Long-term Effects of Changes in Vegetation Condition, Precipitation and Watershed Parameters on Summer Low-flows in the Semi-Arid Pacific Northwest

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Summer low-flow behavior in the semi-arid areas of the Pacific Northwest was studied. Long-term data from thirty-eight streams/rivers and thirty-six precipitation stations was exploited. The study area was divided into five zones based on annual average precipitation. Trends and patterns in summer low-flows and precipitation were identified. Different zones showed different trends and patterns in precipitation over the period of record but significant similarities within each zone. Most of the summer low-flow and precipitation records showed that the 1930's and the late 1980's to early 1990's experienced major droughts. A possible return interval of 50-60 years appeared reasonable for similar major droughts in the study area.

Spring, summer and fall precipitation, on average, were found insignificantly related to the summer low-flows, except for northern Idaho and southeastern Oregon where summer precipitation was significant in explaining the

summer low-flow trends. Winter and annual precipitation were found significantly related to summer low-flows. But the zonal equations constructed to predict summer low-flows using precipitation alone were considered unsuitable for practical use.

Zonal and regional recession models to forecast summer stream flows with significant accuracies were constructed successfully. Extreme summer low-flows were not significantly related to different watershed cover types in eastern Oregon. However, percentage of rangelands appeared to be more related to the extreme summer low-flow than other cover types.

An extreme summer low-flow prediction model was constructed using several watershed and precipitation variables. Many of these variables were found to be significantly related to extreme summer low-flow. Watershed average width and annual minimum precipitation explained 71% of the variations in the extreme summer low-flow. The model finally selected, with the inclusion of watershed end point elevation, was able to explain 79% of the variability in the extreme summer low-flow. Stream and precipitation gauges need to be carefully maintained during dry periods. Also, generalization of climatic trends based on a few observations in a large region can be misleading.

Doctor of Philosophy thesis of Aurang Zeb presented on
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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (continued)

LIST OF TABLES

Table **Page**

Long-term Effects of Changes in Vegetation Condition, Precipitation and Watershed Parameters on Summer Low-flows in the Semi-Arid Pacific Northwest

PROBLEM STATEMENT

Much of the inland Pacific Northwest (PNW) is typical of semi-arid, forest areas found elsewhere in the world. High elevation, steep terrain, weak geologic formations, sparse vegetation, and irregular precipitation make the management of these lands difficult. Such areas need great care for future management planning, soil conservation, fish habitat, wildlife and timber production.

Water yield from the forested watersheds is regulated by climatic and physical parameters as well as specific management activities (Wyk, 1987). For successful watershed management, knowledge of the climate and physical characteristics of the area and their interrelationships is very important.

Hydrological information regarding low stream flows and their relationship with vegetation conditions and rainfall patterns in the inland PNW is incomplete. Guidelines for proper land-use policies and practices require a better understanding of climate and stream flow trends. Stream low-flow characteristics are highly dependent upon vegetative cover, watershed topography, extent of potential aquifers, climate, soil and land use; no single parameter can explain them completely. The difficulty in estimating low-flow quantities and timing reveals that the complexity of low-flow regimes needs to be examined carefully (Chang and Douglass, 1977).

Vegetation is an important component of precipitation-catchment-stream flow interaction. Within a catchment, the physical parameters of a watershed remain unchanged over a long period. However, the vegetation component of a watershed keeps on changing. With changing approaches to forest management, the forest areas of the PNW have gone through various changes during the past 50-60 years. Changes in vegetative cover affect the consumption of water through evapotranspiration, accumulation and melting of snow, timing and quantity of peak and low flows, etc.

An ever-increasing demand for fresh water and increasing concern about fish habitat stresses the need for the study of stream flow particularly during drought periods. A better understanding of stream flow dynamics is needed to effectively manage water resources. Surface water forms a major part of the fresh water resource and is important to human needs during periods of scarce water.

Factors affecting low-flows include topography of the watershed, hydraulics of sub-surface water, vegetative cover, and climate. Definitions of "drought" vary greatly and depend on the uses the water from any given source may have. A drought may be simply defined as a lack of rainfall. In humid areas, a period of several days without rain may be considered a drought. However, in semi-arid areas, drought conditions may be realized only after several years with no, or very low, precipitation. Drought effects can be devastating because of its simple unpredictability and the human existence dependency on agriculture (Harrold, 1990).

Low stream flow periods during the summer season are common. To insure the stability of farming and other summer flow-dependent enterprises in the eastern PNW for a long period, it is necessary to provide for the maintenance of a reasonable balance between the activities carried out in the area and the availability of water during droughts. Low-flow studies giving long-term trends of summer stream flows may help in such planning.

OBJECTIVES

This study's main objective was to develop a thorough understanding of patterns of summer low-flows and their relationship with vegetation conditions, precipitation, and watershed parameters. The outcome of this study will be useful for better management of the semi-arid areas of the PNW. Specific objectives included:

A) identify trends and patterns of summer low and base flows (drought) in each zone, and the study area as a whole.

B) identify trends and patterns of annual precipitation in each zone, and the study area as a whole.

Hypothesis 1: There were no particular trends and patterns of summer low-flows and precipitation in the study area over the period of study. Episodes of dry and wet periods can not be predicted for the next couple of decades in the study area.

C) determine correlation between stream low-flows and precipitation in the study area,

D) determine the effect of winter precipitation on summer low-flows in the forested catchments in the study area.

Hypothesis 2: Summer stream low-flows were not significantly dependent on annual or winter precipitation. Annual and winter precipitation could not explain enough variability in summer stream low-flows to be useful in the study area.

E) to determine the long-term effects of changes in vegetative cover on summer low-flows in the study area.

<u>Hypothesis 3:</u> Type and percent of vegetative cover, and it's change over time, has no affect on summer low-flows in the study area.

F) determine if summer low-flows are unaffected or negatively related to the physical parameters of the watershed.

<u>Hypothesis 4:</u> There was no relationship between summer low-flows and watershed parameters in the study area.

G) develop a recession forecast model for each zone as well as the entire study area.

H) develop a model for predicting summer extreme low flows (hydrologic drought) using percent vegetative cover, annual and seasonal precipitation, and physical watershed parameters for the study area in the semi-arid areas of the PNW.

LITERATURE REVIEW

Hydrologic and biologic records

Instrumental meteorological records in the United States date back to 1715, when the first measurements of precipitation were made at Cambridge, Massachusetts. Instrumental climatic data for the western United States is 100 to 150 years old. The instrumental data for this area is the first of its kind. Older climatic information is collected through dendroclimatic reconstructions. Generally data from the southwestern United States, rather than the western United States as a whole, is used for the precipitation studies in the western United States. Precipitation has been much heavier in the southwest (Bradley, R.S. 1976).

Vegetation and stream flow

Water yield

Vegetation is an important component of the hydrology of a watershed. Hydrologic balance is interrupted by timber harvesting. The fact that removal of forest vegetation increases stream flow has been known since the early 1900's. Research conducted so far has verified this fact; the type and density of vegetative cover affects the amount of rainfall available as runoff (Bosch and Hewlett, 1982; Debussche et al., 1987; Abbas and Hanif, 1987).

Forest vegetation is considered to be an efficient regulator of runoff. It maintains a high infiltration rate, and hence, subsurface storage from which the river flow is sustained during periods of dry weather. A change in vegetative cover may change the hydrology of a watershed. A decrease in vegetative cover usually increases water yield. Reduced evapotranspiration results in increased water available for stream flow and ground water recharge. Nearly every study in forest zones has shown an increase in stream flow following forest cutting or a gradual decrease in stream flow as forest regrowth proceeds.

In well watered regions, stream flow response is proportional to the reduction in forest cover. The magnitude of increase or decrease depends on climate, topography, vegetation, soil and other environmental factors (Baker, 1986; Hibbert, 1967; Gentry and Parodi, 1980; Hibbert, 1967; Cheng, 1989; Hornbeck et al. 1970; Harr et al., 1982; Rothacher, 1970; Swank et al., 1988; Lee et al., 1975; Davis, 1984; Hicks et al., 1991). The type of vegetative cover can play an important role in water yields. Water yields in the Blue Mountains of Oregon were lower from western larch-Douglas-fir dominant basins than from the watersheds comprised of fir-spruce, lodgepole pine, ponderosa pine and mountain meadow, even though they received the same amount of precipitation (Higgins et al., 1989).

Bosch and Hewlett (1982) reviewed 94 catchment experiments and found that 10% change in the cover of pine and eucalyptus forest types increased the water yield on average 1.57 inches. For the same percent of cover change in the deciduous hardwood and scrub forest types water yield increased on average approximately 0.98 inches and 0.4 inches, respectively. Watershed studies in Coweeta, North Carolina, reported maximum changes in water yield averaging 26 inches.

Hornbeck (1975) found an increase in annual stream flow between 9.45 and 13.8 inches in an experimental cutting on two small hardwood forested watersheds in New England. Most of this increased stream flow occurred during summer and early autumn. However, revegetation took the stream flow back to normal after four years. Hibbert (1969) conducted an experiment on a 22-acre catchment in the southern Appalachian that had been cleared of hardwood forest and planted with the grasses, and found no significant change in water yield when grass production was high. However, water yield exceeded the predicted yield by over 5 inches annually as the grass productivity declined.

Swank et al. (1988) studied the long-term stream flow records for control and experimental forested watersheds at Coweeta, North Carolina. Long-term data provided a basis for evaluating hydrologic response to vegetation management. Increases were recorded in most months: about a 100% increase during the low-flow months when water demand was usually high. After harvest, regrowth of hardwoods brought the stream flow back to pre-harvest levels over the next several years. Long-term experiments showed the striking dependence of stream flow on the type of vegetative cover. A 25 year conversion of hardwood to white pine resulted in reduced annual flow by 10 inches, and produced a significant reduction during every month of the year. Evapotranspiration by hardwoods is less than by pines due to lower leaf area.

After intensive logging in the Redwood Creek basin in the western California, Lee et al. (1975) found water yield increased by about 20 percent. They attributed this increase to changes in the hydrology of the area because of reduced vegetative cover, and not because of climate change. They assumed that physical basin changes were significant contributors to the increased surface runoff. They did not try to separate the effects of reduced evapotranspiration and physical basin changes on water yield.

Timber harvest in two small watersheds in western Oregon containing 130-year-old timber increased annual water yield up to 17 inches. Increased summer flows were indicated by a decreased number of low-flow days after logging, particularly within the clear-cut watersheds.

During the drought of 1977 only eight and two low-flow days occurred at clear-cut and shelterwood watersheds, respectively, compared to 143 and 135 low-flow days predicted by the calibrated relationship. However, peak flows did not change significantly, either in size or in time (Harr et al., 1982). Where increased summer flows have been detected, the relatively large summer increases tended to diminish quickly as riparian vegetation reestablished (Hicks et al., 1991).

Harr (1986) studied the effects of clear-cutting on rain-on-snow runoff in western Oregon. He concluded that clear-cut logging altered snow accumulation and melting pattern, and provided a higher rate of water delivery to the soil. In another study, Berris and Harr (1987) concluded that the total energy reaching to the ground in a clear-cut plot was 40% greater than in a forested plot. This results in faster snow-melt and increased peak flows during rain-on-snow events. A 21% increase in water yield was measured in the clear-cut plot over the forested plot during the largest rain-on-snow event of the study. Evapotranspiration is reduced by timber harvesting, resulting in reduced soil moisture depletion during the growing season (with less deficit than before harvesting). Due to lower deficits, water yield is increased during the spring snow-melt period. Golding and Swanson (1986) also found that snow water equivalent (SWE) is greater in a clearing (whether small or large) than in forested areas.

The greatest increases in water yield following logging in the western United States have been recorded in the Cascade Range of Oregon. When a 237-acre watershed in the H.J. Andrews Experimental forest was completely clear-cut the annual water yield increased 18 inches. Significant increases in yield did not occur until 40 percent of the timber had been cut (Rothacher, 1970). Patch cutting 30 percent of a 250-acre watershed, with annual precipitation of 90 inches and annual stream flow of 57 inches, increased water yield by 6 inches.

