ANALYSIS OF THREE RAIN ON SNOW FLOODS IN THE SIERRA NEVADA, CALIFORNIA

by

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During a flood study, we had an opportunity to use observed precipitation, temperature, radiation and wind data in our attempts to reconstitute historic flood flow hydrographs. This paper describes our use of such data for analysis of three floods -- January-February 1963, December 1964 and February 1982.

BASIN DESCRIPTION

The study basins are shown on Figure 1 and are sub-basins of the American River drainage in the Sierra Nevada Range of California. Basin elevations range from under 300 m[2] to nearly 3000 m and average annual precipitation is between 1000 and 2000 mm. Figure 1 shows areal distribution of average annual precipitation. Figure 2 presents topographic, precipitation and snow data for the study basins.

Snowpack and basin snow covered area varies significantly from storm to storm. The least pre-storm snowpack studied had only about 10 cm of snow water content at the 2440 m (8000 ft.)[2] elevation and the greatest had about 33 cm of snow water content at an elevation of 1525 m (5000 ft.), with much more snow at higher elevations.

CLIMATOLOGICAL DATA SOURCES

Daily precipitation data are provided by 16 stations. Three of these lie within the study basin. Hourly precipitation data are provided by eight stations. Four of these lie within the study basins.

Blue Canyon at an elevation of 1610 m (5280 ft.) lies on the northern boundary of the North Fork basin (see Figure 1). Data available for the storm studies are as follows:

1963: Hourly precipitation, daily maximum and minimum air temperatures, daily snowfall and daily snow on ground.

1964: Maximum and minimum daily temperatures, hourly precipitation, hourly air temperature, daily snowfall and daily snow on ground.

1982: Hourly precipitation, three-hour values for air temperature, dewpoint temperature, sky cover and wind, daily snowfall and daily snow on ground.

The U.S. Forest Service Central Sierra Snow Laboratory at Soda Springs at an elevation of 2100 m (6685 ft.) lies about three kilometers outside the northeastern boundary of the North Fork basin (see Figure 1). Data available for the storm studies are as follows:

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2/ Metric units are used throughout this paper. Occasionally English equivalents are noted where they may aid understanding.

1963: Daily snowfall and snow on ground.

1964: Daily precipitation, snowfall and snow on ground.

1982: Hourly radiation, hourly dewpoint temperature, daily snowfall and daily snow on ground.

Oakland 4 a.m. and 4 p.m. sounding data were available for the 1963 and 1964 storms.

Snowpack data in addition to that mentioned for Blue Canyon and Soda Springs were available weekly during 1982 from seven sensors in the area. Also, daily snowfall and snow on ground data were available for Bowman Dam at an elevation of 1635 m.

REDUCTION OF CLIMATOLOGICAL DATA

Data available for 1982 were much more comprehensive than data for earlier storms. Even 1982 had periods with missing or erroneous data. Figure 3 indicates sources used and data reduction required to develop hourly temperature, wind and radiation data.

Hourly precipitation indices were computed for each storm.

Wind speed during 1963 and 1964 storms was arbitrarily set at 12.87 km/hr. During the 1982 storm, wind was based upon 3-hour observations at Blue Canyon.

Air temperature at an elevation of 1610 m (5280 ft.) was estimated for each storm hour. During 1963 and 1964, a "typical" diurnal fluctuation (tempered with "judgement" based primarily on precipitation and Oakland sounding freezing elevations) was applied to recorded maximum and minimum Blue Canyon temperatures. Some 1964 hourly data were available for Blue Canyon. The 1982 air temperature data were estimated using 3-hour Blue Canyon data.

Air temperatures at elevations other than 1610 m were first estimated by applying a lapse rate of 6.4^{o} per 1000 m. This lapse rate appeared to work reasonably well for portions of the basins that were lower than 1610 m. However, high elevations appeared to require a lower lapse rate. The air temperature seemed to drop at no more than 3.5^{o} per 1000 m between 1610 m and 2000 m elevations. Above 2000 m, the 6.4^{o} lapse rate produced reasonable results. These observations are based upon apparent snowpack response and a comparison of dewpoint temperatures discussed later. Part of the problem may be due to Blue Canyon's location at the upwind end of a ridge. Its temperature may be representative of somewhat higher elevations.

