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# Identification and Regional/Spatial Extent of Rain-Dominated Winter Storms in California's Sierra Nevada

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## ABSTRACT

A precipitation type index (PTI) was developed and tested on the record from two meteorological stations in California's central Sierra Nevada that had visual classification of precipitation as rain, snow, or mixed types. The algorithm used new snowfall depth (S) and total precipitation (P), and was more accurate than classifications based on air temperature. The algorithm [PTI = (P x 100) / (P + S)] was applied to the records from several other mountain stations to identify rain-dominated storms, and to analyze the regional patterns of their magnitude and occurrence. Rain-dominated storms are more frequent, and of greater magnitude, on the north-central west slope of the range than in the south or to the east of the crest of the Sierra Nevada. Rain-dominated storms in the north-central portion of the range are most common during November. In the south and east, no single month dominated the temporal distribution of rain-dominated storms.

## INTRODUCTION

About one-half of California's annual precipitation becomes streamflow (California, 1983), and many reservoirs trap a portion of this runoff. Because hydropower generation reduces the need to burn vast quantities of oil, there is an enormous incentive for water managers to understand and predict runoff timing and quantity. Although most of the precipitation at higher elevations in California's inland mountains falls as snow, rain typically falls between two and six times annually on the snowpack at 1500 m (5000 ft) elevation in the Sierra Nevada.

The magnitude and rain-snow elevation line of winter storms are difficult to predict. Storms sweeping eastward into California from the central Pacific Ocean may be "warm storms" that produce significant amounts of rainfall between 1000 m ft and 2000 m (3300 to 6550 ft). If a large, rain-dominated storm follows a snow storm from the Gulf of Alaska, large amounts of rain can fall on an extensive snowcover, potentially leading to serious flooding. Events of this type have led to the largest recorded floods on the western slope of the Sierra Nevada (Kattelmann et al., 1991).

Precipitation can range from 100% snow to 100% rain. During periods of intermittent and mixed rain and snowfall, it is often difficult--even with direct ocular observation--to conclusively classify precipitation type for an entire storm. Temperature-based algorithms aimed at differentiating between rain and snow storms are coarse. A temperature-based algorithm developed by Smith (1982), for instance, correctly identified 88% of the storms classifiable, but more than 40% of the storms of record were unclassifiable because they were on the cusp between rain and snow events.

This paper is part of a larger study whose objectives were to develop a precipitation type algorithm and to characterize both rain- and snow-dominated winter storms in California's inland mountains (McGurk et al. 1992, McGurk et al. in press). The primary focus of this report is (1) development and testing of a precipitation type index (PTI), and (2) application of the PTI to identify regional patterns of occurrence of rain-dominated winter storms.

## METHODS

Three steps are incorporated into this analysis: (1) database development, (2) development and testing of the PTI, and (3) application of the PTI to regional storm occurrence.

**Table 1. Meteorological stations used in rain-dominated winter storm analysis, record length on compact disc, elevation, and river basin.**

| Station name | Duration (year) | Elevation (m) | Elevation (ft) | River basin | Annual Precipitation (cm) | Annual Precipitation (inches) |
|---|---|---|---|---|---|---|
| Blue Canyon | 1948-1988 | 1609 | 5280 | Yuba | 175 | 69 |
| Bowman Dam | 1948-1988 | 1637 | 5330 | Yuba | 157 | 62 |
| Central Sierra Snow Lab. | 1969-1989 | 2103 | 6900 | Yuba | 130 | 51 |
| Giant Forest/Lodgepole | 1948-1988 | 1954 | 6410 | Kings | 93 | 37 |
| Hetch Hetchy | 1948-1988 | 1180 | 3870 | Merced | 83 | 33 |
| Huntington Lake | 1948-1988 | 2140 | 7020 | Kings | 110 | 43 |
| Sierraville Ranger Station | 1948-1988 | 1518 | 4980 | Feather | 66 | 26 |
| Stirling City Ranger Station | 1957-1988 | 1073 | 3520 | Sacramento | 85 | 34 |
| Truckee Ranger Station | 1948-1988 | 1835 | 6020 | Truckee | 74 | 29 |
| Yosemite Park Headquarters | 1948-1988 | 1210 | 3900 | Merced | 93 | 37 |

