ANALYSIS OF 1983 SNOWMELT RUNOFF PRODUCTION IN THE UPPER COLORADO RIVER BASIN

by

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INTRODUCTION

Spring and summer streamflow for 1983 was extraordinarily high in several areas of the Western United States and exceeded predictions of operational forecasters by substantial margins. The upper Colorado and Platte River basins as well as watersheds in the Wasatch Mountains of Utah were among areas where an unexpectedly high runoff occurred. Predictions made on May 1, 1983 at many forecast points in these areas were 30 to over 100 percent low. These underpredictions were widely distributed among the forecast points indicating a systematic cause for the errors. The magnitude of these deviations was very uncharacteristic of what previous experience and error evaluations of past forecast performance indicated was reasonable.

Due to uncertainties concerning the reasons for such widespread forecast errors, a detailed analysis was merited. This study is an attempt to sort out which factors acting either singly or in a synergistic fashion were most responsible for the heavy runoff in 1983. Analysis was made for the Colorado River basin above Lake Powell (Figure 1). However, the authors feel that the conclusions reached in this study are applicable to several other basins that experienced similar events during the 1983 runoff season.

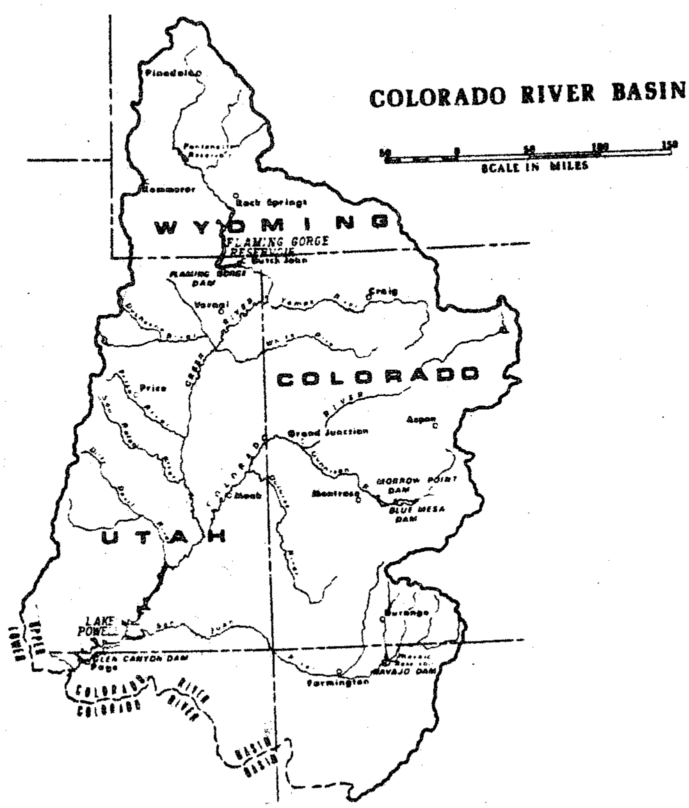

Figure 1. Colorado River Basin above Lake Powell.

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Data on snow water equivalent, seasonal and annual precipitation, snow areal extent, ambient temperature, soil temperature, and soil moisture were evaluated. Examination of the influence of each of these variables gave a better understanding of the physical processes which interacted to produce the volume of runoff that occurred. The evaluation indicated that the predominant cause for the extremely heavy runoff was a combination of a moderately heavy snowpack that peaked at both high and low elevations late in the season, extensive snow covered area, and abnormally warm temperatures in late May that triggered melt at all elevations. Above normal low elevation precipitation in the May-August period was a contributing factor but of lesser significance.

RUNOFF

The Colorado River at Lee's Ferry, Arizona, was selected as a reference gaging station. This point is located 16 miles downstream from Glen Canyon Dam. Flow at this point is a good measure of the contributions of the entire upper Colorado basin. Figure 2 is a monthly hydrograph depicting virgin flow at Lee's Ferry. The magnitude of the 1983 runoff event is clearly shown. Virgin flow is a calculated figure that represents actual production of runoff in the basin above Lee's Ferry; it is the sum of observed flow plus changes in upstream reservoir storage and transmountain diversions. Figure 2 graphically illustrates two points: (1) the basin was in an abnormally wet condition at the beginning of the 1983 water year; and (2) June and July contributed the most to the abnormal nature of 1983 annual and seasonal runoff.