Land on which vegetation is predominantly grasses, forbs, shrubs, and trees such as aspen and woodland species of pine, juniper and oak, is called rangeland (Hibbert, 1983). Evapotranspiration by grass is more in spring and less in summer than hardwood forest (Swank et al. 1988).

Conversion from hardwood to grass may also alter stream flow, depending on the productivity of the grass. There was no significant change in flow from a watershed with a vigorous grass cover, but as grass productivity declined, stream flow increased (Swank et al. 1988). These yearly changes were so small that they would have little affect on the long-term trends.

No significant increases in annual water yield were shown for three small watersheds in northeastern Oregon after shelterwood cutting (30% canopy removal, 50 percent basal area removal) and clear-cutting (Fowler et al., 1987).

In general, annual water yields are found to vary roughly proportional to the amount of vegetation removed. Most research work on the relationship between water yield and vegetation changes has been conducted in other than arid or semi-arid areas. However, general findings are applicable to the semi-arid and arid areas as well. Relative effects on summer stream low-flows in semi-arid areas are considered to be more noticeable than humid areas.

Aquifer and stream low-flow

There are three basic components of stream-aquifer systems:

1. The surface water conveyance system consisting of the main stream, tributaries, diversion canals, supply ditches, and storage reservoirs,
2. The unsaturated flow region in the aquifer transmits water between the ground surface and water table, and the surface water conveyance system; and
3. The saturated flow region acts a storage reservoir and at the same time transmits water from one aquifer point to another.

These three components are in continuous dynamic interaction in natural operating conditions (Illangasekare and Morel-Sytoux, 1982).

Glaciers, frozen reservoirs of water, affect stream flow in several ways. They can contribute an unexpected water volume, delay the maximum seasonal flow and decrease the annual and monthly variation of runoff. The release of water from storage greatly affects the local hydrologic cycle by contributing to stream flow during otherwise low-flow periods (Fountain and Tangborn, 1985).

Snow packs in mountainous areas are important for sustained stream flow. Two-thirds or more of the annual precipitation in the Rocky Mountains is stored in the winter snowpack (Troendle and Leaf, 1981). Redistribution of the snowpack decreases with the increase in the density and cohesion of the snow, and increases with the increase in wind speed.

Snowpack in clear-cut areas melts faster and earlier in the season than forested areas due to increased exposure to solar radiation. Snowmelt advanced by up to several weeks in the clear-cuts in the Rocky Mountain region. Reduced soil moisture requirements on the harvested areas make excess water available to the stream earlier (Troendle, 1983). Generally, forest clearcutting has been found to advance the snow melt runoff by about 5 to 14 days.

Low-flows (drought)

Low-flows are not well defined. Low-flows may be qualitatively defined by a "low" water level. This suggests that less water is discharged than normal, and normal is the given discharge over a given interval (Kaijenhoff and Moll, 1986). Drought, a hydrologic extreme event, can simply be defined as an annual minimum flow, or annual 7-day low-flow. Annual 7-day low-flow is defined as the minimum of 7-day moving average flows (minimum average flow for 7 consecutive days).

The drought defined by the use of precipitation is usually known as a meteorological drought (Chang and Jennifer, 1990). Hydrologic drought is defined by the use of stream flow (Draucup et al., 1980) and represents a period during which stream flow could not supply established uses under a given management plan. It is the stream flow on which the water resources development mainly depends. The extent of the damage done by a drought is not only a function of its severity but also duration. Whipple (1966) used the term drought for the prolonged periods of stream run off which averaged less than the long-term mean.

Drought has a different meaning to different people, depending on how a water shortage affects them. Lower than average precipitation for some time period is generally defined as meteorological drought. However, this fails to consider influences of antecedent conditions, evapotranspiration, and the time-lag factors of hydrologic response. A shortage of water in the root zone of crops such that the yield of plants is reduced considerably is termed as agricultural drought. Hydrologic drought is generally defined in terms of low levels of stream flow, reservoir storage, ground water, or some combination.

Chang (1990) studied droughts using daily stream flow series and different truncation levels. He concluded that low-flow characteristics of natural streams are different from mean flow characteristics. He concluded that during a drought, flow forecasting using the drainage area is not feasible.

Palmer's drought severity index (PDSI) is perhaps the most widely used regional drought index. Karl (1983) tested the sensitivity of the PDSI in relation to changes of derived and prescribed parameters included in the PDSI calculations in order to determine their effect on the spatial characteristics of drought duration. He found negligible effect of sensitivity tests.

It is ambiguous to use the value of PDSI as a measure of hydrologic drought. Considerable caution should be taken in drawing any conclusion about hydrologic drought from the PDSI. It is not uncommon for PDSI values to indicate serious drought condition at times when stream flow or groundwater levels within the climatic divisions are not subnormal at many stations.

During one of his studies, Alley (1985) observed that stream flow index tended to fluctuate in and out of subnormal conditions even during major dry episodes. The

PDSI values were more constant in displaying continued dry-condition throughout periods of major drought. The ground water indicates the occurrence of dry periods later than either PDSI or stream flow index, and is a more conservative indicator of the end of a major drought.

Great care is needed in drawing conclusions from studies of the spatial and temporal characteristics of drought that rely on a single regional index. With the truncation method based on partial duration series for daily stream flows, severity and duration of droughts are better defined, and are shown to have strong correlation coefficients for all gauge stations studied (Chang and Jennifer, 1990).

Low-flows in forested watersheds are affected by precipitation patterns as well as land management activities. Although the effects of different vegetation types on water yield are fairly well understood, further studies are needed to investigate the effects of afforestation on "low-flows" in rivers (Calder, 1986). The specific agents responsible for changes in low-flows in a forested catchment basin can be identified by detailed study of the climatic and physical parameters contributing to the low-flows. Particularly, percentage of the area under vegetation, silvicultural systems being practiced (Brown, 1972) and rainfall patterns affect the dynamics of low-flows.

Douglass and Swank (1975) presented an equation, based on their 40 years of experimentation at Coweeta to predict the annual increase in stream flow from the percent basal area cut and the theoretical extraterrestrial radiation load for the watershed. They found that timing of the increased flow from the watershed depends on the magnitude of the increase. However, results have consistently shown that much of the increase appeared in the low-flow season.

In areas where precipitation falls primarily as rain, research has shown that removing vegetation can increase late summer stream flow. However, timing is largely dependent on the distribution of precipitation. In Pennsylvania, where precipitation is well distributed throughout the year, clear-cutting the lower 20 percent of a 102-acre watershed resulted in a significant increase in water yield. The increased stream flow occurred primarily during the months of May to October, with much of this occurring during the critical low-flow months of July to September (Lynch et el., 1976).

The source of stream flow during the dry season is mainly ground and soil water. Vegetation extracts much of the water held in the surface few meters of soil. Opening the stand enhances the accumulation of snow as well as early melting of snow (Troendle and Leaf, 1981).

On the average, the snowmelt period is moved forward by a few days on low energy sites and to two weeks on high energy sites. Earlier snowmelt is expected to result in decreased late summer flows as the surface and sub-surface water supply ceases earlier and groundwater supply is reduced. Evaporation loss during critical low-flow months of summer is a factor. Croft (1948) studied the canyon-bottom phase of evapotranspiration loss from Farmington Creek in northern Utah, with mixed vegetation and grasses along the stream. He estimated evapotranspiration as one-third of the total stream flow (Croft, 1948)

Harr (1980) found that low-flows were decreased significantly after patch logging in the northern Cascades of Oregon, without changing the annual water yields or magnitude of peak flow. He suggested that reduced contribution from fog drip was responsible for this decrease in low-flows. However, annual water yield and low-flows measured in the subsequent years were higher than before harvesting, although vegetation was still not established.

Johnson and Meginnis (1960) found that the low-flows increased significantly after cutting of a mountain hardwood forest and its woody understory in North Carolina. As the forest cover reestablished with time, stream flow declined.

In eastern Oregon, low-flows occur during winter in snow-covered high elevation areas, and during summer on lower elevations where snowmelt occurs earlier. Higgins et al., (1989) reported that annual 7-day low-flow for streams in the Blue Mountains occurred from July to February, with 86 percent of low-flow events occurring in the months of August (18%), September (37%), and October (31%), covering a range of 0.002-0.323 cfsm.

Elmore and Beschta (1987) suggest that recovered riparian vegetation and the aggradation of formerly incised stream channels may improve summer flows in eastern Oregon. However, it is doubtful that contribution from such a small area (channel bed) could result in increased summer low-flows. The increased evapotranspiration from the new or added riparian vegetation would or could offset any gains. This increased summer flow may be due to the removal of juniper trees (which are high consumers of water) over the catchment area.

In general, low-flows are found to increase with reduction in vegetation. The increase is proportionally higher than increases in annual water yield. Recovery to pre-harvest flow levels may be fairly rapid with regeneration.

Much of the eastern PNW is used for livestock production as well as for agriculture. Summer low-flows are very important for agriculture crops. Grazing affects the vegetation on the streambanks and may influence the stream flow characteristics. Kauffman et al. (1983) found significantly greater stream bank erosion and disturbance occurred due to livestock grazing than with no grazing.

Vegetation along streambanks increases channel stability and provides erosion control. Aggradation of the stream channels results in increased water storage capacity of the channel beds during the wet season, as well as higher water tables and more vegetation. Higgins et al. (1989) did not find any effect of grazing on low-flows in north eastern Oregon, Hicks et al. (1991) attributed decreased August low-flows to increased riparian hardwood vegetation after clear-cut logging in the western Cascade Range, Oregon.

Rainfall pattern and stream flow

Generally, rainfall depth increases with elevation. However, Farmer and Fletcher (1971), while working in central and north central Utah, found that the zone that received the greatest depth was not the highest elevation zone. Bradley et al. (1987) discovered a significant increase in precipitation over mid-latitudes and a concurrent decrease in precipitation over low-latitudes during the last 30-40 years in the northern hemisphere.

Wahl and Lawson (1970) suggested that we should compare recent climatic data with the normals valid for the middle of the last century rather than with the early to the middle 20th century. In the northern hemisphere, they concluded that the region was still in the "little Ice Age", which was interrupted only briefly during the late 19th century to mid twentieth century (~70 years) by a temporary warm spell. Their results showed a return in the second half of the 20th century to a prewarming pattern in the western United States.

The western United States, however, showed a cooler climate during the early to mid twentieth century than the mid nineteenth century. Seasonal normals for precipitation and temperature showed positive deviation for the period during the 1850's and 1860's from climatic normals of the 1931-60's annual averages. Maximum positive departures were shown in early fall.

Both rainfall and stream flow records contain errors resulting from recorder malfunctions, instrument response, observer and processing errors. Rainfall over a catchment varies spatially, and the distribution over the catchment may not be well represented by that measured at the rain gauge (Higgins, 1981). In some cases, precipitation may only be measured at a location outside a watershed.

Usually, long-term temperature and precipitation trends are opposite from each other. Harrold (1990), while explaining the graph from J. E. Oliver (Climate and man's environment) about the generalized temperature variations during the geologic past, found that temperatures were 4.5° F and 2° F above those of today's temperatures around 5000 B.C. and during 800-1200 A.D., respectively.

Temperatures were 1.8° below those of today's temperatures during 1550 A.D. to 1850 A.D., called the "Little Ice Age". World temperatures were slightly warmer during 1850 A.D. to 1940 A.D. The period between 1940 A.D. and the present indicates a levelling off of temperature.

Wahl and Lawson (1970) compared climatic conditions in the 1850's and 1860's with 1931-60 normals. Their results showed positive anomaly in precipitation and temperature over the mountain states for all seasons. They concluded that the climate of the western United States in the 1850's and 1860's was decisively wetter (except for the Pacific coastal region) compared to conditions in 1931-1960.