**Database development**

Ten stations in the Sierra Nevada were selected from *Climatological Data: California* (NOAA, 1989) based on the following criteria:

1) Location in the rain-on-snow zone, e.g., elevations greater than 1000 m (3300 ft), and

2) Availability of at least 20 years of data for new snowfall, temperature, and hourly and daily precipitation.

Forty years of data were available for most of these stations (Table 1, Fig. 1). Unfortunately, only these few stations exist above 1200 m (3900 ft) in the Sierra Nevada with the required data.

Storms that occurred between November 1 and May 30 were sorted into 25.4-mm (1 inch) precipitation depth classes (between 0 and 406 mm) for durations of 1, 2, 4, 5, and 10 days. For completeness, the 406-mm (16 inch) class also included all storm depths greater than 406 mm.

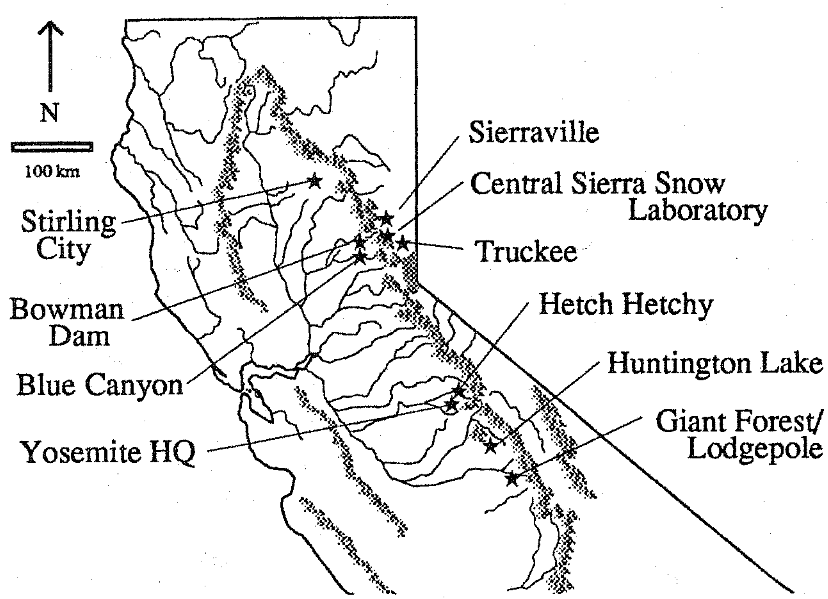


*Figure 1. Meteorological stations in California's Sierra Nevada that have 15-minute and daily precipitation, and daily snowfall data.*

This "winter storm" database was screened further to exclude storms that delivered insignificant depths compared to their duration. Significant events were defined as those that deposited at least 25.4 mm of precipitation over a 1-day period, or 76.2, 101.6, 127, or 152.4 mm (3, 4, 5, and 6 inch) for 2-, 4-, 5-, or 10-day periods, respectively. Additional details of the database development are given in McGurk et al. (in press).

**Development and testing of the precipitation type index**

Temperature-based algorithms aimed at distinguishing between rain, snow, and mixed precipitation are too imprecise. We needed a method for identifying rain-dominated storms from the historical record at stations without visual classification of storm type. Our new classification algorithm differs from traditional methods of estimating snow density (mass or weight divided by volume), and is merely a convenient index for classifying storms. The dimensionless PTI is computationally stable and uses daily new-snow and precipitation depths:

PTI = precip. depth*100/(precip. depth + new snow depth).