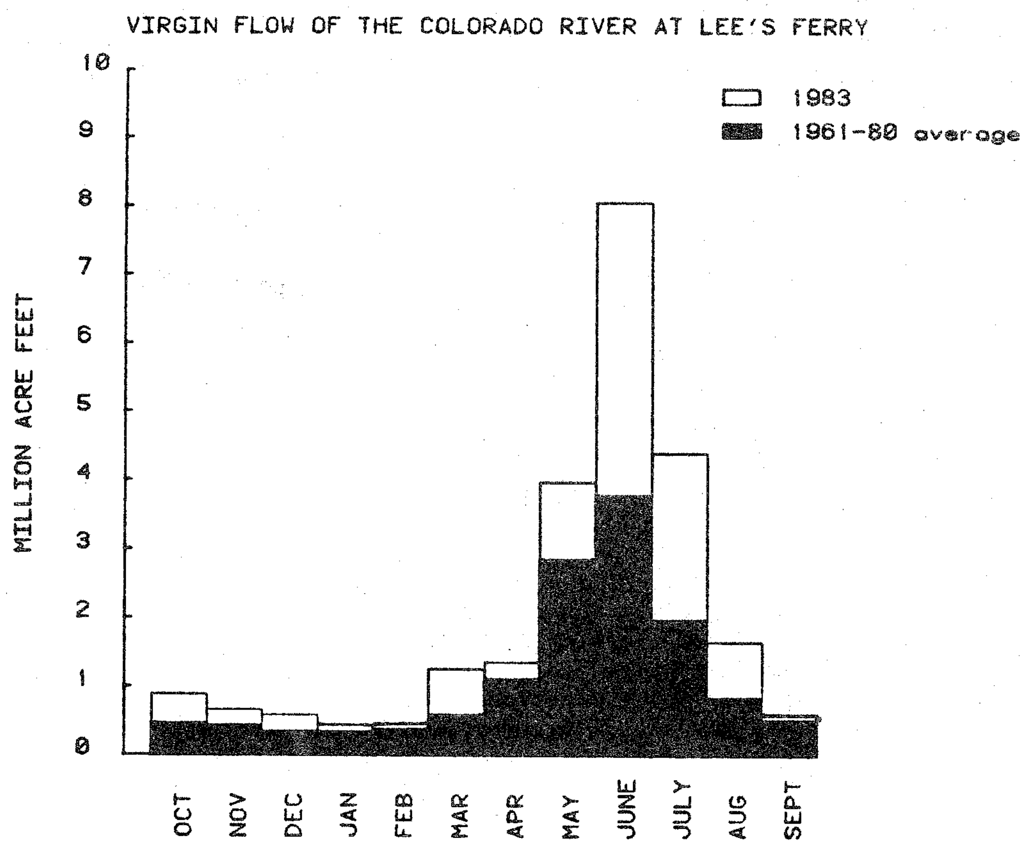

Figure 2. Monthly hydrograph of Colorado River at Lee's Ferry, Arizona, comparing the 1983 runoff to the 1961-80 average.

Frequency analyses were generated for April-September, June-July, and water year volumes based on data for 1906-1982 (Figure 3). Streamflow volumes for 1983 were then compared to fitted distributions. This analysis showed that the June-July flow was approximately a 200-year event, the water year volume a 100-year event, and the April-September volume a 33-year event. The exceptional flow for the June-July period is the most significant aspect of this analysis because it shows the extreme nature of the snowmelt runoff.

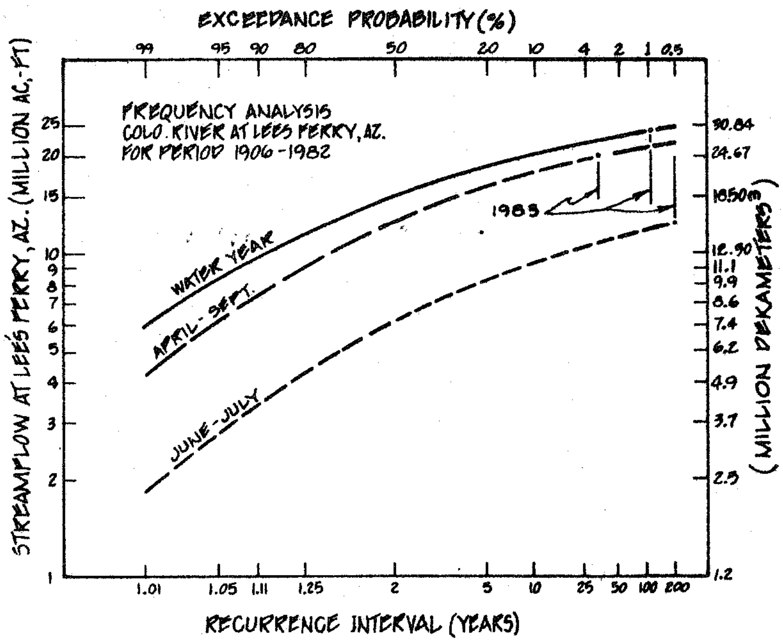

Figure 3. Frequency analysis showing relationship of 1983 virgin runoff volumes for April-Sept., June-July, and water year to historical records on the Colorado River at Lee's Ferry, Arizona.

