in computed daily flows are to some extent random, hence tend to compensate when the data are presented in the form of a frequency distribution.

The generally good success of the subroutine in the reproduction of actual streamflow from snowmelt suggests that it is at least a good approximation to the behavior of the prototype watersheds and that it can be used in exploratory investigations of the basic physical processes. Further extensions to the study should not only try to improve the methods, but should determine how widely such a procedure is applicable. Some possible future extensions are:

1. The areas on which the subroutine has been tested up to this point are fairly limited. Additional testing should be performed on watersheds with different forest cover configurations, elevation ranges, and climatological conditions. More testing is especially needed on watersheds with light or occasional snow cover. Such tests should determine if the subroutine is generally applicable or if additional modifications are needed.
2. Testing the subroutine on large basins would have more engineering applications than the size of watershed which was tested, but this would not appear to offer any additional information on the snowmelt process.
3. Frozen ground has not been considered in this study because cases of its existence were not encountered. To make the subroutine applicable in all climatic areas, cases where rain or snowmelt on frozen ground are known to exist should be tested and procedures developed to handle this phenomenon.

4. The determination of whether the use of additional meteorological data such as shortwave radiation, dew point temperature, or wind speed would cause a significant improvement in the calculation of melt over that calculated using ambient air temperature as the sole index.

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