For example, if the daily record listed 60 mm (2.4 inches) (expressed for this use as 6 cm) of precipitation and 18 cm (7.1 inches) of new snow, the PTI would equal 25. Unlike density, the PTI is not sensitive to the sequence of rain and snow during a storm, so rainstorms that conclude with a small amount of low-density snow would be classified as rain-dominated.

The PTI algorithm was tested by applying it to 350 events at Blue Canyon with depths greater than 25.4 mm (1 inch) between 1949 and 1976 (Table 2). During this period, an observer at Blue Canyon classified daily precipitation as "snow" or "rain." The goals of the test were to determine (1) whether the predicted PTI matched the observer's classification, and (2) what threshold value of the PTI should be used to delineate rain-dominated from snow-dominated storms.

Ideally, a threshold PTI value could be selected above which most (or all) storms that were classified as rain-dominated would have a negligible snow depth in comparison to the total precipitation depth. Application of the correct PTI threshold value would generate a storm list in which the storms from the database that were classified as rain-dominated would match most of the events that were classified as rain-dominated by the observer at Blue Canyon. Further, most of the rain-dominated storms identified by the Blue Canyon observer would be in the storm list derived by applying the PTI threshold value to the database. The selection of the most appropriate threshold value was a double optimization process, roughly analogous to finding the intersection of two lines on an economist's supply-demand chart (Fig. 2).

As the PTI decreased from 50, more storms in the database were classified as rain-dominated, but the proportion of these events that matched the Blue Canyon observer file decreased from 76% to 36% (Table 2, curve A in Fig. 2). Because the number of storms from the database that were classified as rain-dominated increased as the PTI decreased, more of the storms on the Blue Canyon list matched those in the database (Table 2, column 5; curve B in Fig. 2). This situation entails two kinds of errors, labeled A and B for discussion. In Table 2, error A is failing to classify a storm as rain-dominated in the CD storm file when it was a rain-dominated storm in the Blue Canyon observer file. Error B is the reverse: classifying an event from the database as rain-dominated when the Blue Canyon observer classified

**Table 2. Precipitation type index values and rain-dominated storm classification matches and errors between the compact disc (CD) and the Blue Canyon storm records.**

| Precip. type index | Percent of storms from CD that match Blue Canyon list | Error A (%) | Error B (%) | Percent of storms from Blue Canyon that match CD | Number of storms on Blue Canyon list matching CD |
|---|---|---|---|---|---|
| 50 | 76 | 33 | 24 | 67 | 234 |
| 45 | 75 | 30 | 25 | 70 | 244 |
| 40 | 75 | 27 | 25 | 73 | 256 |
| 35 | 75 | 25 | 25 | 75 | 263 |
| 30 | 74 | 19 | 26 | 81 | 282 |
| 25 | 71 | 17 | 26 | 83 | 292 |
| 20 | 68 | 13 | 32 | 87 | 305 |
| >0 | 36 | --- | 64 | 92 | 321 |

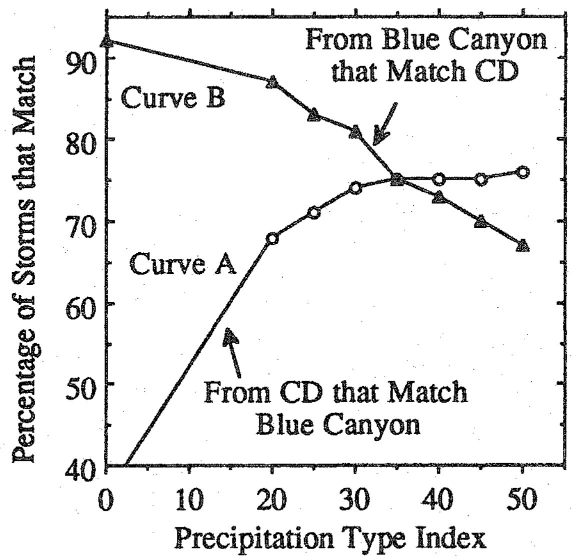


*Figure 2. Comparison of effects of changing the Precipitation Type Index value to match compact disc (CD) and observer storm lists.*

it as a snow-dominated storm.