Their conclusions are based on widely scattered observations, most of which were kept for less than five years within the 20-year period. Also, only in the late 1860's, there were sufficient data to generalize over the whole area, and even then the distribution of stations is heavily weighted towards New Mexico and Arizona. For the most part of the western United States including Nevada, Idaho and Oregon, data are inadequate to support any conclusions for the period (Bradley, 1976). During 1865 to 1890, precipitation was above 1951-60 averages over most of the western United States, while summer and fall were drier than in the 1950's.

Carter (1935) examined the precipitation and temperature trends in the PNW for the period from 1870 to the 1933. Three of the five stations were in the eastern PNW (Boise, Idaho, Spokane and Walla Walla, Washington). On a ten-year average basis, wettest periods for all five stations are shown in the late nineteenth century and driest periods are shown more or less in the 1920's and early 1930's. Warmest years, again, are shown in the 1920's, except at Boise, where the warmest 10 consecutive years were 1869 to 1878. Spring seasons were getting warmer during 1920's and 1930's compared to the late nineteenth century in the PNW . Summers were also getting warmer at all stations except at Boise. The drought of the late 1920's and 1930's in the PNW is reported by several studies (Keen, 1937, Graumlich, 1985).

Effects of topography on climate have been well studied in the past. Pittock (1977) applied a correlation pattern between year-to-year fluctuations in local climatic parameters and indices of larger scale general circulation to precipitation pattern in the state of Washington and surrounding area. He indicated that the major part of the rainfall changes observed in the Washington area during the study period (1941-70) can be accounted for by a change in the general circulation pattern.

Studies on precipitation fluctuations over a region (Bradley et al., 1987) and the relationship between low-flow frequency and basin characteristics (Hammett, 1985) appear more frequently in the literature than do studies on the relationship between stream low-flows and precipitation. Many studies have shown that low-flows are more difficult to estimate than other flow characteristics.

Most often, the explanation for the temporal increase or decrease in stream flow is based on the physical characteristics of the watershed. Characteristics such as area, vegetative cover, etc. are used without considering any changes in the general pattern of precipitation. However, an increase in general precipitation trend may explain the changes in stream flow.

Troendle and King (1985) found a strong correlation between estimated increases in flow, as a result of harvesting, and precipitation during winter and the spring snowmelt period. They suggested that much of the annual reduction of initial increased flow, formerly attributed to regrowth or time, was now explained by precipitation.

Dendroclimatology

It is assumed that precipitation has a similar effect upon tree-growth and stream runoff, and that runoff can be estimated from tree growth. For longer trends behavior, tree-ring studies may be used. Ring widths of trees are sensitive indicators of precipitation variations and can be used to qualitatively construct regional indices of annual precipitation (Graumlich, 1985; Meko, 1982; Rao and Durgunoglu, 1989). Reconstruction of past climate from tree ring data, dendroclimatology, has been extensively applied in many areas of the world.

Scientists have reconstructed drought histories, annual stream flows, and annual precipitation. Tree ring chronologies can be used as proxy hydrological records. For White River, Arkansas, reconstruction of stream flow from a tree ring study resulted in good similarity with the gauge data (Cleaveland and Stahle, 1989). Tree-growth and runoff curves for the Truckee River Basin, when compared, revealed a close agreement between the two (Hardman and Orvis, 1936).

From ten tree ring chronologies, Blasing et al. (1988) reconstructed annual precipitation from 1750 through 1980 in the south-central United States. The reconstructed precipitation series indicated that, throughout this period, severe and prolonged droughts have occurred at roughly 15-to-25 year intervals.

Davis and Sampson (1936) studied the relationship between annual precipitation and growth of trees as measured by the annual rings of ponderosa pine trees in Modoc County, California. They found no correlation between annual precipitation and the growth of the trees. Their yearly trend of precipitation explained only 14% of the trend of growth of ponderosa pine in the area. They concluded that interaction of plants to their environment is so complex that the existence of relationship between any one physical factor to plant-function is obscured.

Although the relationship between moisture conditions and tree-ring width is complicated, large widespread drought or wet periods can be reconstructed from tree-ring records (Stockton and Meko, 1975). From one of their studies, they concluded that the mid-1930's drought in the western United States was unsurpassed in magnitude by any drought in the previous two centuries, and that the period from 1907-1916 constituted the wettest decade since 1700 A.D.

Keen (1937) constructed at an index of ancient climatic history back to the year 1288 through a study of tree rings in eastern Oregon. He used the annual radial growth of 1240 ponderosa pines, measured with a micrometer. He compared the seasonal growth pattern from tree-rings with the Weather Bureau Record and U.S.G.S. water supply records for the period of 1870 to 1935. Mostly peaks and depressions of trends in growth coincided with these records.

The tree ring records for eastern Oregon did not indicate any general trend toward drier or wetter years during the past 650 years. The period from 1917 to the mid 1930's was shown to be the critical drought (when smoothed annual precipitation trend is below normal) for eastern Oregon forests in the last 650 years, not in its duration but in its severity. Growth in 1931, the poorest year, was 68 percent below normal (Keen, 1937).

The intensity of summer drought and the magnitude and frequency of winter storms are governed by latitudinal variations and the position of large scale pressure features. The severity of summer droughts is correlated with the northward extent of Pacific subtropical high pressure cells, while cool season precipitation is governed by the southward displacement of the polar jet stream. The Columbia Basin received higher than average precipitation from 1810 to 1835 and lower than average precipitation from 1850 to 1890. Winter precipitation (November-March) totals for Walla Walla, Washington, for the period 1856 to 1865 are reported to have been above the 1950's average.

Droughts in western lowlands coincide with droughts in the Columbia Basin, but the duration of droughts in the latter is greater. The timing of wet and dry periods differs from north to south. Reconstruction of the precipitation record from tree ring chronologies indicates episodes of wet and dry conditions that differ in timing and duration, without showing any long-term changes in mean conditions (Graumlich, 1985).

Predicting low-flow

Low-flow characteristics of a stream are good indicators of the stream's ability to meet water demands during crucial low-flow periods. In regional draft storage studies, certain of these low-flow characteristics are good variables as a basis for forecasting seasonal low-flows, and as indicators of the amount of groundwater flow to the stream. In order to effectively discuss low-flows, it is necessary to define this variable.

The lowest daily flow in a year is referred to as an annual low-flow. However, the minimum average flow for some consecutive days is more commonly used to define the annual low-flow. The seven-day average low-flow is less likely to be affected by minor circumstances upstream than is the minimum daily flow. The climatic year, April 1 to March 31, encompasses the entire low-flow period of each year in certain regions (Riggs, 1985). For low-flow prediction methods to be most useful, they should be appropriate for watersheds of all sizes throughout the region.

Chang and Boyer (1977) estimated the lowest 7-day stream flow ($7Q_{10}$, 10-year return period for lowest 7-day stream flow) from watershed and climatic parameters for twelve Monongahela tributaries in West Virginia. They found that watershed perimeter alone accounted for about 88% of the spatial variability of 7-day low-flows in a multiple regression analysis. Main channel length and watershed form increased the predictability to about 95%. Precipitation and temperature parameters, which were highly correlated with watershed elevation and latitude, raised the R^2 to 0.999. Their study suggested that meaningful low-flow estimates can be obtained from climate and watershed parameters, or watershed parameters alone, in a mountainous humid region.

In developing regression equations for estimating monthly stream flow characteristics, Parrett, et al. (1989) found that, most of the time, the drainage area was the most significant explanatory variable, followed by the mean annual precipitation. Some times, main channel length, mean basin elevation, percent vegetative cover, or main channel slope were the most significant variable. Even then they found that use of drainage area and mean annual precipitation resulted in only a slightly less accurate estimating equation.

Benson and Matalas (1967) introduced a method to overcome the deficiencies of synthetic hydrology at that time. Synthesis of data from short samples carry large errors due to sampling errors of the original sample and generation of a series for an ungauged location is not possible. Their method is based on use of statistical parameters, which are derived from generalized multiple-regression relations with physical and climatic characteristics of the drainage basin.

Campbell (1971) used a simplified approach to low-flow prediction with good accuracy for areas with dry weather conditions, without directly considering watershed cover, soil type, steepness of terrain, or climatic conditions. Probability graphs were developed from drought frequency plots that were used for prediction of watershed low-flow water yield.

Lee, (1985) using geological maps, soil maps, precipitation data, and low-flow data, defined four hydrologic regions in Louisiana which have distinct low-flow characteristics. Regression equations derived from low-flow data, drainage area (square miles), mean annual precipitation (inches), and main channel slope (ft/mile) were used as independent variables to estimate $7Q_2$, $7Q_{10}$, $7Q_{20}$ low-flows for natural, ungauged streams. The standard errors of the estimate, comparing the estimated discharges to the actual discharges, were ±44 and ±61% in low-flow regions. This was considered well within the ranges of error shown by similar studies in other areas.

Campbell (1971) found little or no similarity within the groups when watersheds were grouped according to size alone. However, grouping the watersheds according to low-flow quantities revealed much similarity within each group, showing similarity of hydrologic characteristics among watersheds with similar low-flow quantities.

A step forward linear regression technique can be used to derive prediction equations relating low-flows to selected watershed characteristics (Campbell et al., 1982). The most significant variables are added at each step, until the F-statistics are not significant at the required probability level. Besides the F-test, R^2 (coefficient of multiple determination) can be used as an indicator of the best set of equations. To have a constant variance among the residuals, log-linear regression can be used.

Loague and Freeze (1985) studied the model performance for three event-based rainfall-runoff models on three data sets involving 269 events from small upland catchments. Performance assessment of the unit hydrograph model, quasi-physically based model, and regression model was carried out both in forecasting (simulated hydrographs of specific future events to be used in making operational decisions) and prediction (suites of simulated hydrographs that are to be used for the purposes of engineering design) mode. The results showed poor performance of the models in forecasting mode compared to the prediction mode.

Perfectly accurate forecasting of low-flows or droughts is impossible. One has to face the problem of uncertainty due to the probabilistic nature of the variation of the low-flows. To predict a drought, approach should be a probabilistic one rather than a deterministic one (Joseph, 1970).

In frequency analysis, roccurrence interval is assigned to a drought corresponding to an annual minimum flow. Minimum flows are ranked in ascending order, then the cumulative probability of drought event less than or equal to is given by

$$P(x)=m/(n+1)=1/(Tr)$$

where m is an integer of the rank, n is the total number of years of the recorded data, and Tr is an equivalent recurrence interval. Flows corresponding to droughts of 2-, 5-, 10-, 20-, 50- and 100- years recurrence interval can be obtained by plotting the observed points on a probability paper and fitting a straight line.

Generally, the most important meteorologic and drainage basin characteristics for low-flow prediction are drainage area, mean basin elevation, gauge datum, channel gradient, stream length, forest cover as percent of total area, latitude, longitude, and mean annual precipitation. Zecharias and Brutsaert (1988) looked at eight different geomorphic parameters of a watershed (generated from U.S. Geological Survey topographic maps) in relation to the groundwater contribution to stream flow in Appalachian plateaus. They found that total length of perennial streams, average basin slope, and drainage density were highly related to the groundwater outflow process and were independent of each other. However, independence of stream length and drainage density is not understandable. These two watershed parameters must be related to some degree.

Campbell et al. (1982) found that watershed area, percent forest cover and mean annual precipitation are the most significant variables associated with low stream flows in eastern Oregon.

Thus far, there has been little research conducted on stream low-flows in the semi-arid areas. A large sample size and a long period of record of daily flows is needed. In the following study, 38 stream gauge records along with the data from 36 precipitation stations, each with about 30 years of stream flow and precipitation records will be utilized. This data set is distributed over a several thousand square-mile area of the eastern PNW and central Great Basin region.