When lapse rates produced a calculated air temperature lower than dewpoint temperature, air temperature was set equal to dewpoint temperature.

Dewpoint temperature at an elevation of 1610 m (5280 ft.) was estimated for each storm hour.

During 1963 and 1964 storms, no dewpoint data were available. Review of Blue Canyon storm data for other storms indicated a typical relationship between air temperature and dewpoint temperature ranges from little or no difference during significant precipitation to as much as three or more degrees during periods without precipitation. Using this somewhat subjective approach, 1963 and 1964 precipitation and air temperatures were used to estimate storm dewpoint temperature.

The 1982 dewpoint temperatures were estimated using 3-hour dewpoint temperatures at Blue Canyon and hourly dewpoint temperatures at Soda Springs. (Central Sierra

Snow Lab.).

Dewpoint temperatures at elevations other than 1610 m were first estimated by applying a lapse rate of 4.56° per 1000 m. As with air temperature, this lapse rate appeared to work reasonably well for portions of the basins that were lower than 1610 m. Higher elevations seemed to have a lower lapse rate.

Figure 4 shows a comparison of storm dewpoint temperatures at Blue Canyon (1610 m or 5280 ft.) and the Central Sierra Snow Lab (2100 m or 6885 ft.). Noted on the figure are lines representing lapse rates of 4.6°, 2.3° and 0.0° per 1000 m. This figure indicates that dewpoint lapse rate between Blue Canyon and 300 to 400 m higher may typically be less than half of 4.56° per 1000 m.

Above 2000 m, the expected lapse rate produced reasonable results.

Hourly solar radiation was estimated for each storm. No radiation data were available for the 1963 or 1964 storms. Using (1) clear sky radiation appropriate for the location and time of year and (2) hourly precipitation, hourly values of radiation were estimated.

Radiation data collected by the Central Sierra Snow Lab during the February 1982 storm were used.

Pre-storm snowpack was based upon available pre-storm data and typical variation in pack over each study basin. Each study basin was divided into sub-basins and a pre-storm snowpack was estimated for each sub-basin.

RUNOFF CALCULATION METHOD

In 1945, C. O. Clark prepared an ASCE paper entitled "Storage and the Unit Graph". This paper presented a method for estimating routing characteristics of a drainage basin and calculating a unit hydrograph using those routing characteristics.

Clark's procedure involved separation of a basin into sub-basins progressing upstream from the basin discharge site with each sub-basin having the same incremental lag time. By routing runoff contribution from each sub-basin through a linear reservoir and aggregating resulting flow at the discharge site, a hydrograph is calculated.

Historic floods in the study area are characterized by large areas that contribute little or no runoff during a storm because snowpack accumulates. As temperature and snowpack conditions change during a storm, the snowline and snowmelt area may change. During a storm, contributing area may vary between 30 and 100 per cent of the basin.

Runoff can be based upon each sub-basin's particular snowpack, precipitation and loss characteristics and then routed to the discharge point.

SNOW ACCUMULATION AND MELT CALCULATION METHOD

The snow analysis procedures are basically those developed by the U.S. Army, Corps of Engineers, presented in their 1956 "Snow Hydrology" and "Runoff From Snowmelt" manual. The basic equation used is presented by Figure 5. This equation is written in English units for easy comparison to the USCE documents.

Albedo is calculated as part of the analysis procedure. It is based upon a snowpack ageing factor plus modification by fresh snowfall or rainfall on the snowpack.

Dewpoint temperatures lower than 0° were assumed to produce snow, dewpoint temperatures greater than 1.11° were assumed to produce rain, and dewpoint temperatures between 0 and 1.11° were considered to produce a 50-50 mix of snow and rain.

A snowpack cold content was used to handle the snowpack priming problem. Cold content is expressed in inches[3/] of 0° frozen water and represents the total heat that would be required to fully melt the pack. As long as cold content exceeds pack water content no snowmelt occurs. Rain, when air temperature exceeds 1.11°, is allowed to pass through the pack and produce runoff even when pack cold content exceeds water content.

