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CAUSES OF PEAK FLOWS IN NORTHWESTERN MONTANA AND NORTHEASTERN IDAHO[1]

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ABSTRACT: Both catchment experiments and a review of hydrologic processes suggest a varying effect of forest harvest on the magnitude of peak flows according to the cause of those peak flows. In northwestern Montana and Northeastern Idaho, annual maximum flows can result from spring snowmelt, rain, mid-winter rain-on-snow, or rain-on-spring-snowmelt. Meteorologic and physical data were used to determine the cause of annual maximum flows in six basins which had the necessary data and were smaller than 150 mi^2. Rain-on-spring-snowmelt was the most frequent cause of annual maximum flows in all six basins, although there was a strong gradient in the magnitude and cause of peak flows from southwest to northeast. Less frequent mid-winter rain-on-snow events caused the largest flows on record in four basins. Mid-winter rain-on-snow should be distinguished from rain-on-spring-snowmelt because of differences in seasonal timing, the relative contributions of rain vs. snowmelt, and the projected effects of forest harvest. The effects of mixed flood populations on the flood-frequency curve varied from basin to basin. Annual maximum daily flows could not be reliably predicted from rainfall and snowmelt data.

(KEY TERMS: surface water hydrology; peak flows; meteorology/climatology; flood frequency; rain-on-snow; forest management.)

INTRODUCTION

Forest harvest effects on runoff have long been a concern of the public and forest managers (Satterlund and Haupt, 1972; Satterlund and Adams, 1992). In the 1950s and 1960s, attention focussed on increasing annual runoff, and a large number of paired watershed experiments were carried out to quantify the effects of forest and brush removal (Bosch and Hewlett, 1982). More recent hydrologic and economic studies have concluded that forest management – partly because of societal constraints – can produce only minor increases in the value and amount of annual water yield (e.g., Troendle, 1983; Rector and MacDonald, 1987; Brown, 1990). Increases in annual runoff also will be less in drier areas and drier years (Bosch and Hewlett, 1982), which is precisely where and when additional water is most needed.

Over the last decade, public and professional concern has shifted to the effects of forest harvest on the magnitude of peak flows (e.g., Coats and Miller, 1981; Grant, 1987). Increases in the magnitude of peak flows can adversely affect aquatic resources through channel incision, bank erosion, and increased sediment transport capacity (e.g., Harr, 1986; Grant, 1987; MacDonald *et al.*, 1991). This concern over the hydrologic effects of forest harvest should generally focus on the upper 1-5 percent of the flow duration curve, as this is when most sediment transport occurs (e.g., Megahan, 1979; King, 1989).

Forest management can increase the magnitude of peak flows by altering a variety of hydrologic processes. Removal of the vegetative canopy decreases interception losses and thereby increases net precipitation. Reduced evapotranspiration increases soil moisture and the magnitude of subsequent runoff events (e.g., Harr *et al.*, 1975; Troendle and King, 1985). Roads and skid trails generate infiltration-excess overland flow, while road cuts can convert subsurface stormflow to surface runoff (Cheng *et al.*, 1975; Megahan, 1983). In snow-dominated areas, forest removal affects the amount of snow and rate of snowmelt by increasing the amount of direct radiation and turbulent heat transfer (Haupt, 1979; Harr, 1981). The frequency and magnitude of rain-on-snow events may increase because of the greater depth and frequency of snow cover (Berris and Harr, 1987).

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This variety of processes suggests that forest harvest will have a differential effect on the magnitude of peak flows according to the cause of those peak flows. In rain-dominated areas, forest harvest – assuming minimal compaction and site disturbance – should not greatly increase the magnitude of the larger peak flows because the principal hydrologic changes are the reduction in interception and evapotranspiration. This hypothesis is supported by several catchment-scale studies (e.g., Harr *et al.*, 1982; Wright *et al.*, 1990).

There is a potentially greater increase in the magnitude of peak flows in snow-dominated areas because of the increased solar radiation and turbulent heat transfer following forest harvest. Observed increases include a 23 percent increase in annual peak discharge after cutting 40 percent of the Fool Creek basin in north-central Colorado (Troendle and King, 1985), 34-87 percent increases in annual maximum daily flows on four small catchments in northern Idaho (King, 1989), and a 50 percent increase in annual maximum daily discharge after clearcutting a basin in southern Colorado (Van Haveren, 1988). Harr (1986) suggested that the largest increase in the magnitude of peak flows will occur in rain-on-snow events, as forest harvest affects snowpack depth, snowpack frequency, turbulent heat transfer, direct and diffuse radiation, and net rainfall.

In summary, an analysis of both hydrologic processes and paired-catchment data strongly suggests that the effects of forest harvest on the magnitude of peak flows will vary according to the cause of those peak flows. Hence, identification of the cause of peak flows is essential to sound forest management.

Peak flows in northwestern Montana and northern Idaho can be due to snowmelt, rainfall, or rain-on-snow (Haupt, 1979; Kuennen and Gerhardt, 1984; King, 1989). Haupt (1968) identified spring rain-on-snow as the cause of 56 percent of the maximum daily flows during the snowmelt season on Benson Creek, a small forested watershed in northwestern Idaho. In contrast, snowmelt without additional rainfall caused most of the springtime peak flows for Boulder Creek, located approximately 35 miles east of Benson Creek, and the South Fork of the Clearwater River, approximately 180 miles to the south (Haupt, 1968).

This apparent variability in the cause of peak flows, together with growing concern over the effects of timber harvest in northwestern Montana, meant that more detailed information was needed on the climatic events which generate peak flows. Hence, the primary objective of this study was to determine the causes of peak flow events in northwestern Montana and northeastern Idaho. A set of secondary objectives followed from this primary objective, and these included: (1) assessing the predictability of annual maximum daily flows from precipitation and snowmelt data; (2) assessing the reliability of flood-frequency curves given the mixed population of peak flow events; (3) evaluating the likelihood of yet larger events on the six study basins; and (4) determining the relative importance of forest harvest in affecting the size of peak flows. Such information is a necessary first step to evaluating forest management effects, and the work reported here is one part of a larger study to evaluate forest harvest effects on stream channels (MacDonald *et al.*, 1995).

METHODS

The initial study area was the Kootenai National Forest (KNF) in northwestern Montana. The paucity of gaged streams caused us to expand the study into northeastern Idaho where climatic conditions were believed similar to parts of the KNF (S. Johnson, KNF, personal communication, 1992).

Four primary criteria were used to select the basins for detailed study. First, at least nine years of continuous streamflow data were needed to provide an adequate sample of annual maximum flows. Second, the discharge record had to be post-1968, which is when daily snow water equivalent (SWE) data first became available through the establishment of the Banfield Mountain SNOTEL site. Third, the study basins had to be smaller than 150 mi^2, as peak flows in larger basins are more diffuse in time and thereby more difficult to relate to specific meteorologic events. Larger basins also incorporate more spatial and temporal variability in meteorologic conditions, and this makes it more difficult to ascribe a specific peak flow to a particular cause. Finally, the study basins could not have large lakes or diversions which would affect peak flows.

Six basins ranging in size from 11-139 mi^2 met these criteria (Table 1; Figure 1). All six basins were forested with little or no urban or agricultural land use. The mountainous terrain means that each basin incorporated a wide range of elevations. Hypsometric curves were developed for each basin from topographic maps. Distance to the nearest weather station ranged from 2-12 mi. In all cases the nearest weather station was at or below the elevation of the gaging station (Table 1). Daily SWE data were obtained from SNOTEL stations located 8-80 miles from the study basins (Figure 1).

The representativeness of the short period of record on Pinkham Creek, Big Creek, and the Bull River was assessed by comparing the flow-duration curve on Flower Creek for 1973-1981 with the flow-duration curve for the entire 30 years of record on Flower

TABLE 1. Basin Characteristics and Sources of Meteorologic Data

Basin Name	Basin Size (mi^2)	Elevation Range (feet above sea level)	Length of Discharge Record and Gage Elevation	Weather Station Name and Elevation (ft)	Distance and Direction from Stream Gage	SNOTEL Site and Elevation	Distance and Direction of SNOTEL Site From Stream Gage
Flower Creek	11	2,866-8,000	30 years 2,866 ft.	Libby Ranger Station 2,100	5 mi. north	Banfield Mountain 6,080 ft.	17 mi. north
Pinkham Creek	76	2,638-6,800	9 years 2,638 ft.	Eureka Ranger Station 2,530	9 mi. northeast	Banfield Mountain 6,080 ft.	21 mi. southwest
Big Creek	137	2,500-7,100	9 years 2,500 ft.	Eureka Ranger Station 2,530	30 mi. northeast	Banfield Mountain 6,080 ft.	13 mi. south
Bull River	139	2,202-8,500	10 years 2,202 ft.	Heron, MT 2,240	7 mi. west	Banfield Mountain 6,080 ft.	40 mi. north
Placer Creek	15	2,840-6,300	21 years 2,840 ft.	Wallace, ID 2,940	2 mi. northeast	Banfield Mountain 6,080 ft.	80 mi. northeast
						After 1982 Sunset, ID 5,540 ft.	8 mi. northeast
Boulder Creek	53	3,445-6,235	56 years 3,445 ft.	Bonner's Ferry, ID 1,780	12 mi. northwest	Banfield Mountain 6,080 ft.	30 mi. east

Creek. Flower Creek was used for this analysis because it is roughly in the middle of the study area and was intermediate for most of the characteristics studied.