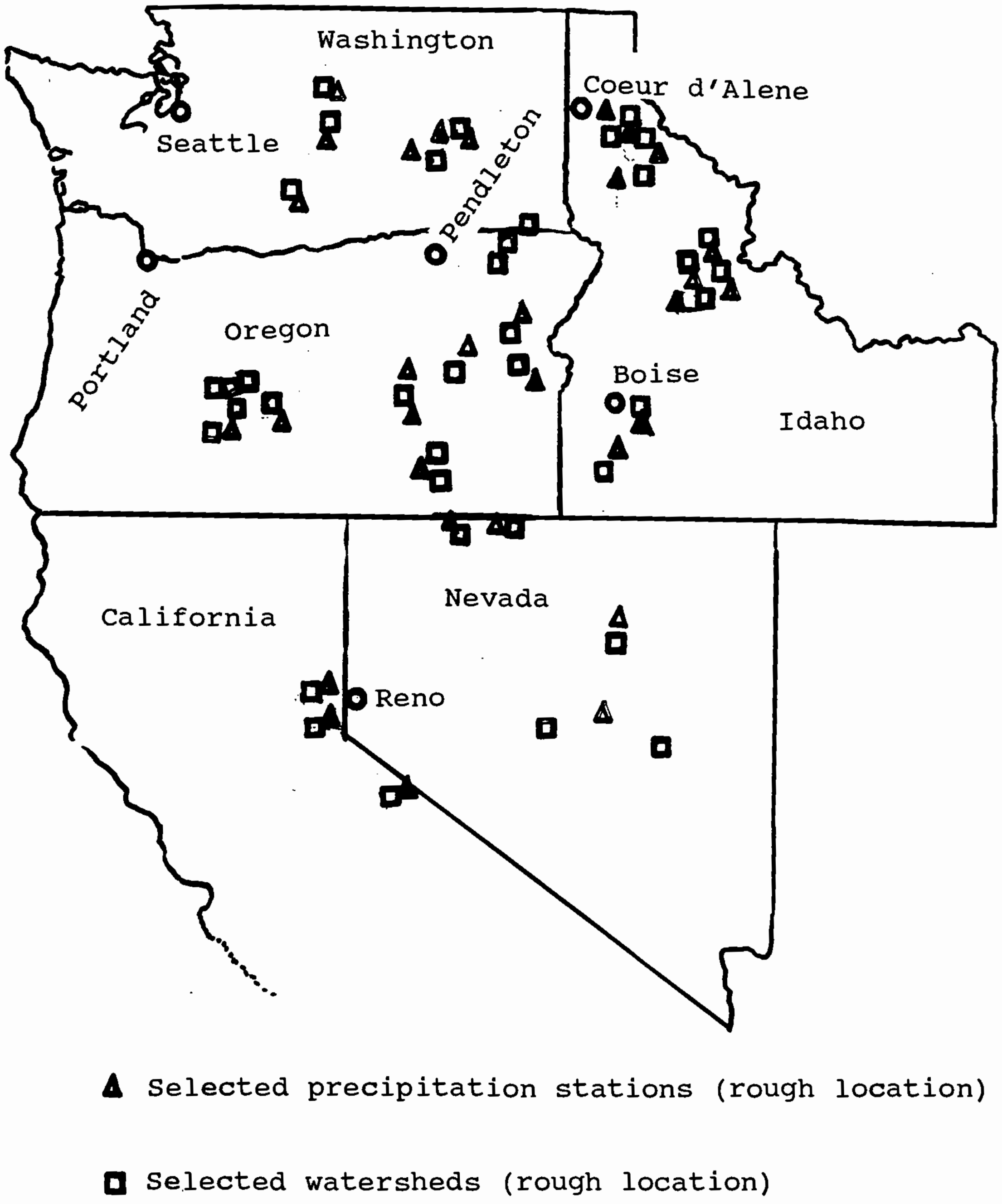
STUDY AREA

The study area includes selected areas within the semi-arid PNW (a major part of the Great Basin, eastern Washington, and north central Idaho). The Great Basin, as defined by Busby (1963), includes eastern Oregon, southwestern Idaho, northeastern California, most of Nevada, and western Utah. The study watersheds are located in eastern Oregon, eastern Washington, the western half of Idaho, northern Nevada and the northeastern part of California (Figure 1). Information regarding low-flows was not available for all streams in the study area as most were ungauged for the period of interest, or if they were gauged, flow was regulated or not natural. Thirty-eight watersheds with unregulated long-term flow records and thirty-six precipitation gauges were selected for this study.

Geology

The northern Washington Cascades are comprised of ancient, mostly folded, sedimentary rocks, partially metamorphosed and with common intrusions of granitic batholiths. The southern Washington Cascades are comprised mainly of andesite and basalt flows with minor amounts of igneous intrusions, sedimentary and metamorphosed rocks. Oregon's High Cascades are a geologically young volcanic area, comprised of rolling terrain which is interrupted at

Figure 1: Map of the study area. Not to the scale.



intervals by glaciated channels. Pumice and ash from repeated volcanic eruptions has mostly obscured the bed rock. The Blue Mountains consist of schists, limestone, slate, argillite, tuff,chert, sandstone siltstone, and shale. Granitic stocks are found in the Wallowa Mountains, and the north slope of the Blue Mountains have Columbia River Basalt (Franklin and Dyrness, 1969).

The Columbia basin consists mainly of Columbia River Basalt formation, ranging in thickness from 0.35 miles to over 0.87 miles. A unique geologic feature called Channeled Scablands is present in the central portion of eastern Washington. This consists of a gigantic series of dry, deeply cut channels in Columbia River Basalt. Southern and southeastern Oregon is made up of basalt, pyroclastics, alluvial sediments, rhyolite, dacite and andesite. The Steens Mountains have also experienced extensive glaciation (Franklin and Dyrness, 1969).

Vegetation

Vegetation composition varies with elevation, largely in response to precipitation and temperature. Precipitation is primarily a cool season phenomenon. Maritime storms cross the mountains from west to east in the fall and winter. Orographic uplift cools the moist air and accentuates precipitation from frontal storms (Helvey and Tiedemann, 1978).

Zonal sequences of dominant vegetation types in the study area are broadly classified for different zones:

Idaho: Ponderosa pine (Pinus ponderosa), Douglas-fir (Pseudotsuga menziesii), Grand fir (Abies grandis), Western hemlock (Tsuga heterophylla), Subalpine fir (Abies lasiocarpa), Western larch (Larix occidentalis), Western white pine (Pinus monticola), and Engelmann spruce (Picea engelmanni).

Eastern slope Washington Cascades Range: Ponderosa pine (Pinus ponderosa), Douglas-fir (Pseudotsuga menziesii), Grand fir (Abies grandis), Western hemlock (Tsuga heterophylla) Silver fir (Abies amabilis), and Subalpine fir (Abies lasiocarpa).

Eastern slopes central Oregon Cascade Range: Juniper (Juniperus occidentalis), Lodgepole pine (Pinus contorta), Ponderosa pine (Pinus ponderosa), White fir (Abies concolor), the Mountain hemlock (Tsuga mertensiana).

Blue Mountains and Ochoco, Oregon: Juniper (Juniperus occidentalis), Ponderosa pine (Pinus ponderosa), Grand fir (Abies grandis), Subalpine fir (Abies laciocarpa), Lodgepole Pine (Pinus contorta), Western Larch (Larix occidentalis), and Engelmann spruce (Picea engelmanni).

Columbia Basin province of eastern Washington: It is comprised of steppe and shrub-steppe vegetation. Zonal associations include Artemisia tridentata, Agropyron spicatum, Festuca idahoensis, Artemisia tripartita, Purshia tridentata, etc.

Southeastern Oregon: Steppe and shrub-steppe also dominates southeastern parts of Oregon. It includes communities like Artemisia tridentata/Agropyron spicatum, Artemisia tridentata/Festuca idahoensis (on deeper soils), Juniperus occidentalis, Juniperus macropoda, Cercocarpus ledifolius, Atremisia arbuscula(on shallow stony soils), Artemisia rigida (on very shallow soils), Atremisia cana (on moister habitats), etc. Steens Mountains have vegetation types ranging from Tall Sage to Alpine Tundra.

Northeastern California: Ponderosa pine (Pinus ponderosa), Jeffrey pine (Pinus jeffreyi), Lodgepole pine (Pinus contorta), Douglas-fir (Pseudotsuga menziesii), and Western white pine (Pinus monticola).

Northern Nevada: Engelmann spruce (Picea engelmanni), White fir (Abies concolor), and Quaking aspen (Populus tremuloides) (Fowler et al., 1979; Franklin and Dyrness, 1969; Harlow and Harrar, 1941).

METHODOLOGY

This study was conducted in order to gain a better understanding of the hydrologic characteristics of stream summer low-flows in the semi-arid PNW. The main objectives of this study were to determine the quantitative relationship of stream flow during the summer low and base-flow periods, precipitation, vegetative cover and physical characteristics of the watershed. To accomplish this goal, a set of 10 tasks were completed:

1) Stream selection and stream flow data
2) Precipitation data
3) Vegetation data
4) Topographic maps and watershed parameters
5) Field observation
6) Independence of data
7) Long-term trends in summer low-flow and precipitation
8) Correlation between summer low-flow and precipitation
9) Recession analysis and forecast
10) Extreme summer low-flow prediction model

Stream selection and stream flow data

There were two basic criteria for selection of stream flow data for this study: 1) daily stream flow data for a stream was available for a period of 30 years or more, 2) the available data was continuous and natural. This means that there was no diversion or regulation of stream flow upstream from the gaging station for the period of record used in the study. This later criteria was necessary because the long-term effects of watershed parameters were of interest, as well as climate and vegetation changes on summer stream flow. A 30 year period is considered reasonable to identify most long-term changes in hydrologic variables. Also, it provides about 30 observations for individual low-flow parameters to yield satisfactory confidence in the statistical analysis.

Thirty-eight streams were selected in the study area (Figure 1). Fourteen of these were located in eastern Oregon, six in eastern Washington, ten in the state of Idaho, three in northeastern California and five in northern Nevada (Table 1). This was done by consulting statistical summaries of stream flow data in Oregon (Moffatt, et al. 1990), yearly U.S. Geological Survey Water-Data Reports for Oregon (Hubbard, et al. 1992), eastern Washington (Miles, et al. 1990), and Idaho (Harenberg, et al. 1991). HYDRODATA compact disk was used to select streams in Nevada and northeastern California (Hydrosphere Inc. 1993). Daily stream flow data for selected streams was obtained from HYDRODATA compact disk.

For each selected watershed, 7-day moving averages of daily flows for the summer months of June, July, and August were extracted for each year. For each year, the lowest of

Table 1: Selected streams/rivers in the study area (Gauge ID=Gauge Identification number, POR= period of record)

Name of River/Stream	Gauge ID	POR	Area(m^2)
Oregon			
1. Silvies River near Burns	10393500	1922-92	934
2. Donner Und Blitzen River near(nr.) Frenchglen	10396000	1937-92	200
3. Bridge Creek near Frenchglen	10397000	1937-70	30
4. Eagle Creek above Skull Creek, nr. New Bridge	13288200	1957-92	156
5. Hurricane Creek nr. Joseph	13329500	1924-78	29.6
6. S.F. Walla Walla River nr. Milton Freewater	14010000	1931-92	63
7. Umatilla River above Meecham Creek, Gibbon	14020000	1933-92	131
8. Strawberry Creek above Slide Creek, nr. Prairie City	1403750	1930-92	7
9. Cultus River above Cultus Creek nr. LA Pine	14050500	1938-92	16.5
10. Cultus Creek above Crane Prairie Reservoir nr. LA Pine	14051000	1937-92	33.2
11. Deer Creek above Crane Prairie Reservoir nr. La Pine	14052000	1937-92	21.5
12. Brown Creek nr La Pine	14054500	1938-92	21
13. Odell Creek nr. Crescent	14055500	1933-76	39
14. Fall River nr. La Pine	14057500	1938-91	45.1
Washington			
15. Stehekin River at Stehekin	12451000	1926-92	321
16. Entiat River nr. Ardenvoir	12452800	1957-92	203
17. Crab Creek at Irby	12465000	1942-92	1042
18. Rocky Ford Creek nr. Ephrata	12470500	1942-92	12
19. American River nr. Nile	12488500	1939-92	78.9
20. Mill Creek nr. Walla Walla	14013000	1939-92	59.6
Idaho			
21. Coeur d'Alene River nr. Prichard	12411000	1950-92	335