Under major warm storm conditions, much snowmelt occurs near the snow surface where snow is exposed to warm air and rain and must travel through the snowpack before runoff occurs. Snowpack delay on melt and rain runoff was incorporated using a lag and routing approach related to snow depth.

LOSS CALCULATION PROCEDURE

Losses were calculated for each hour and each sub-basin. Losses were composed of two components. One component is constant at 0.1 cm per hour for all basins. The second component was variable, being a function of both antecedent conditions and each hour's rainfall and snowmelt. After losses were calculated, some loss was permanently removed from the hydrologic balance while the remainder was routed through a "reservoir" with an 18 to 24 hour transit time.

PROCEDURE SUMMARY

Calculation of rain-on-snow flood flows involved the following:

1. Division of each basin into several sub-basins based upon distance from the stream discharge location for which the flood calculation was being made.
2. Determination of hourly values of precipitation, air temperature, dewpoint temperature, wind, and solar radiation for each sub-basin.
3. Calculation of hourly snowpack condition, including snowmelt or snow accumulation, for each sub-basin.
4. Calculation of hourly precipitation and snowmelt losses for each sub-basin.
5. Calculated hourly values of precipitation and snowmelt excess were routed from each sub-basin to the stream discharge location.

Figure 2 presents basin characteristics and initial snowpack for each basin investigated.

JANUARY-FEBRUARY 1963 STORM

Before the storm, on January 27, snowpack was light and the snowline was over 1830 m. Storminess on January 28 and 29 dropped the snowline to about 1525 m and put a few centimeters of snow on the ground.

A major storm began late in the day on January 29 and continued through February first. Storm temperatures at Blue Canyon ranged from 1.1° to 8.9°. At 1.1° snow falls

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3/ Calculations were conducted using English units. Conversion to SI has been made in this paper.

over about one-half of the North Fork basin and all of the Rubicon Springs basin. At 8.9° both basins receive only rain.

Figure 6 presents a summary of results from the analysis. It shows Blue Canyon precipitation and temperature, sub-basin snowpack water content and flood hydrographs for the North Fork and Rubicon. This figure indicates the increase in snowpack water content occurring at higher elevations during the early part of the storm followed by melt as temperatures warmed and the snowpack became fully primed.

DECEMBER 1964 STORM

The December 1964 storm produced a multi-peaked flood hydrograph. While multi-peaked hydrographs are often broken into separate hydrographs and each reproduced individually, no hydrograph separation was used in this work. Figure 7 presents a summary of results from the analysis.

FEBRUARY 1982 STORM

The February 1982 storm did not produce flood flows as great as either of the 1963 or 1964 storms. In addition, pre-storm basin snow cover was much heavier. The two Rubicon River basins maintained a significant snowpack throughout the entire storm. Figure 8 presents a summary of results from the analysis.

GENERAL COMMENTS

Analysis and flood hydrograph reproduction attempts shown on Figure 6, 7, and 8 all do a good job in reproducing observed hydrographs. They all indicate some difficulty during the initial period of increasing flow. This is partially due to lack of knowledge regarding the initial quantity and priming of the snowpack. Once the pack becomes fully primed, reproduction is generally good.

The studies indicated that it is necessary to have fairly accurate hourly dewpoint temperature and radiation data. If air temperature and precipitation are known, dewpoint temperature can be reasonably estimated. Radiation can be reasonably estimated during a major storm, but it is much more difficult under partly cloudy conditions.

SENSITIVITY

Figure 9 shows a test of procedure sensitivity to snowpack factors. The February 1982 flood inflow to Hell Hole Reservoir was calculated under two alternative assumptions. First, snowpack influence was removed from the analysis and runoff was calculated directly from precipitation, assuming it to be entirely rainfall. Second, the 1610 m (5280 ft.) dewpoint temperature was reduced two degrees (3.6°F), producing substantially more snowfall and less snowmelt.