Annual hydrographs were plotted for each year from 1968 (1960 in the case of Flower Creek) to 1990. Visual inspection generally could distinguish mid-winter rain-on-snow events (Figure 2c), but could not unambiguously identify peak flows due to spring snowmelt without rain, rain-on-spring-snowmelt, or rain with no measured snowmelt. Examination of the annual hydrographs indicated that the discharge from rain-dominated hydrographs receded to near baseflow levels within approximately five days. On this basis we limited the analysis of meteorologic data to the five days prior to the annual maximum flow, and this is the same period used by Haupt (1968).

Causes of peak flows were identified through analyses of precipitation, temperature, snowpack, and topographic data. The serial correlation of flows and the difficulty of identifying distinct runoff events during spring snowmelt meant that the analysis was limited to the maximum annual daily and instantaneous flows on each basin.

Daily temperature, precipitation, and SWE data were obtained for a seven-day period around each annual maximum discharge. The proportion of precipitation falling as snow was estimated by using the wet adiabatic lapse rate, daily minimum and maximum temperatures, and hypsometric curve to determine the minimum, maximum, and average proportion of the basin below freezing for each day.

Mid-winter rain-on-snow and rain-on-spring-snowmelt were separated because these two types of rain-on-snow events were so distinct in terms of their duration and seasonal timing (Figures 2c and 2d). As will be shown, spring rain-on-snow events usually were characterized by small amounts of rainfall which superimposed a small runoff spike on a much larger seasonal snowmelt hydrograph (Figure 2d). Mid-winter rain-on-snow events were more distinct with often much larger spikes during periods of relatively low flow. Figure 2b shows an annual maximum flow that also occurred during the spring snowmelt period, but meteorologic data were required to determine that this peak flow was due to snowmelt.

Classification was based on the annual maximum daily flows, since most of the meteorologic data were

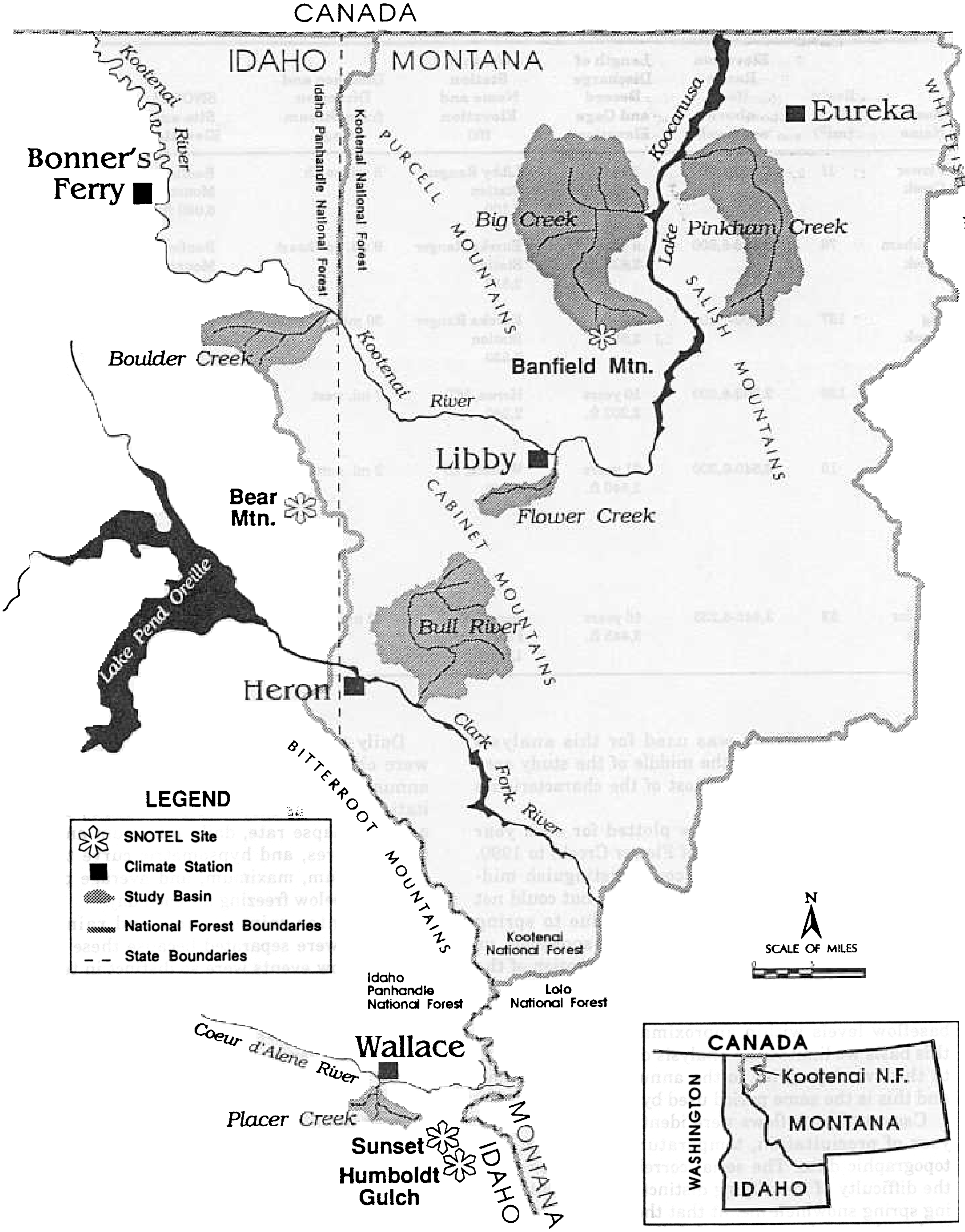

Figure 1. Map of the Study Area.