Table 1 (continued): Selected streams/rivers in the study area (Gauge ID=Gauge Identification number, POR= period of record)

Name of River/Stream	Gauge ID	POR	Area(m^2)
22. Coeur d'Alene River at Enaville	12413000	1939-92	895
23. Coeur d'Alene River at Cataldo	12413500	1920-72 1986-92	1223
24. St. Joe River at Calder	12414500	1920-92	1030
25. Big Jacks Creek nr. Bruneau	13169500	1938-49 1965-92	253
26. Boise River nr. Twin Springs	13185000	1911-92	830
27. Lochsa River nr. Lowell	13337000	1929-92	1180
28. S.F. Clearwater River at Stites	13338500	1964-92	1150
29. Clearwater at Orofino	13340000	1964-92	5580
30. N.F. Clearwater River nr. Canyon Ranger station	13340600	1967-92	1360
California			
31. Buckeye Creek nr. Bridgeport	10291500	1953-80	44.1
32. Blackwood Creek nr. Tahoe City	10336660	1960-87	11.2
33. Sagehen Creek nr. Truckee River	10343500	1953-87	10.5
34. Little Current Creek nr. Currant	10246846	1964-86	12.9
35. Lamoille Creek nr. Lamoille	10316500	1943-87	25
36. Reese River nr. Ione	10325500	1951-81	53
37. E. Fork Quinn River Mcdermitt	10353000	1948-81	140
38. Leonard Creek nr. Denio	10353700	1960-82	52

the 7-day summer flows were selected as the summer low-flow.All the daily flows were divided by the watershed area to convert flow to cubic feet per second per square mile (csm). This was done in order to obtain a comparison between watersheds of different sizes for trend analyses and trend similarities between summer low-flows and precipitation, and recession analysis.

Precipitation data

In theory, the precipitation data should be representative for each selected watershed. Most precipitation gauges are installed in valleys, at lower elevations, receiving lower precipitation than adjacent mountain watersheds. However, it was assumed that precipitation in the valleys had a linear relationship with the precipitation at the upper portions of the catchment over the years.

The assumption of linear relationship between precipitation in the upper and valley areas was tested by correlation. Long-term precipitation averages were selected from stations in Oregon to the average watershed precipitation calculated from a Isohyetal map. The isohyetal map is based on the normal annual precipitation for the period of 1961-1990 (Taylor, 1993).

The analysis showed a statistically significant relationship between upper and valley precipitation. Precipitation calculated using the Isohyetal map was always higher than the gauged precipitation. It was concluded that precipitation in the valleys (where most of the precipitation gauges were located) was not an adequate quantitative representation of the watershed precipitation. However, there was a significant correlation between precipitation upper and valley locations, which made it possible to use the gauged precipitation data for the purpose of this study.

After procuring the stream flow data for the selected streams, 46 precipitation stations were selected from the precipitation maps which were closest in proximity to the selected watersheds. Monthly precipitation data was available for only thirty-six selected stations for about 30 years or longer periods (Figure 1).

Precipitation data for the selected stations in Oregon was procured from the office of State Climatologist, Oregon. Data for the other states was collected through the office of the regional climatologist in Reno, Nevada. Monthly precipitation data was procured (Table 2).

Climatological offices were able to provide the information about the total number of missing days for each month along with the data. A small letter along with monthly precipitation indicated the number of missing days in that particular month, e.g., a=1 day missing, b=2 days missing,....z=26 or more days missing from the record.

Precipitation for each missing value was calculated by averaging the ten values around that missing observation. For those months where precipitation information was missing

Table 2: Selected Precipitation stations in the study area

		Gauge ID Number	Period of record
OREGON			
1.	Austin	0356	1949-92
2.	Burns	1175+1176	1939-92
3.	Enterprize	2678	1970-92
4.	Gibbon	3250	1973-92
5.	Halfway	3604	1949-92
6.	John day	4291	1954-92
7.	Milton Freewater	5593	1929-92
8.	Odell Lake-1,2,3	6251+52+54	1949-92
9.	P-Ranch	6853	1949-92
10.	Wickiup Dam	9316	1942-92
WASHINGTON			
11.	Stehekin 3NW	8059	1932-93
12.	Plain	6534	1949-93
13.	Bumping Lake	0969	1932-67
14.	Ephrata FAA Airport	2614	1950-93
15.	Wilson Creek	9327	1945-76
16.	Odessa	6039	1949-93
17.	Mill Creek dam	5387	1949-93
18.	Mill Creek	5377	1949-73
IDAHO			
19.	Coeur d'Alene RS	1956	1932-86
20.	Kellog AP	4831	1932-93
21.	Burke 2ENE	1272	1949-67
22.	Avery Ranger Station	0525	1932-93
23.	Head Quarters	4150	1960-93
24.	Dworshak Dam	2845	1967-93
25.	Orofin	6681	1949-81
26.	Kooskia	5011	1932-87
27.	Fenn Ranger Station	3143	1949-93
28.	Arrow Rock Dam Near Boise	0448	1932-93
29.	Bruneau	1195	1963-93
NEVADA			
30.	Denio	2229	1952-93
31.	Mcdermitt	4935	1950-76
32.	Lamoille PH	4395	1932-72
33.	Smokey valley	7620	1950-93
CALIFORNIA			
34.	Bridgeport	41072	1958-93
35.	Tahoe	48758	1932-93
36.	Boca	40931	1949-93

for one or more days, known precipitation for that month was averaged over the unknown days also.

Some more sophisticated methods were also tried for a few missing values and results were compared with the simple averages. No significant difference in the resulting values was found using different methods. For example, for Wickiup Dam precipitation station, results for one missing value from regression (with adjacent month), average and MOVE were 3.35 inches, 3.32 inches, and 3.30 inches, respectively. Therefore, the simple average method was used to fill in the missing precipitation data for all the stations.

MOVE, Maintenance of Variance Estimation, utilizes the mean and standard deviation of both the dependent and independent stations. The equation has the form

$$Y = m(y)+[s(y)/s(x)]*[(X-m(x)] \qquad (1)$$

where Y=the estimated precipitation for the station of interest, X=the known precipitation for the long-term station, s(y) and s(x) are, respectively, the standard deviations for dependent and independent variables, and m(y) and m(x) are the means associated with the dependent and independent variables, respectively (Grizzel 1993).

Where data was incomplete, missing day(s) "x"'s precipitation was incorporated by dividing the known precipitation for that month over the known days in that month equally and then adding that average value for each missing day(s) to the monthly precipitation. For example, if a particular month A had "x" missing days in the record, the monthly precipitation was calculated as;

$$P = p+(p/(y-x))*x \qquad (2)$$

where, P=total monthly precipitation, p= the known precipitation and y=the total number of days in that month.

For each gauged station, annual as well as seasonal precipitation were extracted. Annual precipitation was considered from November of one year (X-1) to October of the next year (X). Winter included November and December of the X-1 year and January to March of X^{th} year. Spring included April and May, Summer included June, July and August. September and October formed the fall precipitation.

Vegetation data

The study covered the period from about 1930's to 1992-1993. Due to financial and time constraints, aerial photos for all selected watersheds could not be procured and evaluated. However, watershed cover data (percent forest cover, rangelands, snowfield, open water, wet lands, pastureland, area under agricultural use, clearcut and barren lands) for the catchments in Oregon were obtained for two different periods.

For the earlier period, information was obtained through the GIS section of the Water Resources Department, Salem, Oregon, using the aerial photos taken in the early to mid 1970's. The second data set about the watershed cover was procured through the GIS section of the Forest Service Laboratory at Oregon State University. The aerial photos were taken around 1990. Although vegetative cover keeps on changing, it was not practicable for us to study exact yearly changes in vegetative cover using this information only.

Topographic maps and watershed parameters

United States Geological Survey topographic maps at scales of 1:100,000, 1:250,000 and 1:25,000 were used for different states. For the state of Oregon, topographic maps were available at the scale of 1:25000 as well as 1:100,000. For the rest of the watersheds (except in Idaho), topographic maps at the scale of 1:100,000 were used for the calculation of watershed parameters.

Because of their large size, topographic maps at the scale of 1:250,000 were used to calculate the watershed parameters for watersheds in the state of Idaho. Watersheds were delineated by topographic divides above the gaging stations. All the watershed parameters were calculated from the topographic maps using the CAPTURE digitizing computer program (Welch and CRMS_UGA, 1991) at the graduate computer lab of Forest Engineering, Oregon State University.

To adjust for any error made in measurements all the data sets obtained through topographic maps were corrected by a factor equal to the ratio between the actual watershed area reported by USGS and the area calculated through topographic maps. Several physical watershed parameters which were considered to have relationship with summer low-flows were selected and obtained/developed. These parameters included:

watershed area, perimeter, total perennial stream length, lake area, main channel length, number of different stream channel orders (1st to 6th), watershed length and width, gauge elevation, end point elevation (elevation at the farthest point from the gauge or the point where the main channel reaches the divide when extended), maximum watershed elevation, mean watershed slope, mean channel slope, watershed circulatory ratio, watershed relief, mean watershed elevation, and ratio of watershed length to watershed width.

Field observations

Field visits to study areas were made to determine the current vegetation conditions in the catchments. The nature and condition of the stream and precipitation gauges, and location of precipitation gauges with respect to study watersheds, were noted for the qualitative interpretations of the results. The level of maintenance of gauges, and the kind of gauges used to measure stream flow and precipitation were checked to reinforce the confidence in the data collected.

Independence of data

For some types of hydrologic time series analysis, the occurrence of an event is assumed to be independent of all previous events. Generally, dependence between hydrologic observations decreases with an increase in the time base (Riggs, 1985). As summer low-flows were of particular interest, the water year (October 1-September 30) was used in the analysis.

To evaluate the year-to-year dependence between the summer low-flows, minimum of average 7-day summer low-flows per square mile for June, July and August for each year were calculated. Summer low-flow for year X+1 was regressed against year X for each stream in the study.

Correlation coefficients "r" and p-values were noted. A positive correlation coefficient suggested a positive relationship of summer low-flow on the previous year's flow and vice a versa. The coefficients of determination, r^2, were also noted to show the explanation of summer low flow by the previous year's flow. The regression analysis to calculate the dependence of summer low-flows was performed at a 95% confidence level.

Long-term trends in summer low-flow and precipitation

Stationary time series have the same means and variances (i.e., the distribution does not change with time). A trend may be a smooth motion of the series, or the sequence of values follows an oscillatory pattern. When this pattern indicates almost steady rise or fall, it is defined as a trend. A cyclic time series is one in which the maximum and minimum values occur at equal intervals of time with constant amplitude. A random element, if present, tends to distort this pattern (Chow, 1964).

To find out the time series trend for summer low-flows, 7-day summer low-flows were calculated for each year for all the streams. Seven-day average summer low-flow was used as they were less likely to be affected by minor circumstances upstream than the minimum daily flow.

Annual summer low-flows were regressed against the time (years) to find the slope of the trend. Positive slope indicated an increase in summer low-flow, while, negative slope depicted a decrease in summer low-flows over the period of record. No significant changes in summer low-flows were shown by slopes very close to zero. A steeper regression line (slope) implied greater change in summer low-flows with time. For this purpose, slopes of the regression lines and their significance levels (p-values) were noted for all the streams.

Summer low-flows and annual precipitation were also plotted graphically to examine the oscillatory patterns of their trends over the period of record. Five-year moving averages smoothed the curves reasonably. When less than 5-year moving averages were used, it was less feasible to infer the required information due to "noise" in the data. Moving averages based on periods of more than 5-years obscured valid information in the data.

Long-term means and five-year moving averages for summer low-flows per square mile and precipitation for each zone were calculated. They were plotted against time to graphically study long-term trends and detect patterns in the summer low-flows and precipitation.