Both alternative assumptions produce smaller peak flows. The rainfall only analysis has greater flows early in the storm because snowfall and snowpack priming were removed from the analysis. The analysis with colder temperatures reduced all flows because snowfall was increased and snowpack priming was delayed.

ACKNOWLEDGEMENTS

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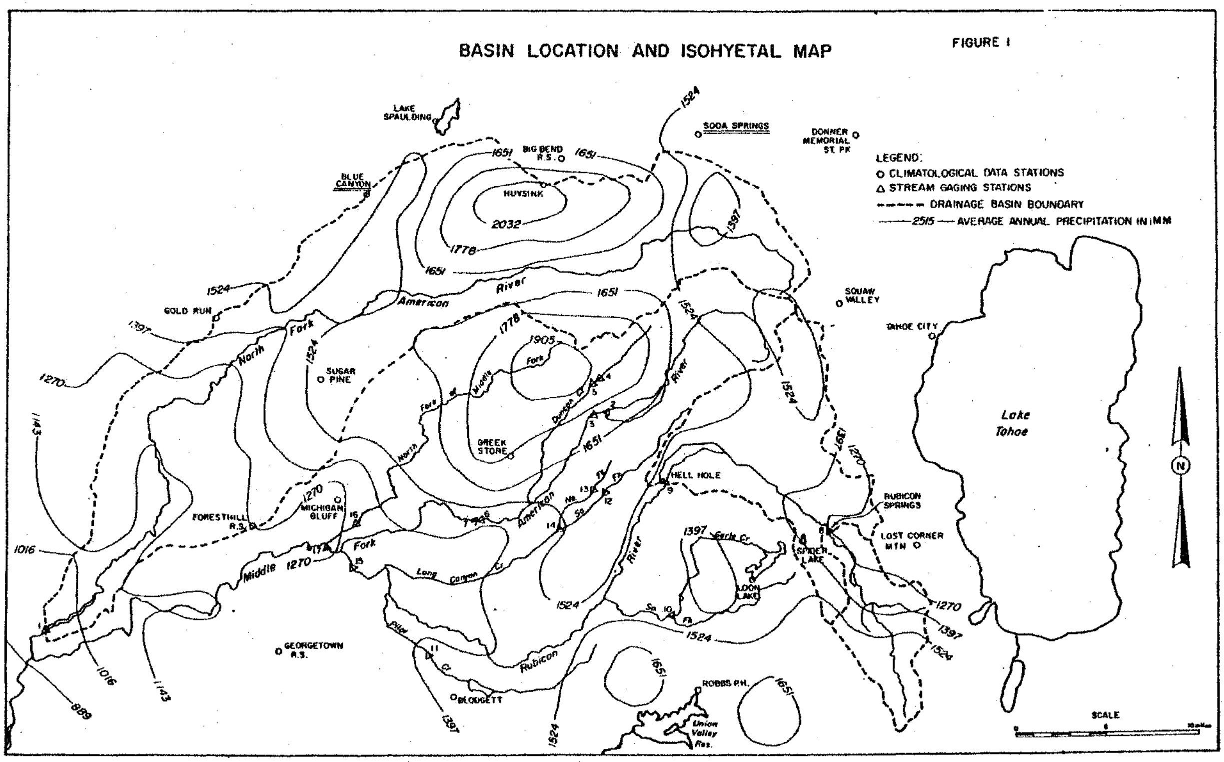