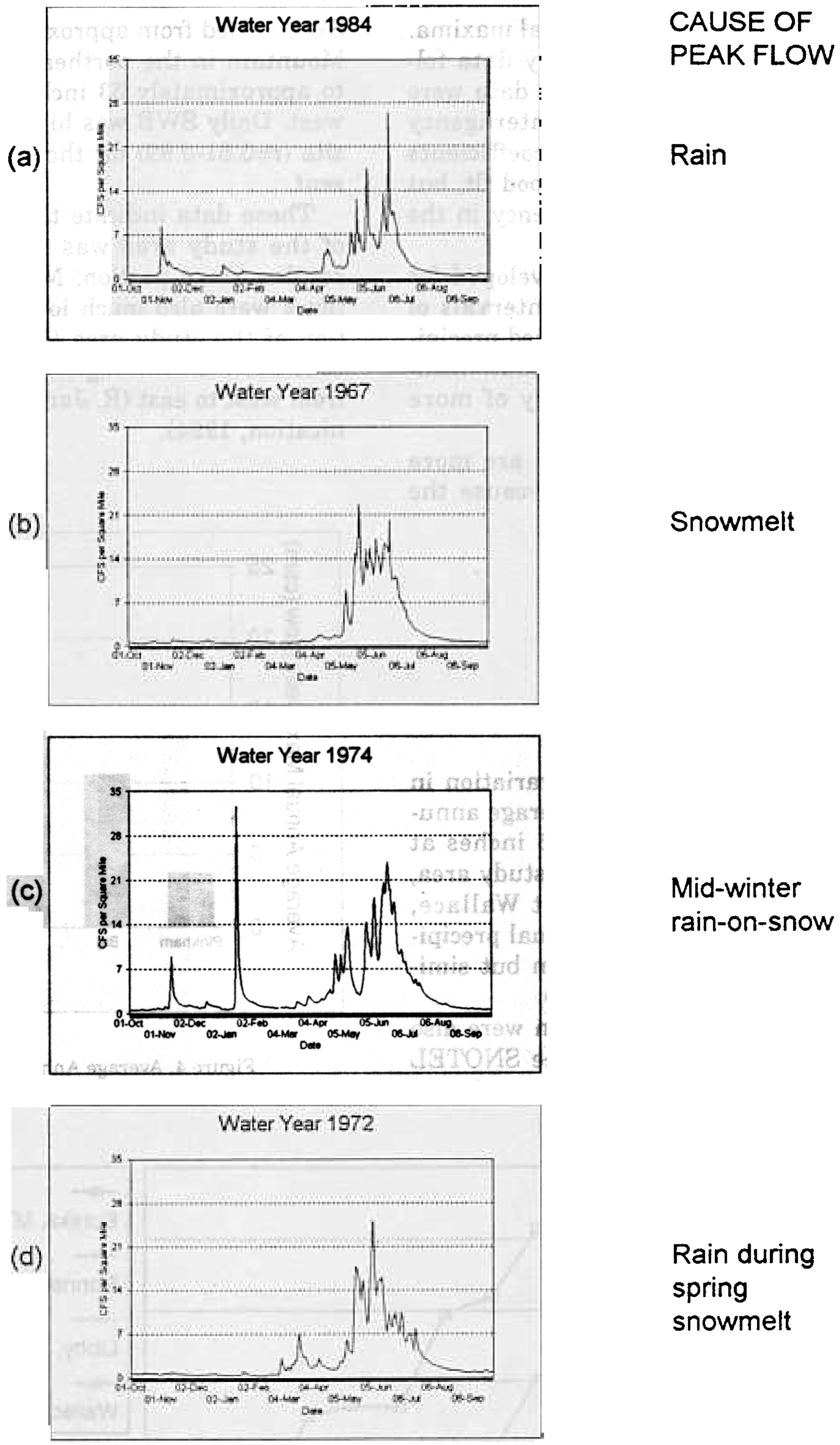

Figure 2. Annual Hydrographs from Flower Creek Showing Examples of the Four Causes of Peak Flows (a) Snowmelt-Generated; (b) Mid-Winter Rain-on-Snow; (c) Rain-on-Spring-Snowmelt; and (d) Rain.

only available on a daily basis. A series of regression models were developed to determine if the magnitude of the annual maximum daily flows could be predicted from precipitation and snowmelt variables.

Flood-frequency curves using the entire period of record were developed for both the instantaneous and daily annual maxima. Daily and instantaneous annual maxima occurred on the same day for all of the largest flows and most of the smaller annual maxima. Plotting the instantaneous flood-frequency data followed standard procedures except that the data were not stratified by meteorological cause (Interagency Committee on Water Data, 1981). Skew coefficients were adjusted for each basin to obtain a good fit, but we also tried to maintain regional consistency in the skew coefficients.

Precipitation-frequency curves were developed for each basin to determine the recurrence intervals of key precipitation events. Comparing observed precipitation during these events with historic rainfall maxima provided insight into the possibility of more extreme runoff events.

English units are used because these are more familiar to the intended audience and because the original data were in English units.

RESULTS

Meteorologic and Physiographic Data

The six basins exhibited considerable variation in mean monthly precipitation (Figure 3). Average annual precipitation varied from less than 15 inches at Eureka, in the northeastern corner of the study area, to approximately 40 inches per year at Wallace, Idaho. Stations with a higher average annual precipitation had much more winter precipitation but similar amounts for June-September (Figure 3).

These differences in winter precipitation were also reflected in the seasonal SWE at the three SNOTEL sites used in this study. Average annual maximum SWE varied from approximately 18 inches at Banfield Mountain in the northeastern part of the study area to approximately 53 inches at Bear Mountain in the west. Daily SWE was highly correlated between each site (r=0.81-0.99) for those days when snow was present.

These data indicate that the northeastern portion of the study area was considerably drier than the southwestern portion. Mean annual maximum daily flows were also much lower in the northeastern portion of the study area (Figure 4). This pattern is in contrast with the regional trend of higher peak flows from west to east (R. Jarrett, USGS, personal communication, 1994).

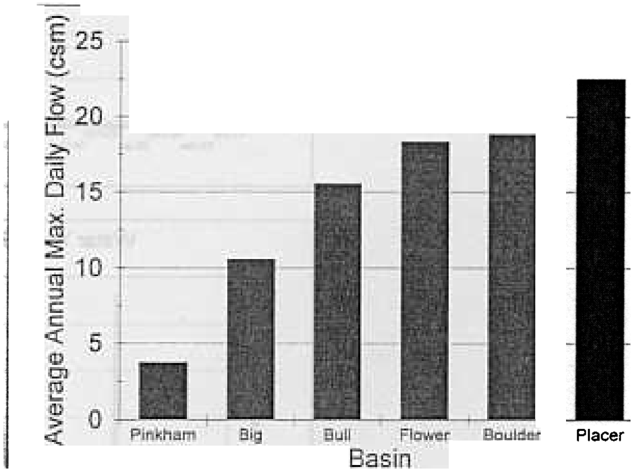

Figure 4. Average Annual Maximum Daily Flows for the Six Study Basins.

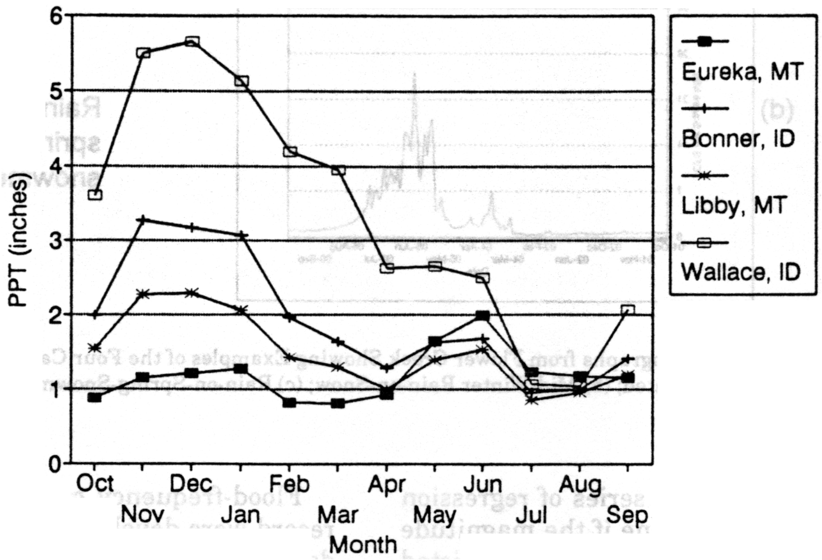

Figure 3. Mean Monthly Precipitation at the Weather Stations Used in This Study.

Hypsometric curves indicate that five of the six study basins are roughly comparable, with median elevations between 4300 and 4900 feet (Figures 5b-f). Four of the basins – Pinkham Creek, Big Creek, Boulder Creek, and Placer Creek – have at least two-thirds of their area between 4000 and 6000 feet. The Bull River catchment has a more even distribution of area over a wider elevation range, while Flower Creek is higher than the other basins (Figure 5a). At least 90 percent of the area of each basin, except Flower Creek, lis below 6080 ft, which is the elevation of the Banfield Mountain SNOTEL site used for most of the snowpack analyses.

The relatively small differences in basin elevation mean that the observed differences in precipitation and runoff are better indexed by latitude and