We desired a threshold PTI value that balanced the two types of error, but selection of the threshold value was unavoidably subjective. One approach would have been to minimize the sum of the error A and error B percentages; this method yielded 25 as the optimum PTI threshold value. Following a supply-demand analogy and finding the point where the curves crossed, we would have selected 35 as the threshold PTI. A PTI value of 30, however, matched the point in the second column of Table 2 where the number of matched values (74% to 71%) decreased sharply. An index value of 30 also corresponded to the largest percentage change in the fifth column of Table 2 (75% to 81%), so a value of 30 was selected for further testing.

The PTI algorithm and the value of 30 was validated with two independent data sets from the Central Sierra Snow Laboratory (CSSL). CSSL is 31 km (19 miles) east of Blue Canyon and nearly 500 m (1600 ft) higher than Blue Canyon in elevation (Fig. 1), so this validation was also a measure of whether elevation plays a role in the PTI. The data sets were: (1) a 20-event set of rain-dominated storms, which included storms depositing as little as 2.5 mm (0.1 inch) precipitation and lasting from 2 to more than 100 hr (Berg et al., 1991); and (2) a 93-event set of storms that were typed on the basis of visual classifications, made between 1969 and 1989 (unpublished data, Pacific Southwest Research Station, Albany, CA). Using 30 as a threshold value, we correctly identified more than 70% of the rain-on-snow storms as rain-dominated, across a wide spectrum of precipitation depths and storm durations. Because both analyses gave similar results, we concluded that the algorithm and a PTI of 30 were appropriate for use with the 10 sites having daily snowfall information.

**PTI classification rules**

Any station's individual storm may be shorter in length than a day, but it is summarized in the database in terms of daily information. The basic classification criterion for a 1-day storm was: a storm that began at midnight of one day and ended within 24 hours was classified as rain-dominated if the PTI was at least 30 and the precipitation depth was at least 25.4 mm (1 inch). For longer storms, precipitation type varied from day to day, so classification rules were formulated. A 1-day storm was rain-dominated only if <u>both</u> of the following conditions were true on at least one of the two consecutive days:

1) The storm deposited at least 25.4 mm (1 inch) of precipitation during the midnight-to-midnight period, and
2) The PTI value for that period was at least 30.

In the simplest case, a storm would start and stop within a single midnight- to-midnight period, deposit more than 25.4 mm (1 inch), and have a PTI of at least 30. A more complex case would be a storm that deposited 13 mm (0.5 inch) of precipitation with a PTI of 35 from noon to midnight on the first day, and deposited 28 mm (1.1 inches) of precipitation with a PTI of 20 from midnight to noon on the second day. This 24-hour event would <u>not</u> be classified as rain-dominated. Storms lasting 48 hours were treated in a similar fashion.

For longer storms, smaller daily depths are possible, so different criteria were applied. A 4- or 5-day storm was classified as rain-dominated if both of the following conditions were true:

1) The storm deposited at least 13 mm (0.5 inch) of precipitation on **any two** days, and
2) The PTI value for the **same two** days was at least 30.

For 10-day storms, the event would be classified as rain-dominated if **any three days** met the above two conditions.

The PTI algorithm and selection criteria were applied to all storms in the database occurring between 1 November and 30 May. This resulted in a list of rain-dominated storm dates and depths for the ten weather stations. A resorting of the rain-dominated database based on month of occurrence was also done to identify months with the greatest likelihood of rain-on-snow events.