Correlation between summer low-flow and precipitation

Annual summer low-flows, previously calculated for the trend analysis were used for these analyses as well. Similarly, annual, winter, spring, summer and fall precipitation for each watershed were calculated. Annual minimum summer stream flows for each stream were regressed against the assigned annual, as well as seasonal, precipitation for that watershed to determine their relative effects on summer drought. Zonal correlation equations between summer low-flows and precipitation were constructed by averaging all the individual watershed regression equations in the respective zones. Same was done for the study area as a whole.

Recession analysis and forecast

In forested areas there is, typically, no basin-wide surface runoff from snowmelt. Practically all snowmelt runoff enters stream channels as subsurface or groundwater flow, or usually as a combination of both. Base flow is that portion of the flow which maintains stream flow during periods of no rain.

The hydrograph of stream flow during periods when all discharge is derived from a groundwater resource is known as a base-flow recession. A curve that averages these recessions is the base-flow recession curve. Stream flow recession curve equations are derived from theoretical equations for flow in an aquifer, which are of the form

$$Q_t=Q_oK^{-t} \qquad (3)$$

where Q_t=the discharge at any instant/day "t", Q_o=the discharge at some initial time, t_0, K=the recession constant, and t=time interval between Q_o and Q_t (Chow, 1964).

Initially, watersheds were grouped according to their geographic proximity to each other. Twelve regions were recognized in this process. The annual average hydrographs of each stream in the region were combined into a single average annual hydrograph for the region. Recession analyses were performed on these regional hydrographs to predict summer low-flows for each region.

Due to higher natural variation in the stream flows, vegetation cover, precipitation, etc., and the smaller number of watersheds available in each region, a re-grouping of watersheds was preferred. This was performed on the basis of precipitation (Appendix 1, Table 10).

There were several independent variables, which were considered for the re-grouping of the watersheds, such as precipitation, area, vegetative cover, etc. Annual precipitation was preferred because this information was available for all the watersheds in the study area on a consistent basis and it is considered a very reliable indicator of the climate.

The average annual precipitation for the study period for each gauge was calculated. Then, every watershed was assigned the precipitation of its closest precipitation station(s). Five zones were recognized on the basis of precipitation (Appendix 1). Zone 1 had less than 10 inches precipitation, Zone 2 had precipitation between 10 and 20 inches, Zone 3 had precipitation between 20 and 30 inches, Zone 4 had precipitation between 30 and 40 inches, and Zone 5 had precipitation above 40 inches.

Instead of constructing an average annual hydrograph for each zone, recession analyses to build the forecast models were performed on individual streams. The entire available data set for each individual stream was used to build the recession forecast model for that watershed. Then, the forecast equations for all watersheds in a zone were averaged to build the forecast model equation for each zone.

Before performing the recession analyses, one stream from each zone was picked randomly and set aside for the purpose of verification of the accuracy of the zonal models. These five streams were not used in the build-up of zonal recession forecast models.

To build the forecast model, the average annual hydrograph for each stream was prepared by averaging the daily flows per square mile of the record for the water year. The position on the recession limb to start recession analysis can be selected arbitrarily as the inflection of the convex portion of the annual hydrograph (Zeb, 1992). From this recession limb, flow for day X+1 can be regressed against the flow for the previous day, day X (Figure 2).

Regression parameters (slope and constant) so obtained can be used to forecast stream flow for day X+1 by using the equation:

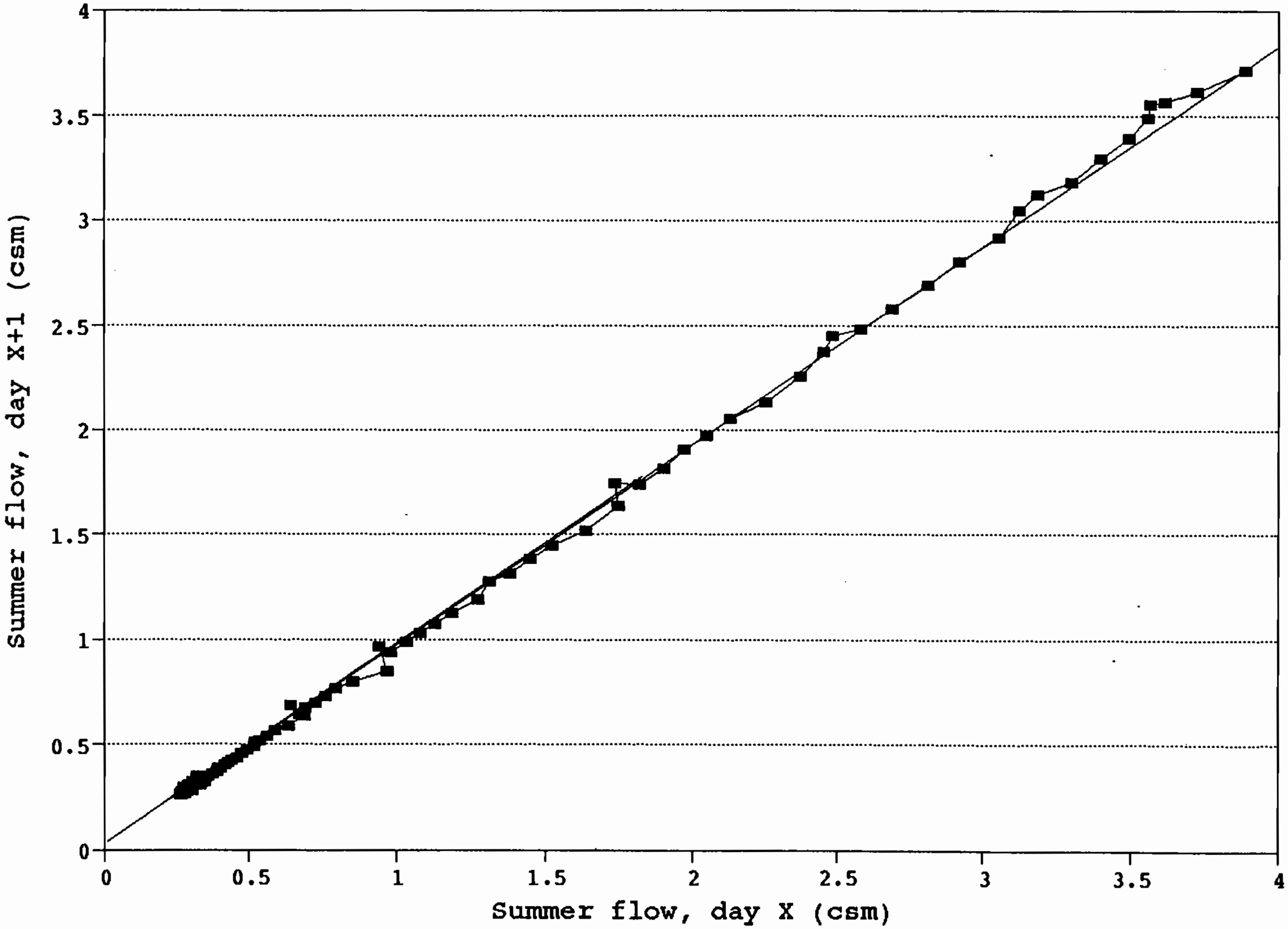
$$Q_{x+1}=Q_x(\text{slope})+\text{constant} \qquad (4)$$

where, Q_x=the flow for day X.

Forecast flow for day X+2 can be calculated using the same regression parameters with flow for day X+1 as Q_x, as

$$Q_{(x+2)} = Q_{(x+1)}(\text{slope})+\text{constant} \qquad (5)$$

Figure 2: Scatter plot of summer stream
flows of day X+1 vs day X (Sagehen Cr.)



This procedure has to be repeated through the end of the water year in order to get the forecast flow for each day.

Time-series analysis technique can also be used to determine the recession coefficients for the same relationship to use in the forecast equation. However, the resulting recession flows by using both methods were not significantly different. Therefore, the simple regression was used to build the equations because it was easier to conduct.

Forecasted flow was compared with average actual flow for that period, and their degree of explanation (r^2) was noted. The whole procedure had to be repeated several times with different starting dates to get the best fit line between the actual and the forecasted flows. The equation which gives the best fit could be selected as the model equation for that watershed (Figure 3). The general form of the model equation derived so was as follow:

$$Q_{(day\ 1)} = Q_o C + C_o \qquad (6)$$

$$Q_{(day\ 2)} = \{Q_o C + C_o\} C + C_o = Q_o C^2 + C C_o + C_o \qquad (7)$$

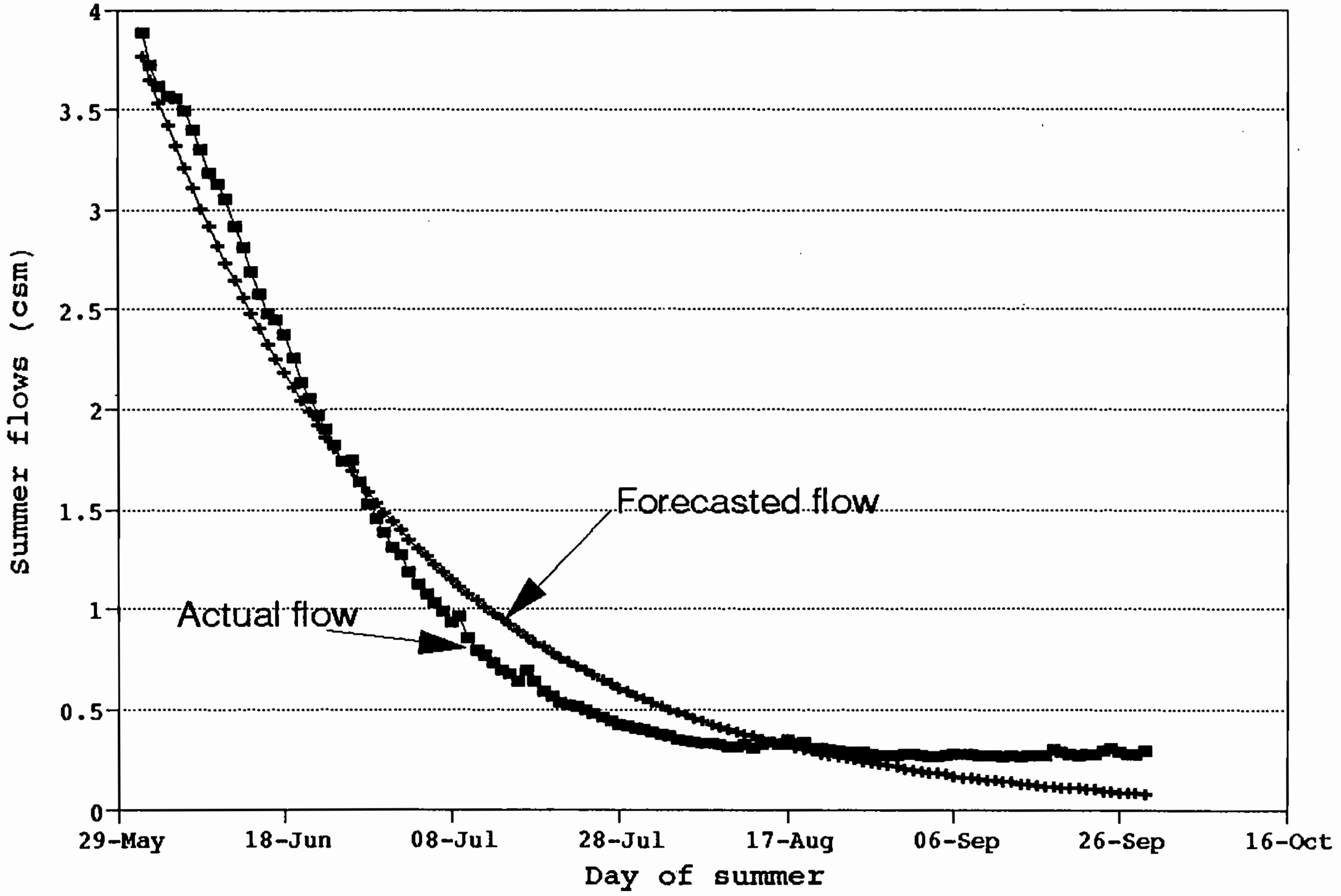
$$Q_{(day\ 3)} = \{Q_o C^2 + C C_o + C_o\} C + C_o = Q_o C^3 + C^2 C_o + C_o C + C_o \qquad (8)$$

This resulted into the general shape of the equation as:

$$Q_n = Q_0 C^n + \sum_{i=0}^{n-1} C_0 C^i + C_0 \qquad (9)$$

where, Q_n=the forecasted flow for the nth day, Q_o=the observed flow on day zero of the forecasted period (starting

Figure 3:Plot showing fit of actual and recession forecast flows(Sagehen Cr.)



day of the model), C=the slope of the regression line, C_o=the regression slope intercept, and n=the number of days after day zero.