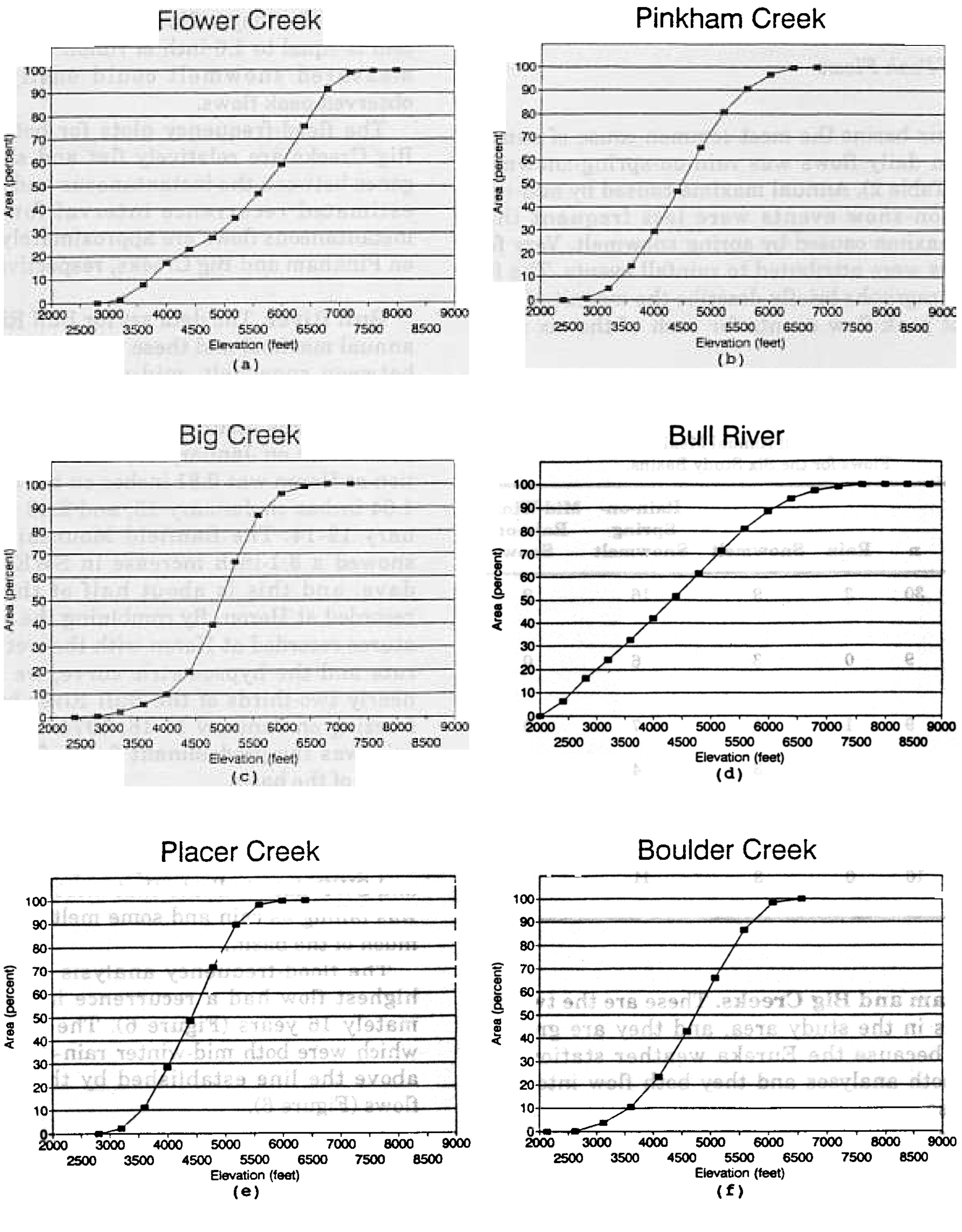

Figure 5. Hypsometric Curves for the Six Study Basins.

longitude than elevation. The mountain ranges running from northwest to southeast create a series of rain shadow effects, and this underlies the documented relationship between precipitation and elevation within the study region (e.g., Satterlund and Haupt, 1972; Kuennen and Gerhardt, 1984). Hence, there was not a positive correlation between elevation and annual precipitation for the five weather stations, or between elevation and the seasonal snowpack from the SNOTEL sites used in this study.

Causes of Peak Flows

In all six basins the most common cause of annual maximum daily flows was rain-on-spring-snowmelt (r-o-s-s) (Table 2). Annual maxima caused by mid-winter rain-on-snow events were less frequent than annual maxima caused by spring snowmelt. Very few peak flows were attributed to rainfall events. The following paragraphs briefly describe the magnitude and causes of peak flow events for each of the six study basins.

TABLE 2. Causes of Annual Maximum Daily Flows for the Six Study Basins.

Basin	n	Rain	Snowmelt	Rain-on-Spring-Snowmelt	Mid-Winter Rain-on-Snow
Flower Creek	30	3	9	16	2
Pinkham Creek	9	0	3	6	0
Big Creek	9	1	1	7	0
Bull River	10	0	3	4	3
Placer Creek	21	0	7	8	6
Boulder Creek	16	0	3	11	2

Pinkham and Big Creeks. These are the two driest basins in the study area, and they are grouped together because the Eureka weather station was used in both analyses and they both flow into Lake Koocanusa. Both basins are snowmelt dominated, with r-o-s-s causing most of the annual maximum daily flows. The largest daily and instantaneous flow on record for both basins was a r-o-s-s event on May 11, 1976. The instantaneous maximum flows were only 9.1 and 19.6 csm (cfs per square mile) on Pinkham Creek and Big Creek, respectively. The Eureka weather station recorded just 0.17 inches of rain on the day of this maximum flow, and no rain during the previous five days. Maximum temperatures for May 6-11, 1976, ranged from 76-82°F, while the minimum temperature on the night before this high flow was a relatively warm 48°F.

The observed melt at the Banfield Mountain SNOTEL site from May 10-11, 1976, was 1.3 inches, or about 50 percent more than the daily average over the previous five days. Since an average daily flow of 27 csm is equal to 1.0 inch of runoff per square mile, the measured snowmelt could easily generate the observed peak flows.

The flood-frequency plots for both Pinkham and Big Creeks are relatively flat and show little divergence between the instantaneous and daily flows. The estimated recurrence interval for the maximum instantaneous flows are approximately 17 and 7 years on Pinkham and Big Creeks, respectively.

Bull River. The data set for Bull River included 10 annual maxima, and these were nearly evenly divided between snowmelt, mid-winter rain-on-snow, and r-o-s-s (Table 2). The largest recorded flow was 28.1 csm, and this occurred during a mid-winter rain-on-snow event on January 16, 1974. Measured precipitation at Heron was 0.81 inches on the day of this event, 1.64 inches on January 15, and 2.48 inches from January 12-14. The Banfield Mountain SNOTEL site showed a 3.1-inch increase in SWE over these five days, and this is about half of the precipitation recorded at Heron. By combining the average temperatures recorded at Heron with the wet adiabatic lapse rate and the hypsometric curve, we estimated that nearly two-thirds of the Bull River basin was above freezing on January 15-16, 1974. This suggests that rain was the predominant form of precipitation over much of the basin.

The second largest peak flow on record also was a mid-winter rain-on-snow event caused by 2.4 inches of precipitation over six days. Again the temperature and SWE data indicate that most of the precipitation was falling as rain and some melt was occurring over much of the basin.

The flood-frequency analysis indicated that the highest flow had a recurrence interval of approximately 16 years (Figure 6). The two highest flows, which were both mid-winter rain-on-snow events, fell above the line established by the next six largest flows (Figure 6).

Flower Creek. The 30-year discharge record on Flower Creek was used to assess the representativeness of 1973-1981, which is the period of record for Pinkham Creek, Big Creek, and Bull River. There was