**Regional storm patterns and magnitudes**

We assumed that sites closer to the rainfall-dominated Cascade Range would have more winter rainfall. Stirling City was therefore deleted from the regional analysis because of both its shorter record and itsproximity to the Cascade Range. Although local topography is always a factor, in this paper we focus on latitude, station elevation, and position with respect to the crest of the range as factors that influence the occurrence of rain-dominated storms. There are several hypothetical groupings of sites: east-slope vs. west-slope stations; rain-on-snow vs. snow-zone station; and latitudinal effects. First, Truckee and Sierraville are east-slope stations situated in the "rain shadow" of the crest of the Sierra Nevada. These two stations should receive less precipitation and might have fewer rain-dominated storms than west-slope sites. Second, the elevational zone between 1370 m to 1980 m (4500 to 6500 ft) (varying somewhat with latitude) on the west slope of the Sierra has traditionally been characterized as the "rain-on-snow" zone. Sites above this elevational band (e.g., CSSL, Huntington Lake) should experience fewer rain-dominated storms than sites like Blue Canyon and Bowman Dam. In the case of latitude, the southern sites (e.g., Giant Forest, Huntington Lake) should have relatively lower frequencies than the northern sites (e.g., Blue Canyon).

To determine if the hypothesized groupings were realistic, daily precipitation from storms identified as rain-dominated by the PTI were tabulated for the nine stations from 1949 through 1989. Storm totals were examined to identify any obvious geographic trends after they were grouped into three categories: (1) a complete set of 200 storms, (2) 73 storms of moderate amount where the sum of the storm totals for all stations exceeded an arbitrary threshold, and (3) 16 major storms where the sum of the storm totals for all stations exceeded twice the threshold for storms classified as moderate.

Four geographic subregions were designated: north (Blue Canyon, Bowman Dam, CSSL), central (Hetch Hetchy, Yosemite), south (Huntington Lake, Giant Forest), and northeast (Sierraville, Truckee). If at least 25.4 mm (1 inch) of precipitation was recorded at one or more stations in each subregion, the storm was assumed to affect that subregion. If every subregion was represented, then the rain-dominated storm was considered to be Sierra Nevada-wide. Storms with 25.4 mm (1 inch) or more of precipitation at both CSSL (2103 m [6900 ft] elevation) and Huntington Lake (2140 m [7020 ft] elevation) were considered to be rain-dominated at high elevation (rain above 2000 m [6550 ft]).

## RESULTS AND DISCUSSION

### Evaluation of the PTI

Initial testing of the PTI with the storms at CSSL and Blue Canyon yielded a 70% match between one-day storms classified as rain-dominated by both the observer and the PTI. We were concerned about the 30% mis-classification, so an additional examination was made using the Blue Canyon files. We suspected that with the large storms, less classification error would occur. After matching the periods of record and screening out intervals with missing records in the database of 1-day storms, we found that the PTI list matched 85% of the observer's list at Blue Canyon. The 20 largest storms in the two lists matched perfectly; the missing six storms were smaller storms from the last 20 events in a listing of storms ranked by precipitation amount. Because the largest storms presumably result in the highest and most damaging flows, the excellent match in the 20 largest storm dates suggests that the PTI is especially effective for identifying large, rain-dominated storms.

### Regional trends in rain-dominated winter storm occurrence

*Long-term storm frequency*

Among the eight sites having 40-yr records (CSSL had 20 yrs), the frequency of rain-dominated storms varied drastically; seven times as many 1-day rain-dominated storms occurred over the 40-yr period at Blue Canyon compared with Huntington Lake (Fig. 3). Among pairs of sites, the relative frequency of storms remained constant across all storm durations (e.g., seven times as many 10-day storms over the 40-yr period at Blue Canyon [85] as at Huntington Lake [12]).

For the north and central station groups, the frequency for storms of all durations (1-day through 10-day) was at least twice the frequency of the other four stations (Fig. 3). This dichotomy was independent of precipitation amount; precipitation at Yosemite and Hetch Hetchy approximated annual precipitation at several of the southern and eastern Sierra stations (Table 1). Three of the four frequent-storm sites had approximately equal frequencies of rain-dominated storms for each of the five storm durations (Fig. 3). The exception, Blue Canyon, experienced more rain-dominated storms. Blue Canyon is distinctive in that of the stations analyzed, it is the one most traditionally identified as in the rain-on-snow zone. These findings support the observation that latitude is at least a partial control on the frequency of rain-dominated storms.