PRECIPITATION ANALYSIS

A composite precipitation index comprised of monthly data from 11 low elevation precipitation stations distributed throughout the basin was constructed and graphed to portray what was happening below 8000 feet (2438 m) (Figure 4). Precipitation tended to be below average for the first 4 months of the year and then increased to well above normal in February through August. Total annual precipitation was only slightly above average, however.

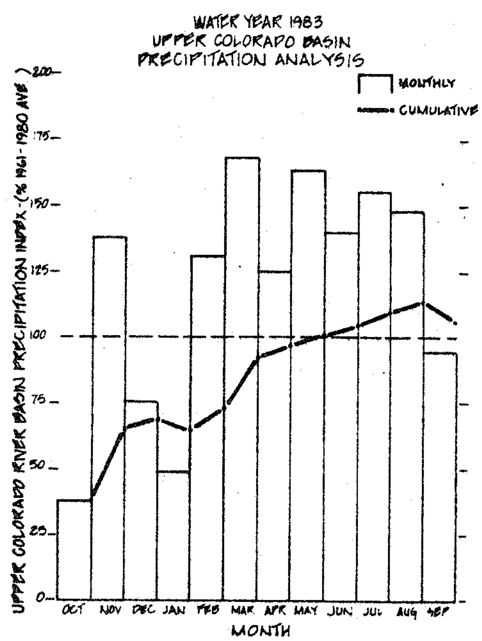

Figure 4. Upper Colorado precipitation index comprised of the following stations below 8000 ft (2438 m): Durango, Grand Junction, Grand Lake INW, Gunnison, Meeker, Steamboat Springs, Telluride, Dillon 1E in Colorado; Pinedale, Wy.; Ft. Duschesne and Green River in Utah.