In the process of building recession forecast model equations, two streams were left out of the recession analysis; the Rocky Ford Creek in eastern Washington and Brown Creek near La Pine, Oregon, showed increasing flows during summer.

Rocky Ford Creek was perhaps a spring fed creek whose source area was unknown. USGS has reported that the watershed area for the Creek is about 400 square miles but the contributing area is only about 12 square miles. However, from the study of its annual hydrographs, it seemed that its contributing area was uncertain due to the nature of its annual hydrograph. Precipitation in that region did not support an increase in the stream flow during summer.

Brown Creek near La Pine, Oregon, also showed an increasing flow during summer until the end of the water year. Therefore, it was also excluded from the analysis. Other streams near the La Pine area also showed increasing flows but during early summer only (probably due to the late snow melt) and then receding flows during the middle to late summer.

The areas for the watersheds near La Pine were calculated by delineating their apparent divides. However, their hydrological boundaries were not very clear (Moffatt, 1990). That may be generally true for many catchments, but the degree of uncertainty in the watershed boundaries in the case of eastern Cascade streams of Oregon was higher. Enough supporting information was lacking to exclude others from the analysis was unavailable.

The forecast equations were built by forcing regression slope intercept to zero during the process of regressing flows of X+1 days against flows of X days. By doing this the individual variability in summer low-flows from stream to stream within the zone was reduced in order to better predict the summer low-flows for streams of various sizes in the region. Theoretically, if there was no flow on day 1 there will be no flow on day 2, unless precipitation occurred that day. But, in the process of the recession analysis, input through precipitation was not incorporated (it may be hidden in the recession equation as a part of the actual recession limb of average flows of each watershed).

Statistically, when y has no value when the observed value is zero; the intercept is meaningless. By using the prediction equations to compute intercepts resulted in negative flows during the later part of the summer for some of the streams, which is physically impossible. Therefore, the regression slope intercepts were forced to zero to build model equations. It reduced the regression relationship between the actual and predicted flows to some degree, but reduced the variability in low-flow levels to a great extent. By doing that, it increased the ability of these equations to predict summer low-flow for any stream in the zone more accurately.

Recession analysis for each watershed was performed individually for four different starting dates as June 1 (J1), June 15 (J15), June 20 (J20), and June 25 (J25). These fixed dates were used to achieve consistency in the forecast equations for each zone and to better meet the objectives of the study instead of locating the best forecasting date for each stream. The best fit starting dates for all the streams were in between June 1 to June 25 (based on preliminary analyses).

The resulting forecast equations from each stream were averaged to construct one zonal equation for each date to forecast summer low-flows for that zone. Each of these zonal recession forecast model equations were tested against previously set aside streams within the same precipitation zone.

Finally, one general equation for each of four starting dates was constructed for the entire study area. The individual watershed recession model equations were used to make the general equation. These regional recession forecast models were tested against the previously set aside five streams individually and the results were examined for their degrees of accuracy.

Extreme summer low-flow Prediction model

Minimum summer low-flow for each stream, average and minimum annual and winter precipitation, and watershed physical variables were calculated or obtained for each watershed. Watershed variables calculated and used are listed in Appendix 2 (Table 11).

Normality of the summer low-flow data was tested for all selected streams using the statgraphics software (Manugistics, 1992). There were a few streams which had summer low-flows not normally distributed. However, it was difficult for the data set to be normally distributed when it was an extraction of low values of a relatively small data set.

A stepwise linear regression technique was used to derive the best prediction equation relating low-flows to the selected watershed and climatic variables for the study area as a whole. The most significant variable in terms of explaining the variability in the extreme summer low-flow was added at each step, until the F-statistics were not significant at the 95% probability level (an F-statistic of 4 was used as a limit to include or exclude any variable from the final model). Every included variable was examined for its significance after the inclusion of a new variable.

Selection of a best equation using the all-possible-regressions which involved calculation of regression equations having every possible combination of the X-variables was also utilized. However, there is a large probability of getting a significant regression by chance using the all-possible-equation method (Haan, 1977).

A number of independent variables were used to calculate the final equation. Independent variables do not interact in multiple linear regression and have their additive effect on response when they are not significantly correlated with each other.

However, it is very difficult to find purely independent variables in hydrological studies. Most of the times, a degree of correlation is found between independent variables. Using the correlation analysis, many of the independent variables used were highly correlated with each other.

The best selected model may still contain some independent variables which are correlated to each other. The resulting equation may be acceptable statistically in terms of its end product. However, the partial regression coefficients may have values which are not a true picture of their correlation or effect upon the dependent variable. Even if they are standardized, they still have some effect from the interaction with other independent variables in multiple regression.

Partial regression coefficients of independent variables do change with the exclusion or addition of another correlated independent variable. Therefore, when there are more than one correlated independent variables in a model, the coefficient values are not a reflection of the true effect of a particular independent variable on a dependent variable, but only a marginal or partial effect (Neter, et al. 1983).

Normally, R^2 is used as a guide to show the significance of a regression model to explain the variation in the dependent variable. However, R^2 will increase with the addition of more independent variables. Standard error is a good indicator to avoid the inclusion of an independent variable that helps little in the efficiency of the model.

Adjusted R^2 also takes care of that problem. It adjusts for the degrees of freedom of the model. If a variable is not contributing significantly towards the improvement in explaining the variability in the response variable, adjusted R^2 will decrease rather than increase (Neter, et al. 1983). Standard error and adjusted R^2 values were used to indicate the improvement or otherwise of a regression model with the addition or exclusion of an independent variable.

RESULTS AND DISCUSSION

Semi-arid areas of the PNW are typical of such areas having patterns of wet and dry periods of different lengths and intensities (Graumlich, 1985, Keen, 1937). Floods or peak flows are of shorter duration than droughts and leave very clear impact on the structures and other spheres of life that are habitual to normal stream flow levels.

Therefore, extreme high events have been the focus of attention by the scientific and administrative community in an attempt to prevent them or to be able to reduce their effects on human lives. Today, as a result, much more is known about floods, their forecasting, causes and consequences than about low-flows. Relatively, little is known about summer low-flows or drought events in semi-arid areas.

Hydrological drought can be assessed by low level of stream flows, lack of or below average precipitation. Occurrence of droughts is of longer duration and their effects are not immediately apparent. Nevertheless, drought can cause loss of productive lands, timber, biotic community, and even the human lives. Its occurrence is a complex natural phenomenon and is difficult to prevent at smaller scale.

However, it is believed that with better knowledge about trends and patterns of drought occurrences in the semi-arid areas, and with forecasting or predicting capabilities, resources can be managed accordingly. This can help take benefits for the management and rehabilitation of watersheds, fisheries, wildlife, and irrigation projects through the proper adjustments.

This study was conducted in order to gain a better understanding of the hydrologic characteristics of summer low-flows in the PNW's semi-arid regions, and to determine the quantitative relationship between summer low-flows, precipitation, vegetative cover and physical parameters of the watershed. These semi-arid regions are critical due to detrimental effects of dry conditions on their habitat and overall environment. Characteristics of droughts needed to be understood more carefully for proper and effective management of semi-arid areas.

Selection of the study watersheds was done by consulting the annual water reports by the water resources departments of Oregon, Washington, Idaho, north-eastern California, Nevada, and the Statistical summaries of the stream flow data for the state of Oregon. Many streams in the study area are ungauged. Most of the gauged streams did not fulfill the requirement of being continuous and having natural flow for a long enough period of time to be analyzed. As a result, only 38 streams were selected within the study area of five western states. Most of the data collected by USGS from the selected watersheds was good or fair. The data was used as it was and no extension or maintenance of it was considered useful for the study.

To accurately correlate precipitation to stream flow, the precipitation data should be as representative of the entire watershed as possible. However, in actual practice this was not the case. The study was based on the long-term data collected by the state agencies. The gauges were located where it was required or convenient to achieve their objectives. Mostly, the precipitation gauges were within or near a community, in the valleys, quite a distance from the selected watersheds. These gauges almost always had less precipitation collected in them than fell in the adjacent mountains.

For all the watersheds, annual average precipitation was calculated for the study period using the monthly precipitation data collected through the gauges placed around these watersheds, mostly at lower elevations. For the same period, annual average precipitation was calculated for watersheds in Oregon from the isohyetal map based on normal precipitation for the period of 1961-90. When both precipitation data sets for Oregon watersheds were compared, the precipitation averages calculated through monthly recorded data through the gauges were always lower, ranging from 34.32% to 88.8% of the precipitation averages calculated using the isohyetal map.

Accepting the fact that precipitation was lower in the precipitation gauges and was not a true quantitative representation of the watersheds, both values were regressed against each other to see the relationship between them. The correlation coefficient was found to be 0.77. This was deemed as satisfactory for the purpose of trend and pattern analysis considering the techniques used to calculate the watershed precipitation and the errors associated with the gauges themselves. Therefore, the precipitation data used in the analysis was well correlated (for the purpose of this study) to the actual watershed's precipitation, but lower in quantity.

Independence of data

For the statistical analysis, the observations are required to be independent and normal. Dependence is expected to be minimum between hydrologic events with a long time base in between them. Lowest summer low-flows have a one year time base separation between individual observations. Summer low-flows for year X+1 were regressed against year X for each stream in the study area (Table 3).

Most of the streams showed independence of the summer 7-day low-flow from the previous year's flow. Average r^2 for the regression analyses was 9.7%. It ranged from 0.003% to 48.7%, with a standard deviation of 14%. Those streams

Table 3: Regression relationships between summer low flows of X+1 year vs X year for the dependence analysis. B0=regression intercept, B1=regression slope, r^2=coefficient of simple determination, Sey= standard error of y-estimate (csm), r=correlation coefficient and p=p-value

Name of watershed	B0	B1	r^2	Sey	r	p
Cultus River, OR	2.825	0.293	0.084	1.171	0.290	0.035
Cultus Creek, OR	0.063	0.258	0.070	0.091	0.265	0.063
Deer Creek, OR	0.007	0.239	0.060	0.008	0.245	0.077
Brown Creek, OR	1.080	0.376	0.140	0.534	0.374	0.006
Odell Creek, OR	0.750	0.248	0.061	0.433	0.246	0.112
Fall River, OR	0.990	0.690	0.443	0.543	0.666	0.000
Silvies River, OR	0.005	0.526	0.277	0.009	0.526	0.000
Strawberry Creek, OR	0.592	0.100	0.042	0.232	0.205	0.115
Eagle Creek, OR	0.680	0.095	0.009	0.198	0.096	0.697
Hurricane Creek, OR	1.517	-0.024	0.001	0.480	-0.023	0.870
South Fork Walla Walla River,OR	0.680	0.593	0.354	0.189	0.595	0.000
Umatilla River, OR	0.237	0.294	0.087	0.036	0.295	0.025
Mill Creek, WA	0.260	0.743	0.487	0.077	0.698	0.000
Donner Und Blitzen River, OR	0.116	0.444	0.196	0.063	0.443	0.001
Bridge Creek, OR	0.244	0.328	0.107	0.054	0.328	0.067
East Fork Quinn River, NEV	0.010	0.008	0.000	0.006	0.008	0.968
Leonard Creek, NEV	0.040	0.120	0.016	0.032	0.125	0.590
Lamoille Creek, NEV	0.363	0.208	0.043	0.239	0.207	0.188
Reese River, NEV	0.062	-0.105	0.011	0.042	-0.106	0.590
Little Currant Creek, NEV	0.095	0.179	0.032	0.124	0.180	0.672
Buckeye Creek, CAL	1.090	-0.381	0.148	0.450	-0.385	0.057
Blackwood Creek, CAL	0.284	0.111	0.013	0.237	0.112	0.586
Sagehen Creek, CAL	0.193	0.290	0.084	0.145	0.290	0.102
Coeur d'Alene River near Prichard,ID	0.302	0.045	0.002	0.067	0.045	0.785
Coeur d'Alene River at Enaville, ID	0.329	0.007	0.000	0.078	0.007	0.959
Coeur d'Alene River at Cataldo, ID	0.272	0.183	0.033	0.081	0.181	0.198
St. Joe River, ID	0.397	0.175	0.030	0.101	0.174	0.146
Big jack Creek, ID	0.003	0.373	0.139	0.011	0.373	0.013
Boise River, ID	0.335	0.255	0.063	0.127	0.252	0.029
Lochsa River, ID	0.370	0.179	0.022	0.161	0.149	0.249
South Fork Clearwater River, ID	0.190	-0.006	0.000	0.072	-0.006	0.972
Clearwater River at Orofino, ID	0.297	0.071	0.003	0.140	0.055	0.237