The four stations comprising the other two groups experienced appreciably fewer rain-dominated storms than the north and central sites. The location and elevation of Sierraville and Truckee further reduce the likelihood of rain-dominated storm occurrence. The low frequency of rain-dominated storms at Huntington Lake is somewhat anomalous. Annual precipitation at Huntington Lake is relatively high, but its 2140-m (7020 ft) elevation puts it above the

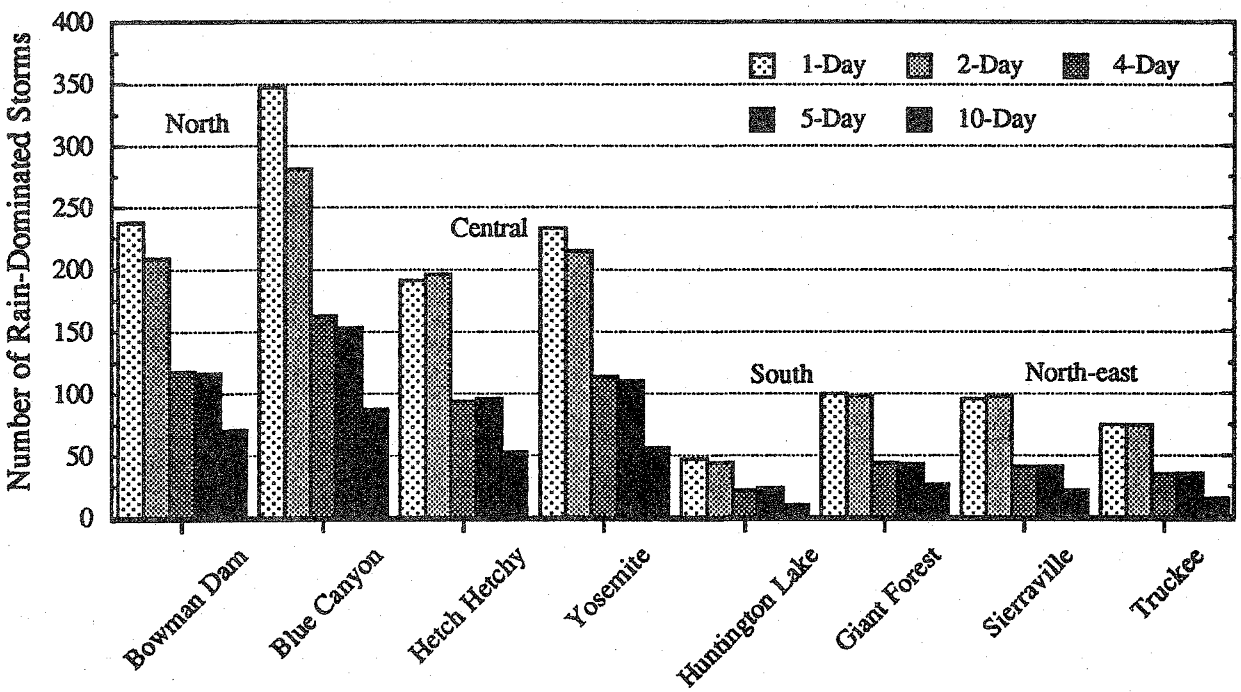


*Figure 3. Number of rain-dominated storms for 40-yr period (storms with at least 25.4 mm [1.0 inch] of precipitation were included).*

typical upper level of the rain-on-snow zone. These findings support the observation that east slope vs. west slope location and location within the rain-on-snow zone affect the frequency of rain-dominated storms.