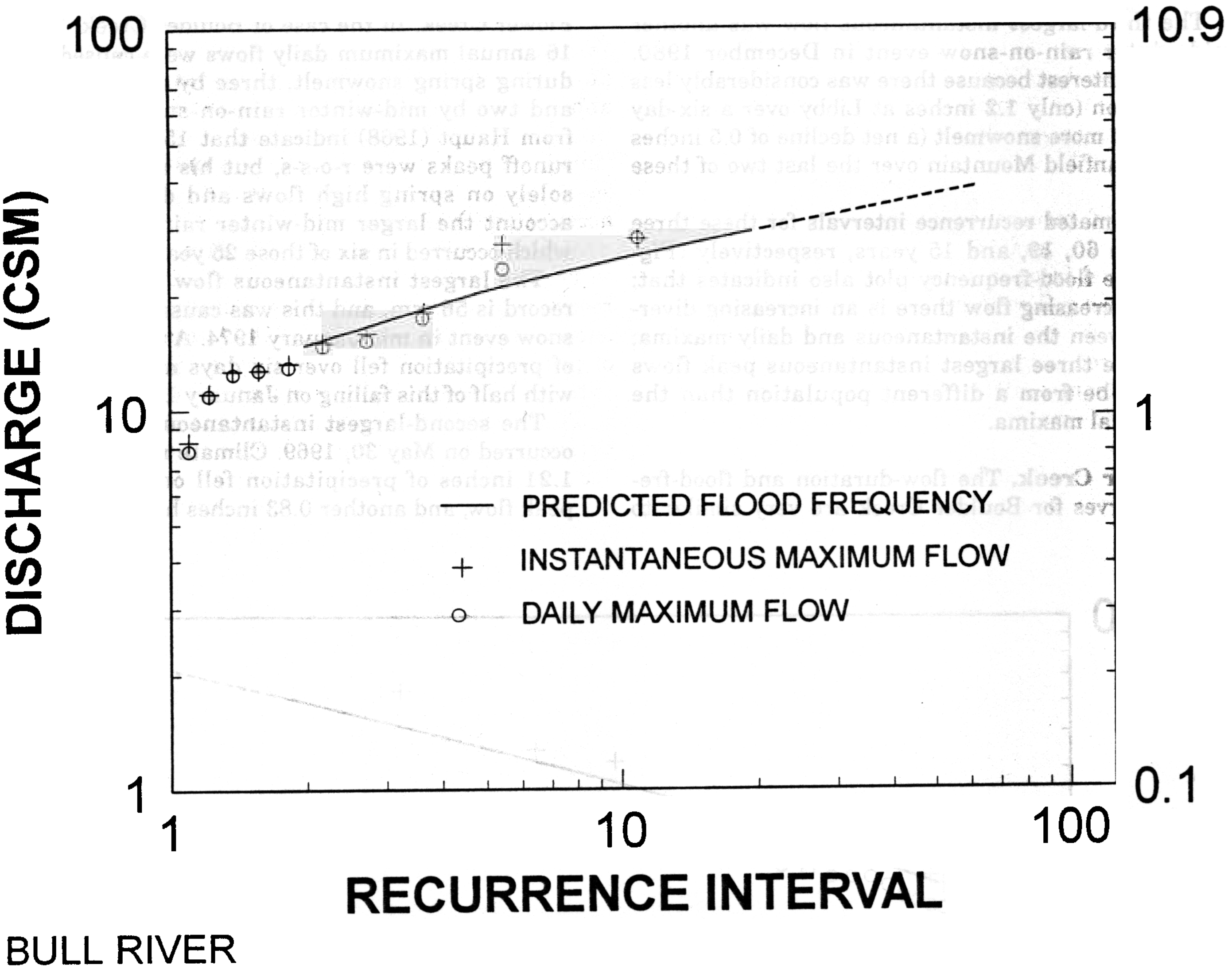

Figure 6. Flood-Frequency Curve, Bull River. Skew = 0.7.

no more than a 12 percent difference in discharge between the upper part of the flow duration curves from 1973-1981 and 1961-1990, respectively. This suggests that the results for Pinkham Creek, Big Creek, and Bull River are representative despite their short discharge records.

Sixteen of the 30 annual maximum daily flows on Flower Creek were attributed to r-o-s-s, while nine of the annual maxima occurred during spring snowmelt when no rain was recorded at the Libby weather station. Three of the peak flows were attributed to rain, and only two of the annual maximum flows were caused by mid-winter rain-on-snow. In the case of Flower Creek it also was possible to classify the seven annual maximum daily flows prior to 1968, as these all occurred during the spring when no precipitation was recorded at Libby.

A mid-winter rain-on-snow event in January 1974 generated the largest instantaneous flow on record, 64 csm. This same storm also caused the largest flows on record on Bull River, Placer Creek, and Boulder Creek. This event was largely rainfall-driven, with temperatures at Libby above freezing and 1.7 inches of precipitation recorded on January 15-16. Over these same two days there was only a net increase of 0.3 inches in SWE at the Banfield Mountain SNOTEL site.

The second-largest instantaneous flow was 45 csm on June 21, 1984. This was caused by 2.18 inches of rain at a time when there was no snow at the Banfield Mountain SNOTEL site 17 miles to the north. The 2.18 inches of rain at Libby is the maximum 24-hour precipitation event over the 86 years of record.

The third-largest instantaneous flow was another mid-winter rain-on-snow event in December 1980. This is of interest because there was considerably less precipitation (only 1.2 inches at Libby over a six-day period) but more snowmelt (a net decline of 0.5 inches SWE at Banfield Mountain over the last two of these days).

The estimated recurrence intervals for these three events are 60, 19, and 15 years, respectively (Figure 7). The flood-frequency plot also indicates that: (1) with increasing flow there is an increasing divergence between the instantaneous and daily maxima; and (2) the three largest instantaneous peak flows appear to be from a different population than the other annual maxima.

Boulder Creek. The flow-duration and flood-frequency curves for Boulder Creek are very similar to Flower Creek. In the case of Boulder Creek, 11 of the 16 annual maximum daily flows were caused by rain during spring snowmelt, three by spring snowmelt, and two by mid-winter rain-on-snow events. Data from Haupt (1968) indicate that 15 of the 25 spring runoff peaks were r-o-s-s, but his analysis focussed solely on spring high flows and did not take into account the larger mid-winter rain-on-snow events which occurred in six of those 25 years.

The largest instantaneous flow over the 60-year record is 56 csm, and this was caused by the rain-on-snow event in mid-January 1974. A total of 4.3 inches of precipitation fell over six days at Bonner's Ferry, with half of this falling on January 15-16.

The second-largest instantaneous flow of 49 csm occurred on May 30, 1969. Climate records show that 1.21 inches of precipitation fell on the day of this peak flow, and another 0.83 inches had fallen over the

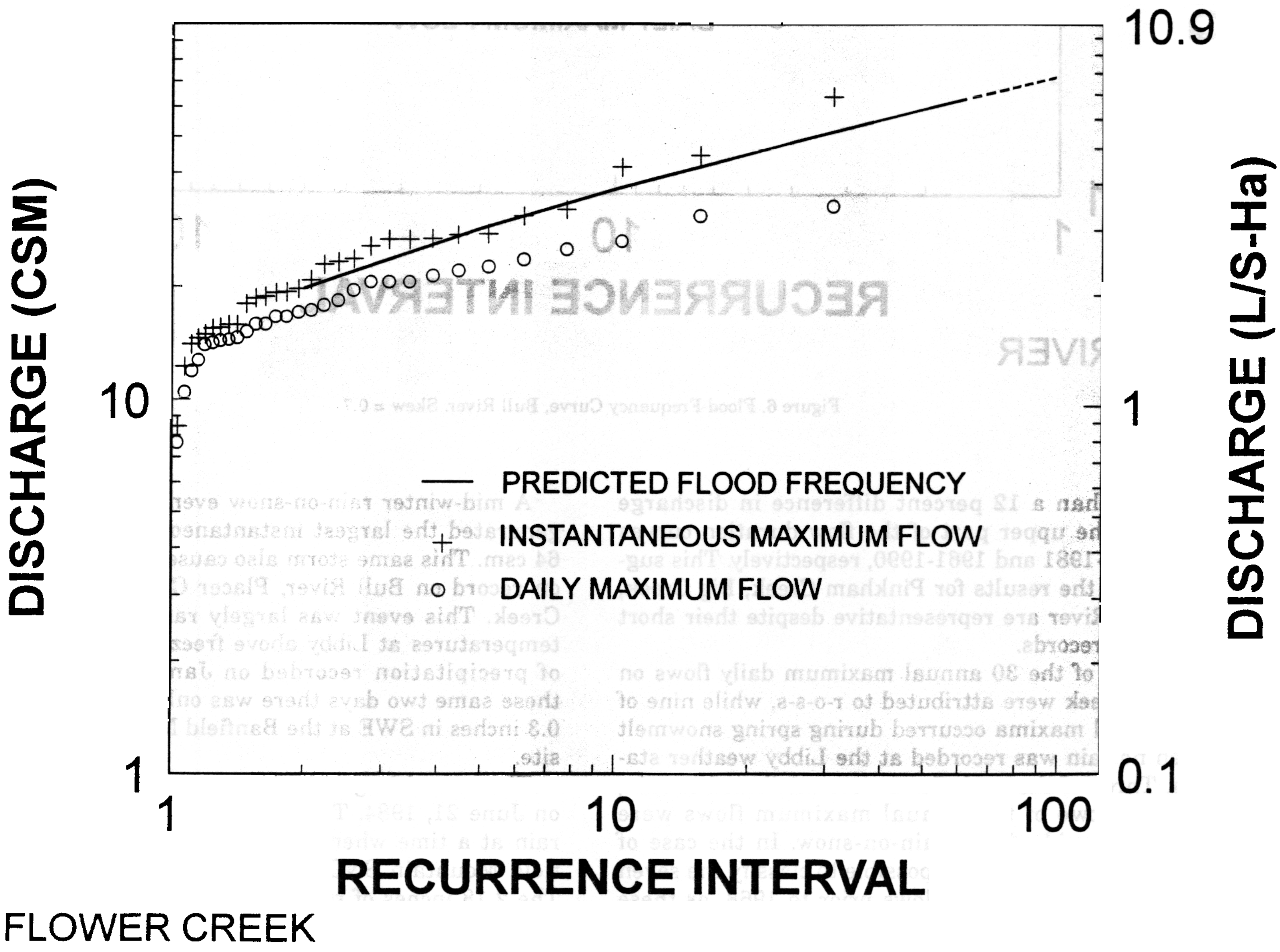

Figure 7. Flood-Frequency Curve, Flower Creek. Skew = 1.1

previous four days. Although the snowpack at the Banfield Mountain SNOTEL site had melted out three days earlier, the event was still classified as r-o-s-s. Rapid snowmelt prior to May 27 had "primed" the catchment, and the wet conditions, combined with residual snowmelt in sheltered or higher elevation areas, caused the observed large runoff response.