BASIN LOCATION AND ISOHYETAL MAP

Sub-Basin No.	Average Annual Precipitation (mm)	Sub-Basin Area (Sq. km.)	Elevation Range (m)	Representative Elevation (m)	Storm Change in Snowpack Water Content					
					Jan-Feb 1963		December 1964		February 1982	
					Start (cm)	End (cm)	Start (cm)	End (cm)	Start (cm)	End (cm)
North Fork American River at North Fork Dam										
1	1143	57.5	210- 730	490	0	0	0	0	0	0
2	1270	148.4	275-1130	775	0	0	0	0	0	0
3	1448	147.1	300-1370	1020	0	0	0	0	0	0
4	1600	133.9	365-1525	1190	0	0	2.5	0	5.1	0
5	1753	166.5	610-2010	1625	3.6	0	3.8	0	33.0	27.9
6	1829	127.4	850-2285	1880	6.4	7.6	25.4	19.0	45.7	43.2
7	1499	69.7	1060-2500	1990	8.1	10.9	45.7	43.7	63.5	61.7
8	1549	35.2	1460-2750	2265	10.9	16.5	53.3	56.4	71.1	77.2
Rubicon River at Rubicon Springs										
1	1448	18.6	1825-2680	1830	7.6	0.5	-	-	53.3	49.3
2	1905	42.5	2100-2800	2195	8.9	14.2	-	-	63.5	64.8
3	2108	20.2	2250-3050	2410	9.9	19.3	-	-	71.1	86.1
Rubicon River above Hell Hole Reservoir										
1	1448	77.2	1400-2350	1675	-	-	-	-	38.1	32.5
2	1448	97.6	1700-2620	1920	-	-	-	-	45.7	42.4
3	1549	57.8	1825-2740	2010	-	-	-	-	53.3	51.8
4	1905	42.5	2100-2800	2200	-	-	-	-	63.5	66.0
5	2108	20.2	2250-3050	2410	-	-	-	-	71.1	86.1

Figure 2

SOURCES AND REDUCTION REQUIRED TO
DEVELOP HOURLY CLIMATOLOGICAL DATA

	January-February 1963	December 1964	February 1982
Air Temperature	Max-Mins & 2-Soundings/day	Max-Mins, 2-Soundings/day & some hourly	3-hour observations
Dewpoint Temperature	Adjusted Air Temperature	Adjusted Air Temperature	3-hour observations & hourly CSSL
Wind	8 mph	8 mph	3-hour observations
Radiation	Based on precip.	Based on precip.	hourly CSSL

Figure 3

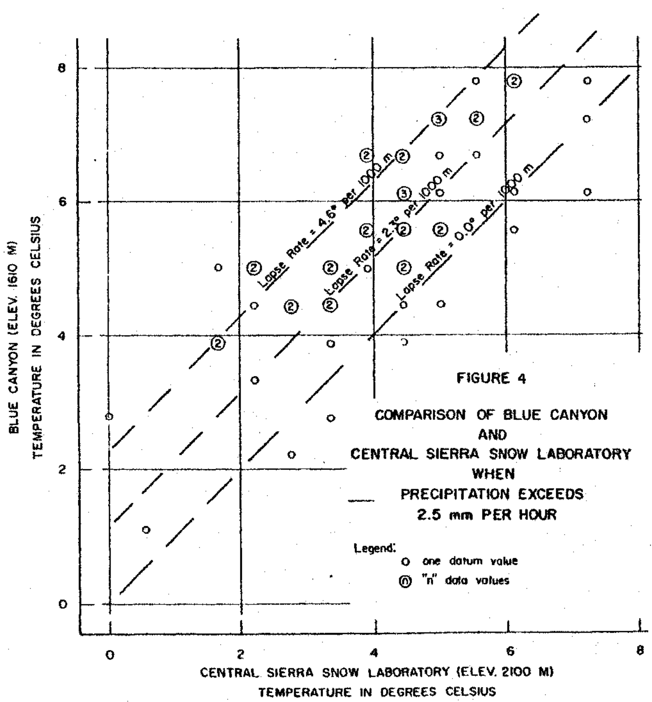

FIGURE 4

COMPARISON OF BLUE CANYON AND CENTRAL SIERRA SNOW LABORATORY WHEN PRECIPITATION EXCEEDS 2.5 mm PER HOUR

Figure 5

SNOWPACK HEAT EXCHANGE EQUATION

$$\text{Melt} = k'(1-F)(0.0041)(1-a) + k(.0084V)(.22Ta + .78Td) + F(.0029Ta) + 0.007(Pr)(Ta)$$

Where:

- Melt = snowmelt in inches per day
- k' = radiation melt factor (set as 1.0)
- F = effective shade provided by forest (set as 0.4)
- I = solar radiation in Langleys per day
- a = snowpack albedo
- k = convection-condensation melt factor (set as 1.0)
- V = wind speed 50 feet above snow in miles per hour
- Ta = air temperature less snow surface temperature in ^{o}F (snow set as 32^{o}F)
- Td = dewpoint temperature less snow surface temperature in ^{o}F (snow set as 32^{o}F)
- Pr = rainfall in inches

Equation combines Equations 18 and 24 in USCE Engineering and Design Manual, "Runoff From Snowmelt".