*Monthly storm frequency*

The two northernmost sites (Bowman Dam and Blue Canyon) experienced more rain storms in November than any other month (Fig. 4). November had more rain-dominated storms than any other month at these two sites for all storm durations. Moving south, November was seldom the month with the greatest number of rain-dominated storms, particularly for the 1- and 2-day storms. December had the most 1- and 2-day rain-dominated storms at the central and southern Sierran sites. These findings support the observation that northerly latitude and topography are important determinants of monthly frequency of rain-dominated storms.

*Large-magnitude, rain-dominated storms*

All of the 16 large-magnitude storms, were represented in all four subregions. Precipitation was substantial at all stations during the largest rain-dominated storms for the 40-year study period. Ten of these storms also met the high-elevation criterion. Of the 73 storms classified as moderate, 52 (70%) covered the entire Sierra Nevada and 21 (30%) produced substantial rainfall at the two stations above 2000 m (6550 ft) elevation. None of the 127 storms with minor amounts of precipitation (not meeting the moderate criterion) covered all regions of the Sierra Nevada. These observations suggest a strong association between storm magnitude and geographic extent.

**Return periods for rain-dominated and all winter storms**

Return-period calculations for both rain-dominated and all winter storms were made for storms of 2-, 5-, 10-, 20-, 50-, and 100-yr return periods for storms of 1-, 2-, 4-, 5-, and 10-day duration (McGurk et al. 1992). The question of interest is whether rain-dominated storms alone deposit more precipitation than when rain and snow storms are aggregated together. For eight of the ten stations, the 10-day, rain-dominated storms with 100-yr return periods were larger than overall winter storms. For those eight stations, the mean difference in total storm precipitation between the rain-dominated subset of storms and the winter storms was 66 mm (2.6 inches), with the range of differences 4 to 156 mm (0.2 to 6.1 inches). Statistically- significant differences were not identified for shorter storms or more frequent storms.

Estimated precipitation depths for rain-dominated storms at sites in the traditional rain-on-snow zone (i.e., Blue Canyon and Bowman Dam) were greater than for nearby sites both at higher elevation (CSSL) and to the east of the Sierra crest (Figure 5). The precipitation depth pattern is generally parallel among sites along the central Sierra elevational transect for storms of varying duration and return period. An exception is the relative increase in precipitation depth at CSSL for moderately long, low-return period