Flood-frequency analysis indicates that the largest instantaneous flow has an estimated recurrence interval of slightly more than 40 years (Figure 8). In contrast to Flower Creek, the largest events on record fall along the flood-frequency curve defined by the other annual maxima.

Placer Creek. Placer Creek had the highest instantaneous and daily flows of any of the six study basins and the highest frequency of mid-winter rain-on-snow events. Eight of the 21 annual maximum daily flows were classified as r-o-s-s, seven as spring snowmelt, and six as mid-winter rain-on-snow. The two largest events on record were both mid-winter rain-on-snow events, and these had instantaneous maximum flows of 141 and 81 csm, respectively.

The largest flow occurred on December 26, 1980, and this was associated with 3.08 inches of rain over a six-day period. Snowmelt probably contributed much of the runoff, as minimum temperatures remained above freezing at Wallace and the maximum daily precipitation was only 0.89 inches on December 25.

The second-largest flow was caused by the mid-January 1974 rain-on-snow event. Total precipitation over a six-day period was 5.2 inches, with 1.81 inches recorded on the day prior to the peak flow and 2.53 inches on the day of the peak flow. The 2.53 inches of precipitation which fell on the day of this peak flow

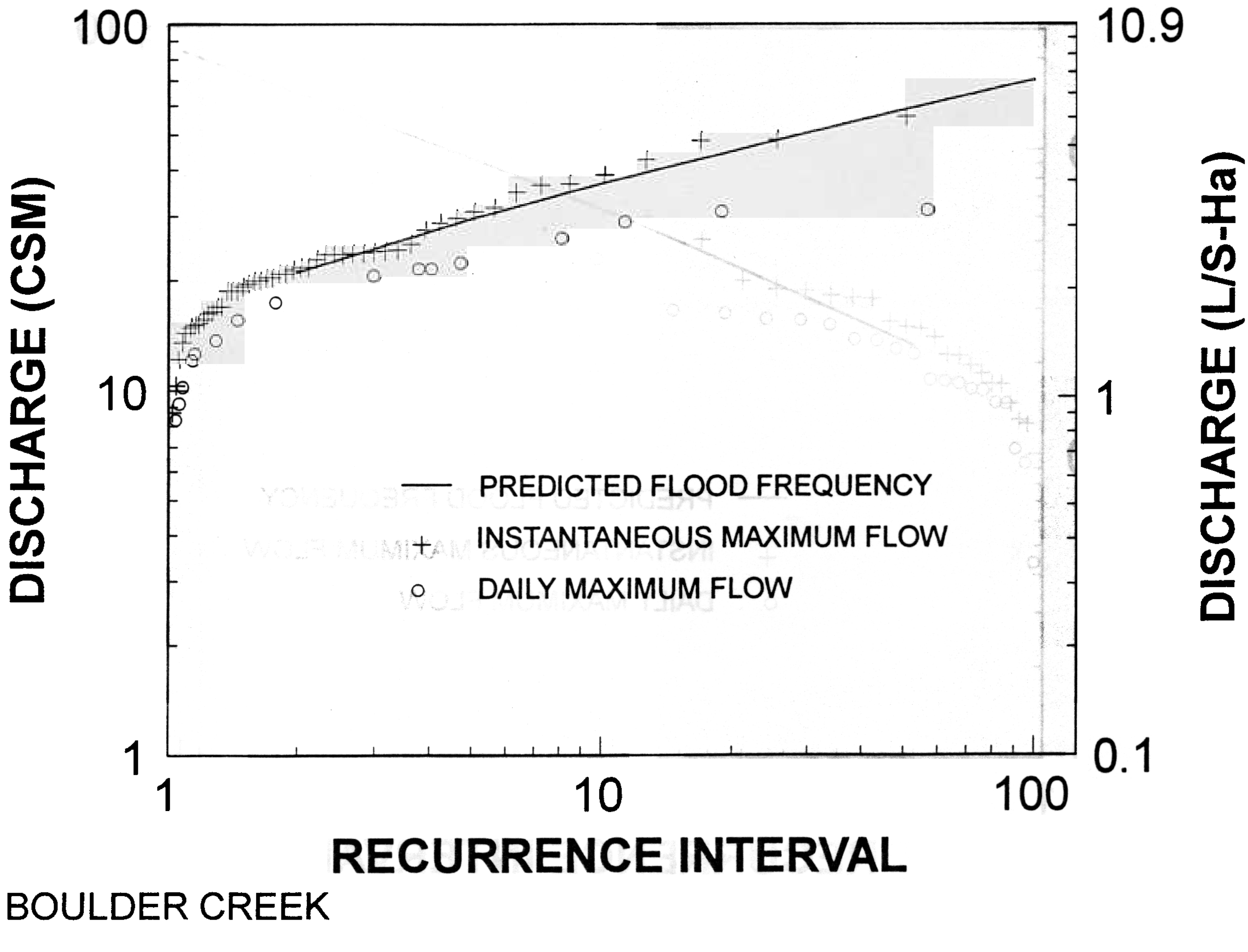

Figure 8. Flood-Frequency Curve, Boulder Creek. Skew = 1.2.

has an estimated recurrence interval of 15 years. The relatively cool temperatures immediately prior to this event probably explain why the relatively large amount of precipitation did not result in a record high flow.

Only one other instantaneous flow exceeds 37 csm, and that was another rain-on-snow event on February 20, 1982. The next five highest annual maximum daily flows were all classified as r-o-s-s. Measured precipitation associated with these r-o-s-s events was relatively small (0.04-1.40 inches) as compared to the precipitation associated with the three mid-winter rain-on-snow events (3.1-5.2 inches).

Flood-frequency analyses indicate that the four highest instantaneous and two largest daily flows fall above the line defined by the remaining annual maxima (Figure 9). The estimated recurrence interval of the largest rain-on-snow event is 45 years.

DISCUSSION

Geomorphic Importance and Classification Errors

The six basins analyzed in this study exhibited considerable variation in both the magnitude and cause of annual maximum daily and instantaneous flows. Mid-winter rain-on-snow events, while relatively infrequent, caused the largest flows on record in four of the six basins. Rain-on-spring-snowmelt was the most common cause of annual maximum daily flows in all six basins. To determine the relative importance of the different types of peak flow events on sediment transport and stream channel stability, one must evaluate whether the annual maximum daily flows are representative of the population of interest. Given the aquatic resources of concern, the population of