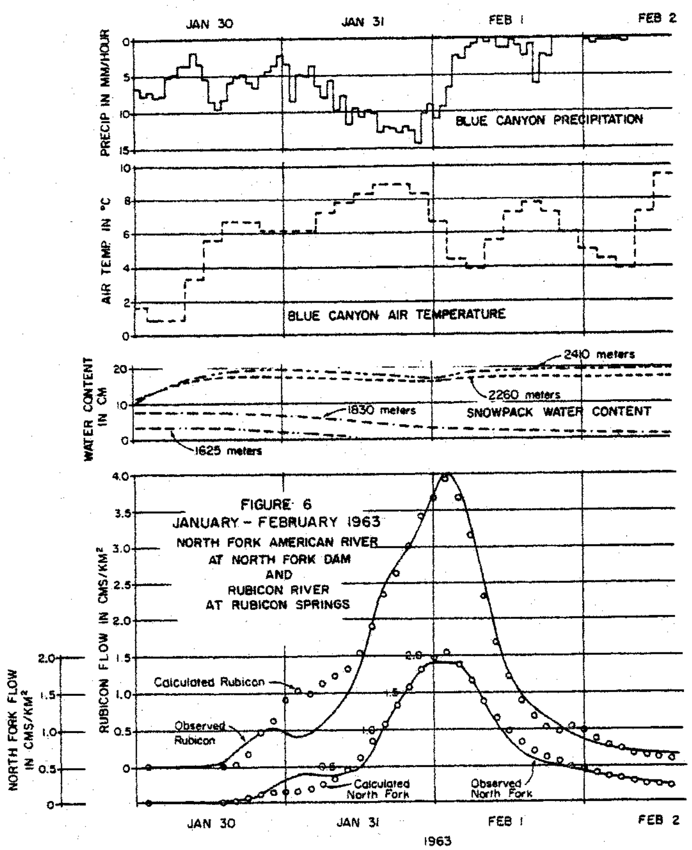
FIGURE 6
JANUARY - FEBRUARY 1963
NORTH FORK AMERICAN RIVER
AT NORTH FORK DAM
AND
RUBICON RIVER
AT RUBICON SPRINGS
JAN 30
JAN 31
FEB 1
FEB 2
PRECIP IN MM/HOUR
BLUE CANYON PRECIPITATION
AIR TEMP IN °C
BLUE CANYON AIR TEMPERATURE
WATER CONTENT IN CM
SNOWPACK WATER CONTENT
2410 meters
2260 meters
1830 meters
1625 meters
RUBICON FLOW IN CMS/KM²
NORTH FORK FLOW IN CMS/KM²
Calculated Rubicon
Observed Rubicon
Calculated North Fork
Observed North Fork
1963