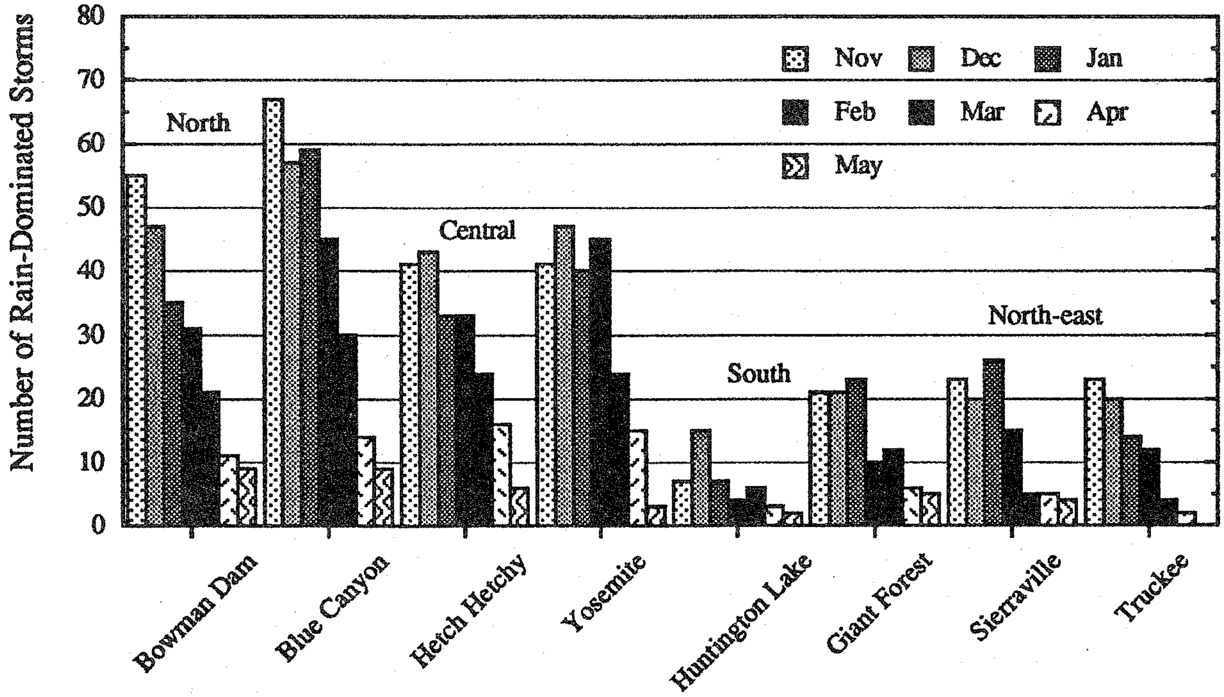


*Figure 4. Monthly frequency of rain-dominated storms, 2-day durations (storms with at least 25.4 mm (1.0 inch] of precipitation were included).*

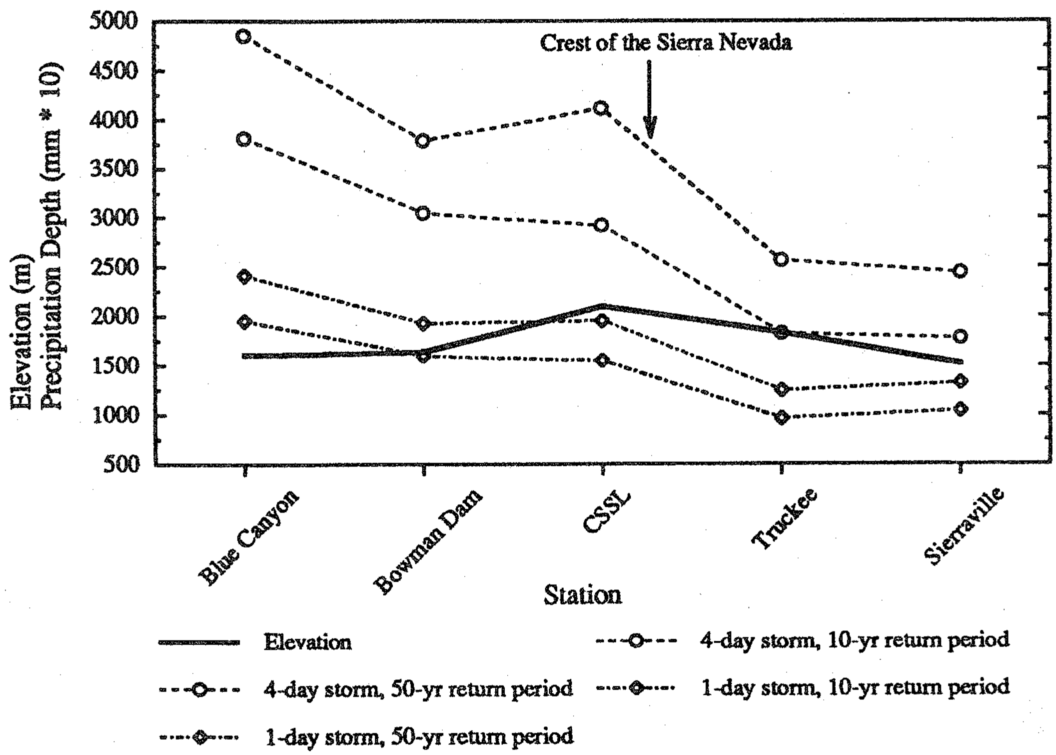


*Figure 5. Precipitation depth along an elevational transect in the central Sierra Nevada for four storm duration-return period combinations.*