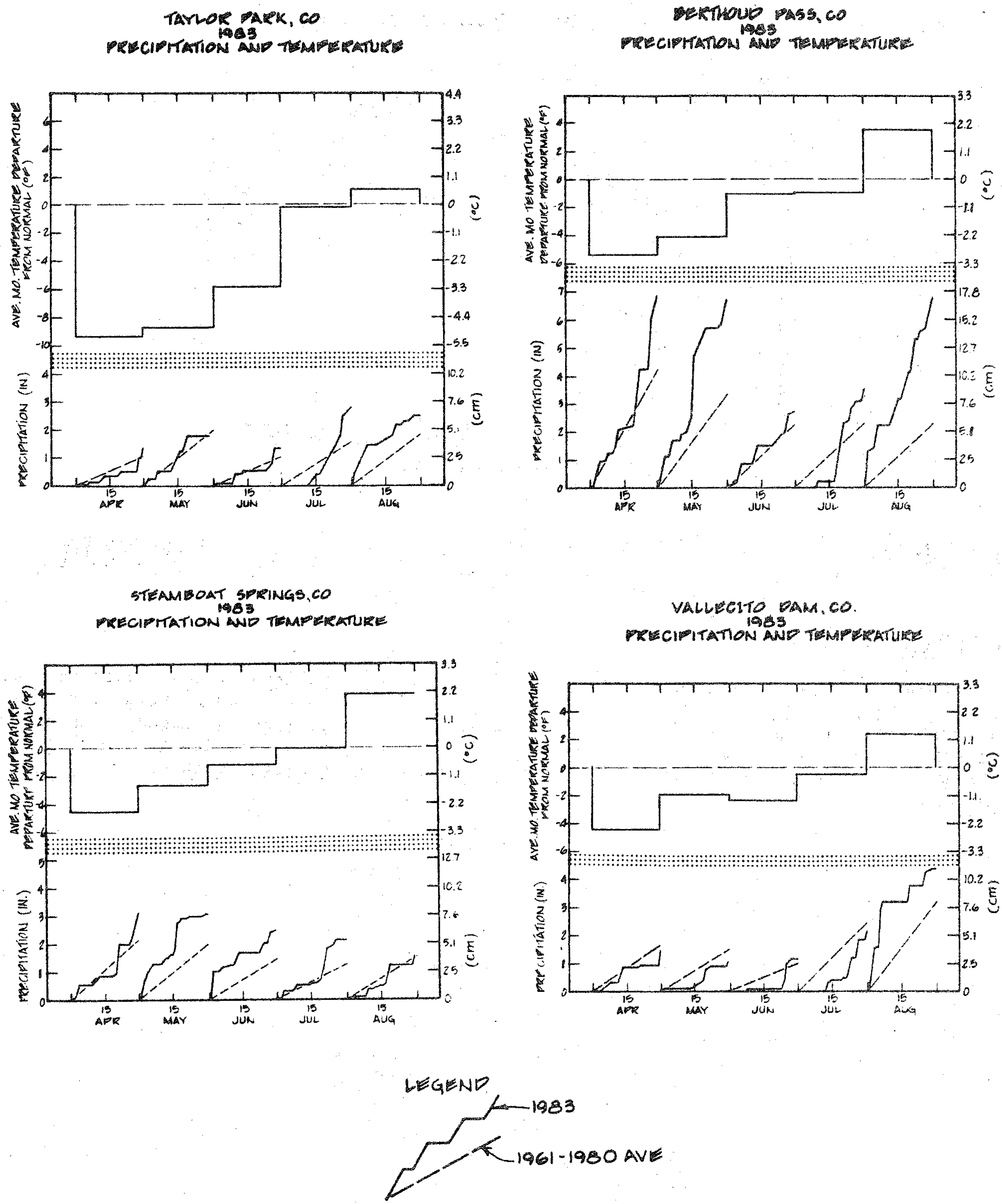

Figure 5. Mass curves of daily precipitation and mean monthly temperature departures from normal during spring and summer 1983 for Taylor Park (9206 ft.), Berthoud Pass (11,300 ft.), Steamboat Springs (6770 ft.) and Vallecito Dam (7650 ft.) in Colorado.

Examination of Figure 4 suggested a need for an in-depth analysis of the timing of precipitation occurring in the April-August period. The effects of temperature were also analyzed for this interval. Figure 5 shows for some key stations in the upper Colorado basin, mass curves of daily precipitation compared to average, and mean monthly departures from normal temperatures during April-August. These graphs clearly demonstrate that abnormally cold weather accompanied the heavy precipitation in the April-June period. Cold temperatures in April and May coupled with above normal precipitation generated a significant net increase in snowpack at elevations above 9000 feet (2743 m) and greatly retarded melt everywhere in the basin. Figure 5 also shows that precipitation during June was not heavy at all locations in the basin. Examination of precipitation amounts from a large number of additional stations revealed that highest percent positive departures from normal in June were generally confined to elevations below 8000 feet (2438 m); above 10,000 feet (3048 m) departures were markedly less extreme.

A method was needed to place in perspective the precipitation received in 1983 compared to historical records. Figure 6 shows results of a frequency analysis performed on a composite precipitation index made up of four headwaters stations having data for the 1909-1982 period. These stations were chosen because of their length and quality of record. Precipitation totals for the water year, October-April, and May-September periods were fitted to a frequency distribution. Data for 1983 were compared to the resulting curves. Recurrence intervals for 1983 precipitation for the water year, October-April, and May-September periods were 3.5, 1.9, and 4.4 years, respectively. The return interval for May-September demonstrates that although spring and summer precipitation was above normal at the index stations, it was far from record setting.

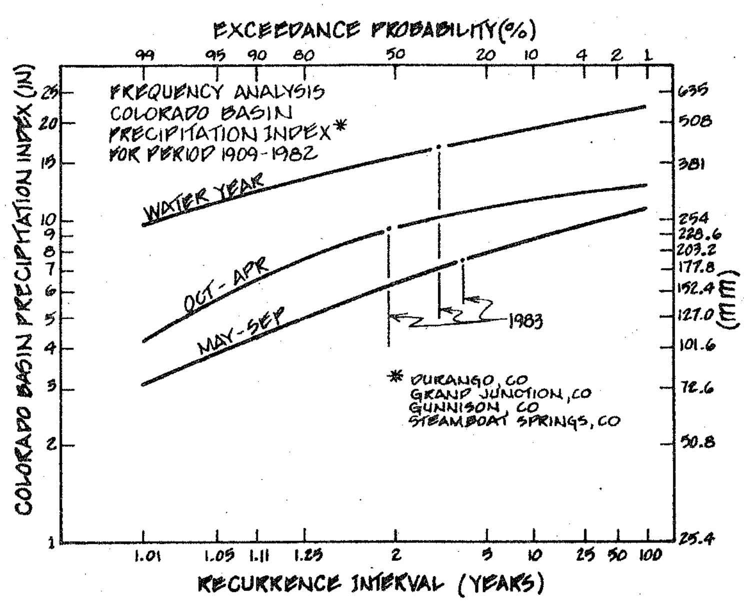

Figure 6. Frequency analysis showing relationship of 1983 precipitation computed from four index stations compared to historical records for the period 1909-1982.

SNOWPACK ANALYSIS

Snowmelt is normally the dominant source of runoff in the Colorado basin. Figure 7 illustrates mountain snowpack conditions in the Colorado basin within the state of Colorado during 1983. Snowpack percentages were calculated from 149 snow course readings near the first of each month February through May. Percentages for January 1, May 15, and June 1 are estimates derived from approximately 20 snow courses located at relatively high elevations on mountain passes. Snowpack conditions were not unusual until May 15 and June 1 readings, at which time they climbed dramatically.