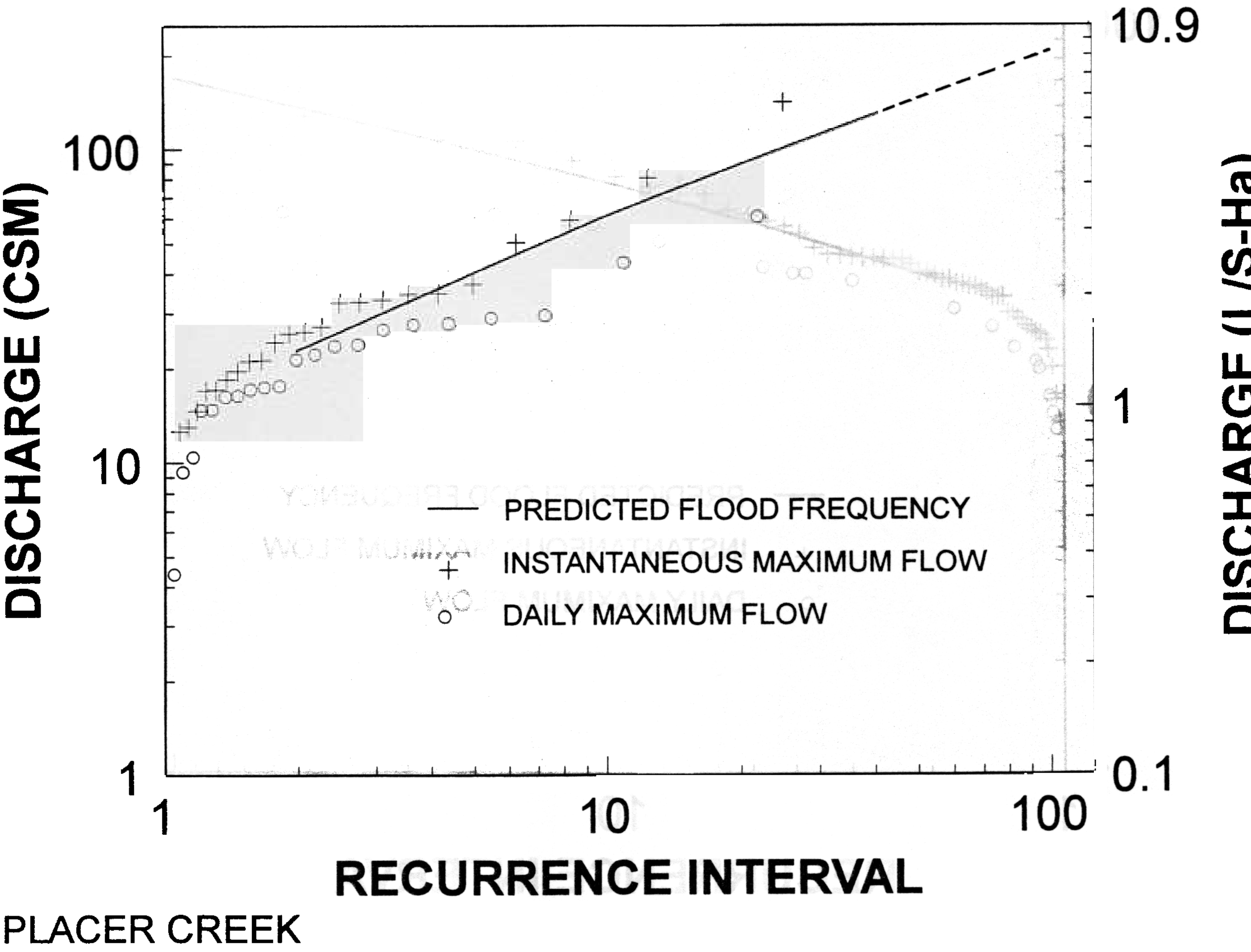

Figure 9. Flood-Frequency Curve, Placer Creek. Skew = 1.4

interest is those flows which contribute most of the geomorphic work (Grant, 1987).

The problem with assessing representativeness is that daily flows are serially correlated and the relative contribution of snowmelt and precipitation cannot be defined for an autocorrelated sequence of high flows. In this study, we evaluated snowmelt and climatic conditions for up to six days prior to the event because that period appeared to encompass most of the quickflow resulting from a particular snowmelt or rainfall input. We believe that both spring snowmelt and r-o-s-s would be of greater importance if one evaluated all high flows, since both rain-generated peak flows and mid-winter rain-on-snow events were relatively sharp-peaked and therefore would contribute less geomorphic energy than implied by the classification of annual maximum daily flows.

Most of the likely errors in classification would also increase the frequency of r-o-s-s. It is possible, for example, that rainfall occurred at higher elevations during spring snowmelt but no rain was recorded at the low elevation weather stations used in this study. SNOTEL rain gage data were not used because of the large distances between SNOTEL sites and most of the study basins.

An increase in the number of r-o-s-s events would also result from the failure to identify snowmelt after snow had disappeared from the SNOTEL site. Three of the four annual peaks attributed to rainfall occurred on Flower Creek. For two of these events, total six-day precipitation was less than 1.0 inch. Since 40 percent of the Flower Creek basin is higher than the Banfield Mountain SNOTEL site, it is highly likely that snowmelt was still occurring in the Flower Creek catchment during these events.

Predicting Daily Discharge from Hydrologic Inputs

Efforts to predict the magnitude of the annual maximum daily flows from snowmelt and precipitation were notably unsuccessful. Table 3 indicates the percent of the variation in the annual maximum daily flows on each basin that could be explained by 11 different precipitation and snowmelt variables. The highest correlations were between precipitation measured by the low-elevation climate stations and the magnitude of the annual maximum daily flows on Bull River and Placer Creek, respectively (Figures 10a and 10b). These relatively high correlations between precipitation and runoff are surprising because approximately 40 percent of the peak flows in these two basins were caused by spring snowmelt, and the size of peak flows on basins dominated by

TABLE 3. Percent Variation in Annual Maximum Daily Flows Which Can Be Explained by Each of the Meteorologic Variables Used in this Study (d refers to the day of the event; 6 days means that precipitation or snowmelt was summed for the day of the event and the five previous days; adjusted precipitation means that the precipitation was adjusted for the amount falling as snow). *n=22 for all equations which include melt on Flower Creek.

Basin/ Independent Variable	Flower Creek n=30*	Pinkham Creek n=9	Big Creek n=9	Bull River n=10	Placer Creek n=21	Boulder Creek n=16
PPT (d)	0.21	0.11	0.12	0.36	0.52	0.12
PPT (d+(d-1))	0.35	0.00	0.35	0.50	0.50	0.21
PPT (6 days)	0.36	0.01	0.02	0.77	0.39	0.16
Melt (d)	0.03	0.13	0.28	0.23	0.05	0.00
Melt (d+(d-1))	0.02	0.03	0.30	0.25	0.10	0.00
Melt (6 days)	0.02	0.00	0.22	0.33	.09	0.00
PPT+Melt (d)	0.00	0.02	0.30	0.09	0.05	0.03
PPT+Melt (d+(d-1))	0.01	0.02	0.27	0.01	0.04	0.04
PPT+Melt (6 days)	0.00	0.00	0.23	0.03	0.10	0.10
Adj. PPT (d)	0.09	0.11	0.12	0.25	0.18	0.21
Adjusted PPT (d+(d-1))	0.12	0.00	0.35	0.43	0.56	0.29

spring snowmelt were less predictable. In the case of Placer Creek, the higher predictability of annual maximum daily flows on Placer Creek is largely due to the few mid-winter rain-on-snow events which had both high precipitation and high daily discharge values.

The inability of snowmelt and precipitation data to predict annual maximum daily flows suggest that: (1) peak daily discharges are a complex response to much more than the estimated precipitation and snowmelt inputs; and (2) precipitation and snowmelt as measured by nearby climate stations and regional SNOTEL sites may not accurately represent the hydrologic inputs for a particular basin. Daily change in SWE was not nearly as well correlated between SNOTEL sites (Table 4) as total SWE. These results indicate that considerable spatial variability in climatic conditions within the study area and that extrapolations of only a few miles could lead to large errors in estimated hydrologic inputs.

Another problem lies in the use of daily data. Delineation by calendar day can disrupt the correlation between the timing of the precipitation or snowmelt and the resultant runoff. On larger basins, peak snowmelt runoff occurs in the late evening, and this means that the runoff from days with high melt rates will be spread across two discharge days. Several of the smaller basins showed an increasing discrepancy between daily and instantaneous flows with increasing recurrence interval. This probably is due to the smaller peak flows being snowmelt-dominated, while the larger peak flows are more rain-dominated and therefore more transient.

The timing of precipitation within a day was not incorporated into our analysis, and this can greatly affect the estimated amounts of rain vs. snow. The adiabatic lapse rate may also be a poor predictor of freezing level. Recent soundings indicate a higher freezing level than predicted by the wet adiabatic lapse rate during mid-winter rain-on-snow events (S. Johnson, KNF, personal communication). Errors in the estimated amounts of rain and snow will adversely affect the predictability of peak flows.

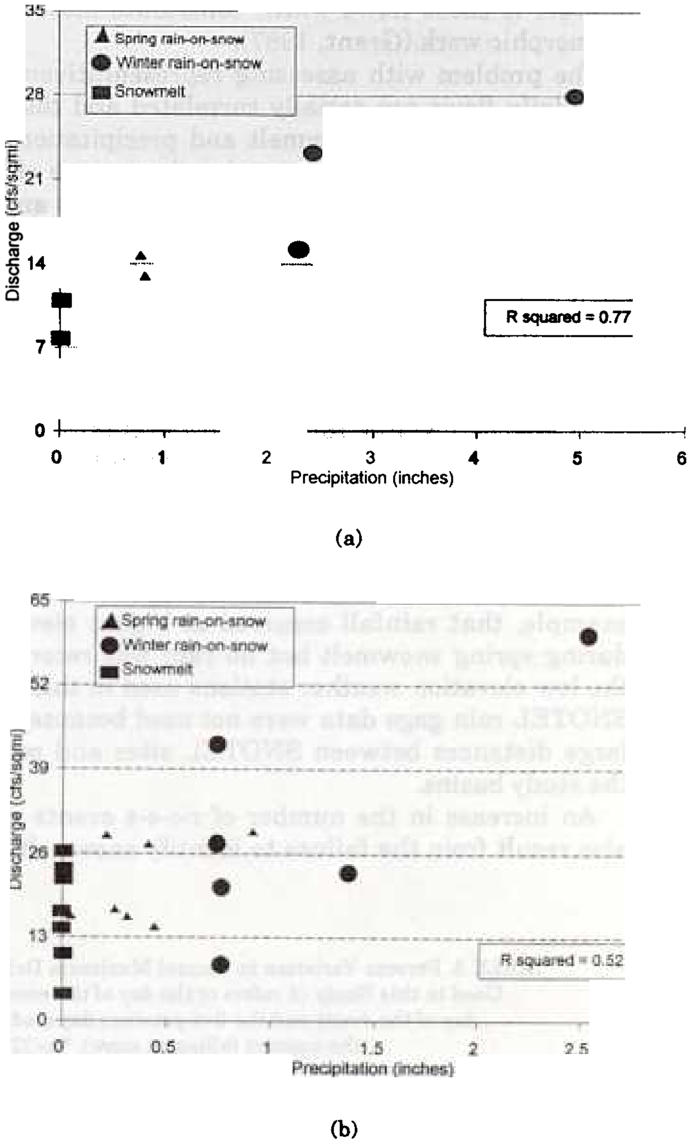

Figure 10. (a) Relationship Between Annual Maximum Daily Flow on the Bull River and Total Precipitation Over the Six Days Prior to and Including the Day of Peak Flow; (b) Relationship Between Annual Maximum Daily Flow on Placer Creek and Precipitation on the Day of the Peak Flow.