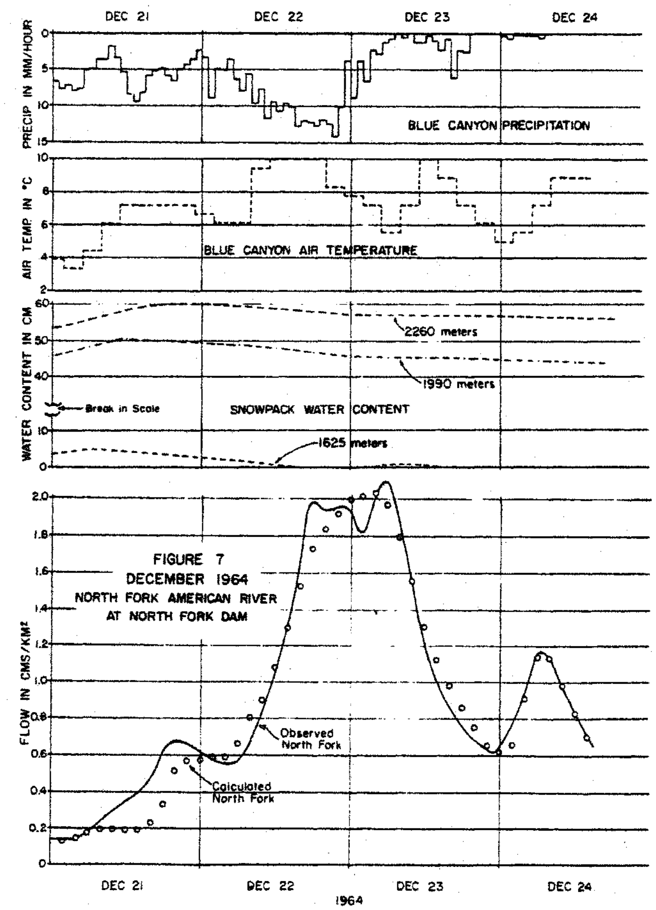
FIGURE 7
DECEMBER 1964
NORTH FORK AMERICAN RIVER
AT NORTH FORK DAM
DEC 21
DEC 22
DEC 23
DEC 24
PRECIP IN MM/HOUR
BLUE CANYON PRECIPITATION
AIR TEMP IN °C
BLUE CANYON AIR TEMPERATURE
WATER CONTENT IN CM
SNOWPACK WATER CONTENT
2260 meters
1990 meters
1625 meters
Break in Scale
FLOW IN CMS/KM²
Observed North Fork
Calculated North Fork
1964

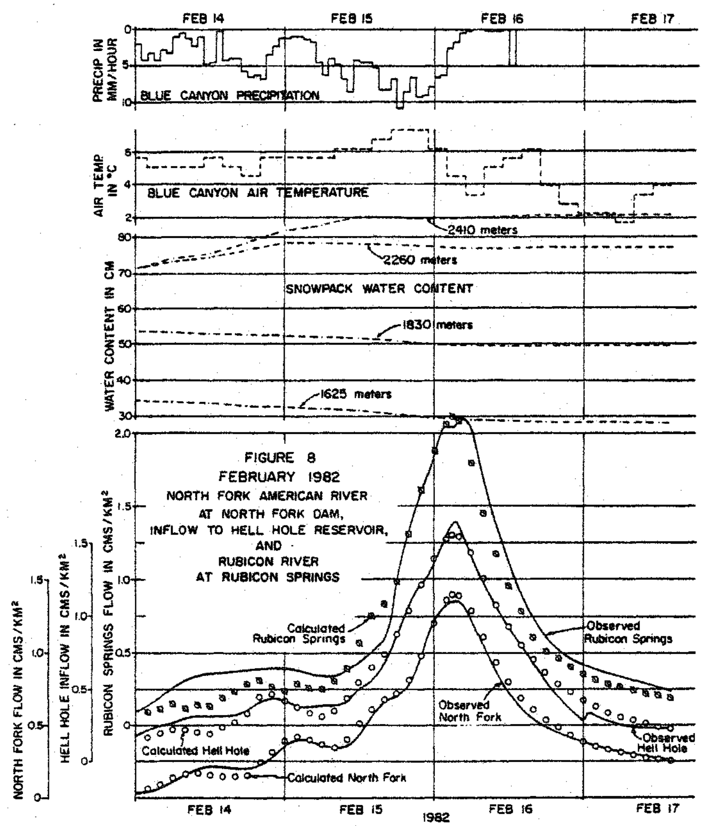

FIGURE 8
FEBRUARY 1982
NORTH FORK AMERICAN RIVER AT NORTH FORK DAM, INFLOW TO HELL HOLE RESERVOIR, AND RUBICON RIVER AT RUBICON SPRINGS

FIGURE 9
SENSITIVITY TEST
FEBRUARY 1982 FLOOD
INFLOW TO HELL HOLE RESERVOIR