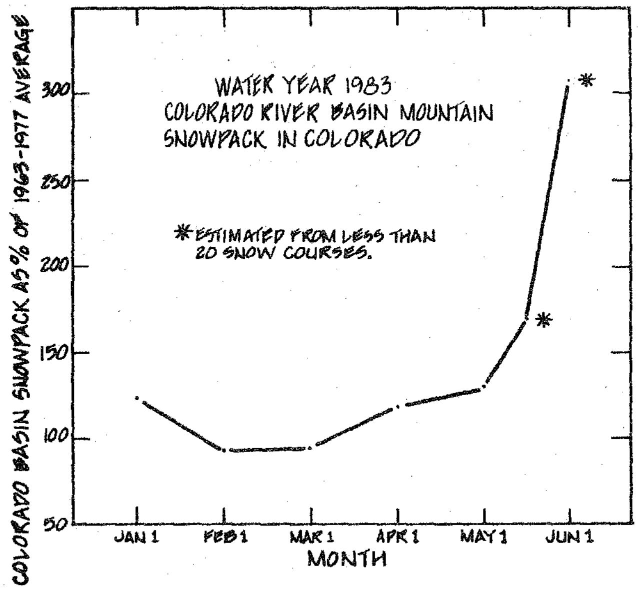

Figure 7. Mountain snowpack index for the Colorado River basin in Colorado during 1983.

To aid in interpreting the significance of the May 15 and June 1 data, a frequency analysis was performed on a snowpack index comprised of data from 6 snow courses with records available for the 1955-1982 period (Figure 8). Data for 1983 were then compared to the fitted distribution. Recurrence intervals of 5 and 23 years were computed for May 15 and June 1 data, respectively. These figures indicate that the late season snowpack was high as a consequence of unseasonably cold temperatures inhibiting melt and continual snowfall, but not radically higher than historical extremes represented by the index during the past twenty-eight years.

Daily snow water equivalent records from SNOTEL sites in the basin were compared to data for 1979 through 1982. Figure 9 depicts snow pillow hydrographs for three SNOTEL sites in Colorado for 1979 through 1983. Elevations of these three sites range from 9300 feet (2835 m) at Columbine to 11,300 feet (3444 m) at Berthoud Summit. These sites were selected to be representative of conditions throughout the basin and were verified by 72 additional sites.

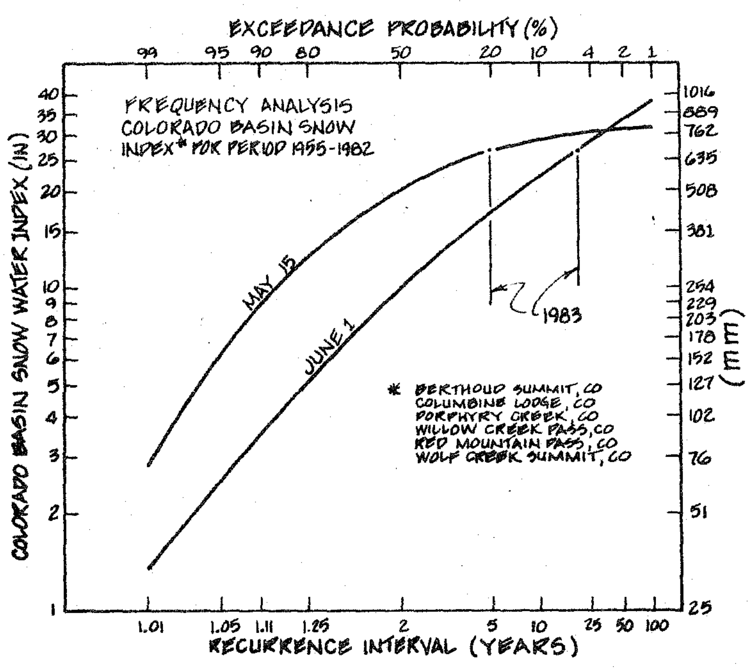

Figure 8. Frequency analysis showing relationship of 1983 late season snow pack to historical records for the period 1955-1982.