TABLE 4. Correlations of Daily Change in SWE Between SNOTEL Sites for Days When Snow was Present at Both Sites, 1985-1992.

SNOTEL Sites	Correlation (r)							
	1985	1986	1987	1988	1989	1990	1991	1992
Sunset-Bear Mountain	.749	.766	.409	.793	na	.708	.722	.723
Sunset-Banfield Mountain	.655	.684	.689	.451	.713	.646	.675	.614
Banfield Mountain-Bear Mountain	.770	.623	.691	.183		.815	.761	.813

Flood-Frequency Analyses

The flood-frequency analyses violated the principle that one should not mix different causes of peak flows (Interagency Committee on Water Data, 1981). The problem with separating peak flows by cause is that the sample size for the different populations, such as mid-winter rain-on-snow events, then becomes too small to develop reliable flood-frequency curves.

For Boulder and Pinkham Creeks, the mixing of several populations did not severely disrupt the flood-frequency curve derived from the instantaneous annual maxima. On the other hand, the largest mid-winter rain-on-snow events on Flower and Placer Creeks did not fit the flood-frequency curve defined by the other peak flow events. This poor fit was more pronounced for the instantaneous than the daily annual maximum flows, and this is probably due to the fact that the drainage areas of Flower and Placer Creeks are only 11 and 15 mi^2, respectively. In such small basins, a rain-on-snow peak is likely to be relatively brief and the daily flow would not be well correlated with the instantaneous peak flow. In both these basins the highest instantaneous peak flow is more than twice the corresponding peak daily flow, while the maximum instantaneous peak flows in the two largest basins (Bull River and Big Creek) are less than 40 percent larger than the corresponding maximum daily flow.

Positive logarithmic skews of 0.7-1.4 were required to fit the observed instantaneous peak flows in five of the six basins. Larger skews were generally associated with higher instantaneous flows. It is not clear why the skew value for Big Creek (–0.7) was so different from the other five basins. Possible causes include the short discharge record, large basin size, and lack of mid-winter rain-on-snow events.

The potential for yet larger mid-winter rain-on-snow events can be qualitatively assessed by comparing the precipitation associated with the largest flood on record to the maximum recorded precipitation (Table 5). Only on Placer Creek does the precipitation associated with the largest recorded flow approach the maximum 24-hr precipitation. Considerably larger floods appear possible on both Flower and Boulder Creeks, since maximum (or near maximum) precipitation and the highest flow have both occurred in mid-winter, but the amount of precipitation associated with the largest flow is less than half of the maximum recorded 24-hr precipitation. Maximum instantaneous flows for these lower elevation basins lie under the envelope curve for Montana of 1.7 $m^3/s/km^2$ (155 csm) for gaging stations above 1650 m (5450 ft) (Jarrett, 1993). Paleoflood studies could improve the reliability of the estimated recurrence intervals for the largest events, and these would be most useful on Placer and Flower Creeks.

The possibility of larger floods on Pinkham Creek, Big Creek, and the Bull River would require a determination of rainfall depth-duration-frequency curves for the months of maximum snowmelt, since the record maximum daily precipitation at Eureka and Heron occurred in summer (Table 5). It is of interest that the maximum daily loss of 2.3 inches SWE at Banfield Mountain is comparable with the maximum decline in SWE observed by Haupt (1979) in northern Idaho, but 65 percent larger than the mean maximum percolation in 2.7 ft^2 snowmelt lysimeters (Haupt, 1979).

TABLE 5. Maximum Daily Precipitation on Record and the Daily Precipitation Associated with the Largest Daily Discharge on Record.

Basin	Maximum 24-hr ppt. (in)	Date of Maximum Precipitation	24-hr. ppt. On Day Prior to Maximum Flow (in)	24-hr. Precipitation on Day of Maximum Flow (in)	Date of Maximur Flow
Big and Pinkham Creeks	1.47	August 1966	0.00	0.17	May 1976
Bull River	2.94	August 1970	1.64	0.81	January 1976
Flower Creek	2.18	June 1984	0.96	0.73	January 1974
Placer Creek	3.08	January 1975	1.81	2.53	January 1974
Boulder Creek	2.50	January 1954	1.27	0.87	January 1974

Effects of Forest Harvest

The analysis of the causes of peak flows, when combined with our understanding of the hydrologic effects of forest harvest, suggests that the impact of forest harvest could vary considerably among the different basins. Pinkham and Big Creeks are dominated by spring snowmelt and r-o-s-s, so forest harvest could increase the magnitude of peak flows by increasing both incoming net radiation and the turbulent transfer of energy to the snowpack.

The largest recorded events on the other four basins are caused by mid-winter rain-on-snow, and the impact of forest harvest on the magnitude of these events is still controversial. Lysimeter studies have shown increases of 40 percent in northern Idaho (Haupt, 1979) and 1-138 percent in the Western Cascades (Coffin and Harr, 1991), but the magnitude of the increase depends on the period analyzed and the amount of canopy melt (Beaudry, 1984). A reanalysis of data from several small watershed studies in western Oregon showed that logging increased the magnitude of small and moderate peak flows (Harr, 1986). Attempts to discern the effects of logging on the larger peak flows were hampered by the small sample size, high variability, and lack of detailed snowpack and climatic data (Harr, 1986).

For the six study basins, there was no apparent correlation between the magnitude of peak flows and the amount of forest harvest. Pinkham Creek has been the most heavily cut, but it has the smallest annual maximum flows. Placer Creek has the largest flows, but the mixed ownership makes it difficult to determine the actual percent harvested. It appears that local climatic conditions are the dominant control on the magnitude of peak flows. However, the effects of forest harvest on the magnitude of peak flows is of concern if we presume that each channel has formed in response to its unique pattern of high flows. Related work has shown a fining of the substrate in the study area in association with predicted increases in discharge due to forest management (MacDonald *et al.*, 1995). The effects of forest harvest on the magnitude of peak flows is the topic of a literature review now being conducted by the senior author.

CONCLUSIONS

There is considerable variability in the magnitude and cause of peak flows in northwestern Montana and northeastern Idaho. Maximum daily flows on record for the six basins analyzed in this study ranged from 6.4 to 60 csm, while the maximum instantaneous flows ranged from 9 to 140 csm.

Two types of rain-on-snow events were identified: mid-winter rain-on-snow and rain-on-spring-snowmelt. The former, while less frequent, generally caused the largest events on record and were associated with up to five inches of rain over a six-day period in mid-winter. Rain-on-spring-snowmelt was the most frequent cause of maximum annual daily flows in each of the six basins, but in most cases the amount of rainfall was small relative to the amount of snowmelt. Most of the remaining peak flow events were caused by spring snowmelt. The respective contributions of precipitation and snowmelt to a particular peak flow cannot be partitioned, nor can these independent variables be used to accurately predict the magnitude of a particular runoff event.

Forest harvest would be expected to cause differential increases in the magnitude of the observed peak flows, but climatic differences are the dominant control on the size of peak flows within the study area. For four of the six basins, flood-frequency analyses appear to be relatively robust despite the different populations of flood events. For Flower and Placer Creeks, the largest mid-winter rain-on-snow events do not fit the flood-frequency curve developed from the other annual maxima, and this discrepancy is much greater for the instantaneous flows than the annual maximum daily flows.

Accurate classification of the causes of peak flows requires detailed temperature, precipitation, and snowmelt data on the basin of interest, but these are rarely available. Accurate prediction of flood recurrence intervals, maximum likely flows, and the effects of forest harvest on peak flows require an accurate determination of the causes of peak flows.

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