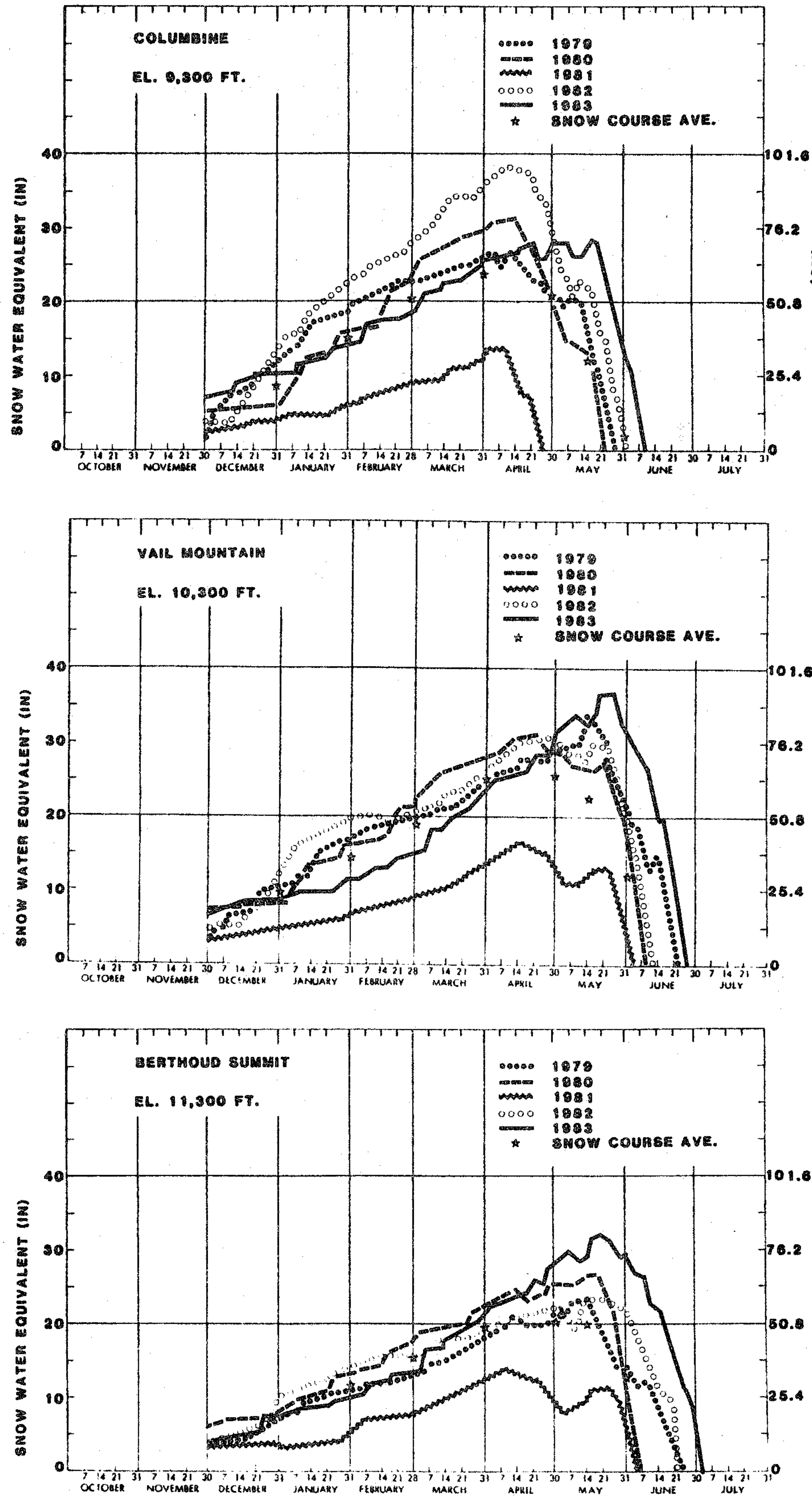

Figure 9. SNOTEL snow pillow hydrographs for three selected sites in Colorado for 1979-1983 showing effects of a drastically altered melt season in 1983. Particularly noteworthy is the simultaneous peaking of seasonal water equivalent from low to high elevations and sudden melt commencing May 21.

Compared to SNOTEL data and snow course averages for co-located snow courses for the previous 4 years, 1983 was different in two important respects. Snowpack at relatively low elevations near 9000 ft (2835 m) did not enter a normal melt phase near mid-April; instead, snowpack continued to increase for another five weeks into the third week of May. At higher elevations, the snowpack also continued to increase for three weeks after the first of May when melt normally commences. As a result, low, middle, and high elevations in the basin reached the apex of their seasonal snowpack accumulation at very nearly the same time.

This situation prevailed until May 21. By this date, snowpacks at both low and mid-elevations were either at or near isothermal conditions. During the week of May 22, much of the western U.S., including the Colorado basin, experienced unusually warm weather. Average daily temperatures recorded at Red Mountain Pass SNOTEL site at an elevation of 11,100 feet (3383 m) reached 49°F. (9.6°C.) with daily minimums above freezing (Figure 10). Daily temperatures on Berthoud Pass, Colorado, at 11,300 feet (3444 m) reached 56°F. (13.3°C.) during this week. At this same time, of near surface soil temperatures at three SNOTEL sites north of Grand Junction, Colorado, showed soils were near 0°C. but the soils were not frozen under snowpacks at elevations below 9000 feet (2835 m).

An entire week of much above average temperatures was sufficient to bring even deep snowpacks up to an elevation of 12,000 feet (3658 m) to isothermal conditions. The graphs of Figure 9 show an almost simultaneous onset of melt over a large elevational range triggered by the warm temperatures. By May 26, active melting and snowpack depletion were occurring in the 8000 feet (2438 m) to 12,000 feet (3658 m) zone.

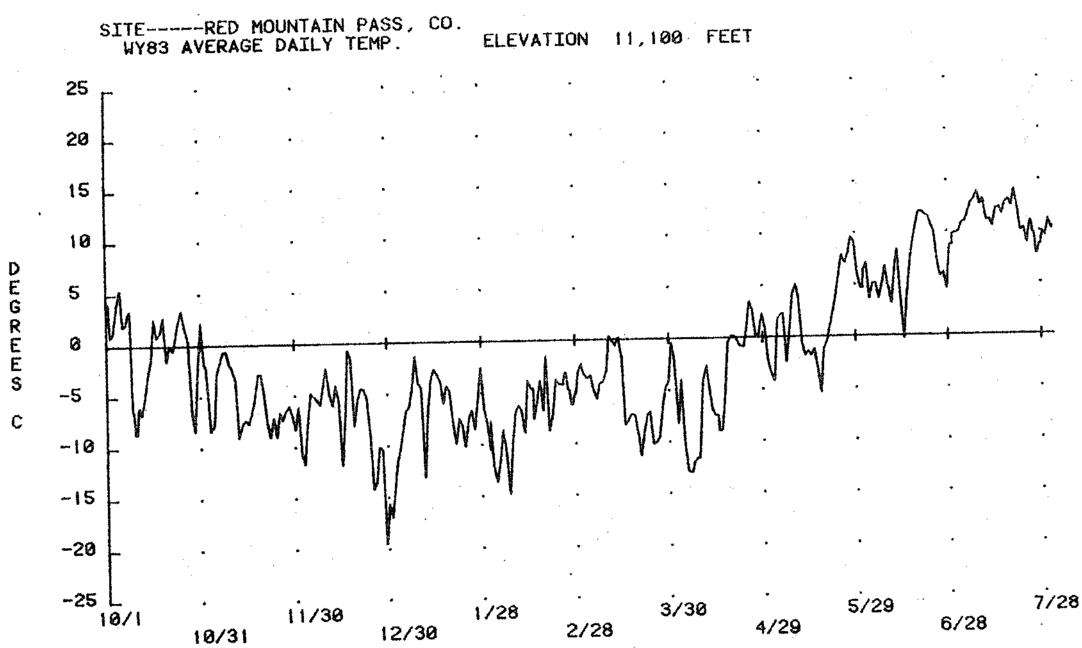

Figure 10. Mean daily temperatures at Red Mountain Pass, Colorado, SNOTEL site at 11,100 feet (3353 m), showing a cold spring and rapid warming in late May.

SNOW AREAL EXTENT

In order to estimate the geographic area involved in producing runoff from snowmelt during late May and June, NOAA-6 satellite imagery was acquired for May 4, 21, 26, and June 3. With the aid of a zoom transfer scope, snow cover was mapped for the basin above Lake Powell on these dates and planimetered to obtain the area covered by snow. Table 1 summarizes these data.

DATE	SNOW COVER (mi^2)	SNOW COVER (km^2)
May 4, 1983	30,101	77,962
May 21, 1983	23,796	61,632
May 26, 1983	13,974	36,193
June 3, 1983	10,867	28,145

Table 1. Snow-covered area above Lake Powell obtained from NOAA-6 imagery.

SNOTEL records from 75 sites and data contained in Table 1 revealed that until the first of June, nearly the entire basin had 100 percent snow cover above 9000 feet (2743 m) and was actively melting. At several low elevation snow courses, water equivalent readings near June 1 were greater than ten times their average. Application of a snowmelt runoff equation helps illustrate the impact of what was happening. The formula used is:

$$Q = cmTA$$

where:

Q= Daily runoff
c= Runoff coefficient
m= Melt rate factor
T= Average daily temperature
A= Snow-covered area

During the first week of June, SNOTEL data from Berthoud Summit, Red Mountain Pass, Columbine, and Cathedral Bluffs in Colorado were used to calculate an average melt rate factor of 0.085 in/deg. F-day (0.39 cm/deg. C-day) for the basin at an average elevation of 10,000 feet (3048 m). This melt rate factor is identical to the average value reported by the U.S. Army Corps of Engineers (1960). Taking an observed average daily temperature of 40° F. (4.4° C.) at 10,000 feet, and assuming a runoff coefficient of 0.70, and a snow covered area of 10,867 mi^2 (28145 km^2), an estimated daily runoff volume of 275,877 acre-feet (340,307 dekameters^3) was possible on June 3. A runoff coefficient of 0.70 was chosen based on work by Shafer et al. (1982). For comparison, the unregulated flow into Lake Powell near the first of June averaged approximately 250,000 acre-feet (308,386 dekameters^3) per day.

This computation illustrates the importance of having current snow areal extent information during the melt period. Observed snow cover information provides two dimensional data that is normally only inferred from index snow courses and SNOTEL sites, or synthetically generated as a fitted parameter in some models.

CONTRIBUTIONS TO STREAMFLOW

The series of events described led to a situation throughout June where much of the basin above 9000 feet (2743 m) was snow covered and melting at rates approaching annual maximums. At the same time, lower elevations were receiving precipitation 150 to 300 percent of normal. Although precipitation at lower elevations was well above average, and soils were close to saturation due to snowmelt and antecedent rainfall, the amount of rainfall runoff produced was small in comparison to that generated by snowmelt. Most low elevation precipitation stations received only 1 to 3 inches of precipitation for June. This precipitation was distributed throughout the month and was relatively inefficient in producing streamflow. In contrast, SNOTEL pillow data showed an average of 1 inch (2.54 cm) per day of snowmelt was produced during all of June at elevations above 10,000 feet (3048 m).

Assuming a conservative mean snow areal extent of 6000 mi^2 (15,540 km^2) for the month of June (based on a straight line projection from June 3 snow covered measurement to no snow on July 1), 9.6 million acre-feet (11.8 million dekameters^3) of meltwater was produced. If 70 percent of that volume appeared as streamflow, 6.7 million acre-feet (8.3 million dekameters^3) of streamflow could be attributed to snowmelt alone. This amount represents 84 percent of the virgin flow for the Colorado River at Lee's Ferry for June.

The above calculations serve not only to demonstrate the contribution of snowmelt to total streamflow, but also to demonstrate the potential value of observed daily snow water equivalent data and snow areal extent information in more accurately assessing events as they unfold. When viewed together with other hydrometeorological data, a clearer picture begins to emerge of the major elements that contolled the runoff sequence in 1983 on the upper Colorado River basin.

Based upon the preceeding analysis, it is believed that events witnessed during 1983 in the Colorado basin and elsewhere were the result of the combined interactions described below:

1. Four to six-week delay in melt with concurrent increases in mountain snowpack above 9000 feet (2743 m).

2. Abnormally warm temperatures in late May which brought the snowpack at nearly all elevations to isothermal conditions at peak seasonal water equivalents.

3. Simultaneous onset of melt in late May over an extremely large geographic area and an elevation range of 4000 feet (1219 m).

4. Compression of the melt season into one-half its normal length when melt rate factors were at a maximum reduced infiltration, deep percolation, and evapotranspiration opportunity, and resulted in high runoff efficiencies.

5. June-August precipitation was above average throughout the basin.

6. Unusually wet soil moisture conditions prevailed from early in the water year.

Conventional regression forecast techniques are inadequate to predict the consequences of events such as those that occurred in 1983 because of a lack of historical precedent in available data sets used to develop the procedures. It is also difficult for regression procedures to reflect the influence of time as a variable in physical processes where increments of a few days to weeks are important.

Physically based conceptual forecast models offer a better framework for understanding and predicting such events. Data on daily snowpack, precipitation at high elevations, and snow areal extent must be used as direct input variables in the models, however, if they are to realize their full potential.

SUMMARY

A study of the causes of the 1983 record breaking spring and summer runoff in the upper Colorado basin was undertaken to better comprehend the sequence of events and relative importance of contributing factors so that forecast techniques might thereby be improved. Influences of precipitation, temperature, snow water equivalent, areal snow cover, and soil moisture conditions were evaluated. Primary causes for the extraordinary runoff in 1983 in order of their impact are:

1. Cold temperatures and heavy precipitation in April and May increased snowpack levels at all elevations and delayed normal melt patterns by 4 to 6 weeks.

2. Unseasonably high temperatures brought almost all snowpacks to isothermal conditions at peak seasonal water equivalents over an area of nearly 24,000 mi^2 (62,160 km^2) in the week of May 22.

3. The melt season for 1983 was compressed mostly into the last half of the normal melt season when melt rates are at their seasonal maximum; this circumstance substantially reduced the opportunity for normal evapotranspiration and deep percolation losses and resulted in high runoff efficiencies.

4. Above normal precipitation at lower elevations throughout the basin during May-August added flow to the runoff from snowmelt at higher elevations.

Events such as the 1983 runoff season are rare, but when they do occur, much can be learned from post event analysis. This study emphasizes the importance of using all the data available to piece together a complete picture of an extreme event. Data on daily high elevation precipitation, snow water equivalent, and temperature from SNOTEL as well as remotely sensed snow covered area from NOAA-6 were invaluable in understanding the 1983 events. We must incorporate these data into future streamflow forecasting techniques to enable forecasters to make more accurate and timely assessments of runoff for use by the public.

ACKNOWLEDGMENTS

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