Table 3 (continued): Regression relationships between summer low flows of X+1 year vs X year for the dependence analysis. B0=regression intercept, B1=regression slope, r^2=coefficient of simple determination, Sey= standard error of y-estimate (csm), r=correlation coefficient and p=p-value

Name of watershed	B0	B1	r^2	Sey	r	p
North Fork Clearwater River, ID	0.665	0.153	0.004	0.386	0.063	0.765
Stehekin River, WA	1.129	0.361	0.023	1.030	0.152	0.226
Entiat River, WA	0.430	0.340	0.004	0.726	0.066	0.707
American River, WA	0.637	0.025	0.000	0.342	0.012	0.935
Crab Creek, WA	0.005	0.370	0.134	0.006	0.366	0.010
Rocky Ford Creek,WA	0.044	0.718	0.479	0.033	0.692	0.000
Average	0.463	0.234	0.097	0.230	0.217	0.317
Minimum	0.003	-0.381	0.000	0.006	-0.385	0.000
Maximum	2.825	0.743	0.487	1.171	0.698	0.972
Standard deviation	0.543	0.231	0.135	0.275	0.227	0.353

which had less variation in their annual summer low-flow showed greater dependence upon the previous year's summer low-flow, although the majority of them were statistically insignificant.

Watersheds in the Blue Mountains showed higher dependence of summer low-flows over the previous year's summer low-flows than other sub-zones. Mill Creek in the Blue Mountains showed the maximum dependence among summer low-flows(r^2=48.7%) followed by Fall River near La Pine, Oregon (r^2= 44.3%). The hydrological boundary of Fall River is uncertain. It has some contribution from springs within the catchment. It had the highest summer low-flow (csm) among all the streams studied with least variation in its flows over a year as well as over the period of the record.

This may be a confirmation that it has a broader or more sustained source for stream flow than other streams in the neighborhood.

Reason(s) for the dependence of summer low-flows for the Mill Creek was, however, not very clear from the available information. This watershed is a protected one and the water is being used for drinking by the city of Walla Walla, Washington. Slow melting of accumulated snow at higher altitudes, as well as snow pack carry over from one year to the next, can be a plausible explanation for higher than average dependence of summer low-flows for the Blue Mountains watersheds. The average correlation coefficient "r" for these analyses was 0.22, ranging from -0.38 to 0.70, with a standard deviation of 0.23 (Table 3).

The frequency distribution of the summer low-flows suggested relatively normal distribution for the majority of the streams. None of the stream summer low-flow data showed strictly normal distribution; some of stream data appeared skewed. However, the data was analyzed as it was. A perfectly normal distribution should not be expected from such a short sequence of effects where negative values are not possible. Besides, the data was an extraction of the extreme values from the annual data. Lack of normal distribution does not suggest that the data was abnormal (Haan, 1977). Physically, maximum possible observations were collected for the study area based on criteria for selection.

Trend Analysis

The extracted 7-day summer low-flows were regressed against a time series to determine the trends in summer low-flows over the period of record (Table 4). On the average, there was no trend in summer low-flows over the period of record as the average slope of the regression lines was close to zero (0.001). The range of the slope of the regression lines ranged from -0.01 to 0.01, with a standard deviation of 0.004.

The correlation of summer low-flows with time was also calculated and was found to be insignificant for the majority of the streams. The average correlation coefficient (r) was 0.11, ranging from -0.58 to 0.54, with a standard deviation of 0.23. Generally, the summer low-flows had a statistically non-significant relationship with the time series. But the trends for the summer low-flows in Crab Creek, Washington, and Silvies River, Oregon, were found to be statistically significant. Summer low-flows decreased over the period of record for the Crab Creek, whereas, trend for the Silvies River' summer low-flows was positive.

Deer Creek, Oregon and Hurricane Creek, Oregon, also showed significant negative and positive trends,

Table 4: Regression relationships between summer low flows and time trend analysis. r^2=coefficient of determination, B1=regression slope, B0=regression intercept, r=correlation coefficient, and p=p-value

Name of watershed	R^2	B1	BO	r	p
Cultus River, OR	0.004	-0.005	13.730	-0.062	0.655
Cultus Creek, OR	0.001	0.000	-0.293	0.033	0.814
Deer Creek, OR	0.093	0.000	0.385	0.305	0.005
Brown Creek ,OR	0.010	-0.004	8.722	-0.098	0.480
Odell Creek, OR	0.055	0.008	-14.621	0.235	0.124
Fall River, OR	0.027	-0.007	17.795	-0.163	0.238
Silvies River, OR	0.214	0.000	-0.397	0.462	0.000
Strawberry Creek, OR	0.001	0.000	-0.188	0.035	0.792
Eagle Creek, OR	0.021	0.003	-6.041	0.145	0.410
Hurricane Creek, OR	0.183	0.013	-23.195	0.428	0.001
SF Walla Walla River, OR	0.028	0.002	-2.736	0.168	0.196
Umatilla River, OR	0.040	0.000	-0.508	0.200	0.128
Mill Creek, WA	0.024	0.002	-1.953	0.154	0.071
Donner Und Blitzen River, OR	0.064	0.001	-1.977	0.253	0.065
Bridge Creek, OR	0.069	-0.002	3.289	-0.263	0.139
EF Quinn River, NEV	0.023	-0.001	-0.171	-0.153	0.397
Leonard Creek, NEV	0.291	0.003	-5.121	0.539	0.010
Lamoille Creek, NEV	0.060	0.005	-8.701	0.246	0.112
Reese River, NEV	0.079	0.001	-2.608	0.281	0.140
Little Currant Creek, NEV	0.143	0.007	-13.696	0.379	0.094
Buckeye Creek, CAL	0.000	0.001	-0.814	0.013	0.950
Blackwood Creek, CAL	0.046	0.006	-12.176	0.215	0.281
Sagehen Creek, CAL	0.106	0.005	-9.239	0.325	0.060
Coeur d’Alene River near Prichard,ID	0.001	0.000	0.217	0.028	0.960
Coeur d’Alene River at Enaville, ID	0.008	0.000	-0.604	0.091	0.520
Coeur d’Alene River at Cataldo, ID	0.092	0.002	-2.765	0.303	0.040
St. Joe River at Calder, ID	0.065	0.001	-1.933	0.255	0.031
Big Jack Creek, ID	0.046	0.000	-0.588	0.215	0.080
Boise River, ID	0.043	0.001	-1.944	0.209	0.071
Lochsa River, ID	0.066	0.002	-3.310	0.256	0.010
SF Clearwater River at Stites, ID	0.006	-0.001	1.576	-0.080	0.840
Clearwater River at Orofino, ID	0.004	-0.001	1.972	-0.067	0.010

Table 4 (continued): Regression relationships between summer low flows and time trend analysis. r^2=coefficient of determination, B1=regression slope, B0=regression intercept, r=correlation coefficient, and p=p-value

Name of watershed	R^2	B1	BO	r	p
NF Clearwater River, ID	0.019	-0.003	6.432	-0.137	0.220
Stehekin River, WA	0.035	0.004	-6.789	0.186	0.030
Entiat River, WA	0.000	0.000	0.978	-0.019	0.103
American River, WA	0.001	0.000	0.027	0.028	0.113
Crab Creek, WA	0.340	0.000	0.506	-0.583	0.000
Rocky Ford Creek, WA	0.108	-0.001	2.139	-0.329	0.020
Average	0.064	0.001	-1.700	0.106	0.242
Minimum	0.000	-0.007	-23.195	-0.583	0.000
Maximum	0.340	0.013	17.795	0.539	0.960
Standard deviation	0.079	0.004	7.248	0.232	0.295

respectively, in their summer low-flows over the period of record. However, the slopes of the regression lines for almost all the streams were very close to zero. It is safe to conclude that, overall in the study area, there was no big change in the summer low-flows from the 1940's to the early 1990's.

Long-term trends in summer low-flow and precipitation. Their graphical investigation

Five-year moving averages of summer low-flows, as well as precipitation, were used to show the long-term trends in the zonal precipitation and summer low-flows in the study area. Several combinations of moving averages were used to select the one which presented a better picture of the trends, or lack of them, without obscuring any significant information.

Two-year, three-year, four-year, five-year, seven-year and ten-year moving averages were constructed for various streams. Five-year moving averages were selected for the graphical study of the data as they smoothed the curve to the degree that was considered best for the purpose of explaining the behavior of summer low-flows and precipitation over the study period. Less than 5-year moving averages did not smooth the data as well, so inferences from the information were more difficult. Moving averages on a basis greater than 5-years obscured valid information in the data by over smoothing.

In the preliminary evaluations, long-term means and five-year moving averages for summer low-flows, csm (cubic feet per second per square mile), and precipitation for each zone were calculated. They were plotted against their long-term means so as to see long-term trends and detect patterns in the summer low-flows and annual and winter precipitation. There were a few inherent problems encountered in this procedure. All the stations had different lengths of records for both precipitation and stream flows. For individual watershed analysis it was not a serious hinderance. When the stream flows and precipitation records were averaged for zonal analysis, the quantitative, as well as the time-base, differences limited the ability to construct the actual picture for the zones.

The extension of records to a common base period for all the stations in each zone could be a solution to graphically present the average relationship between precipitation and stream summer low-flows as well as their trends and patterns.

There are a few record extension techniques which could be used for that purpose. However, there were other problems concerning the extension of records. First, the availability of gauged streams with longer natural flows were rare around the vicinity of the streams with shorter records. Relationships with the stream flows further away from the area of concern were generally very poor. Secondly, it might have contributed additional error in the data and hence lessen the confidence in the results of the study.

Because the data already had potential errors in the measurements of stream flow and precipitation, it was considered appropriate not to extend the records. Also, at the beginning of the project, it was decided to use all the actual observations and information available.

The zonal division of the study area was done on the basis of precipitation. When the average annual, winter, and summer precipitation was observed with respect to individual stations, their quantitative similarities were understandably very good. Also, no major differences were found in their trends and patterns over the period of their records. The average values of annual, winter, and summer (if needed) precipitation were used to study their trends and patterns and their graphical similarities with the summer low-flows.

On the other hand, the summer low-flows in each zone were much different from each other in quantity as well as their trends and patterns. In some cases the common period for all the gauges was not more than 15-20 years. Inclusion or exclusion of a watershed with a very low or very high summer low-flows compared to other streams in the zone changed the entire look of the trend and patterns of summer low-flows for that zone and distorted the actual relationships. It was decided to study the trends and patterns of precipitation and summer low-flows and their similarities (or lack of it) were studied on individual watershed basis.

Zone 1 (precipitation 0-10 inches)

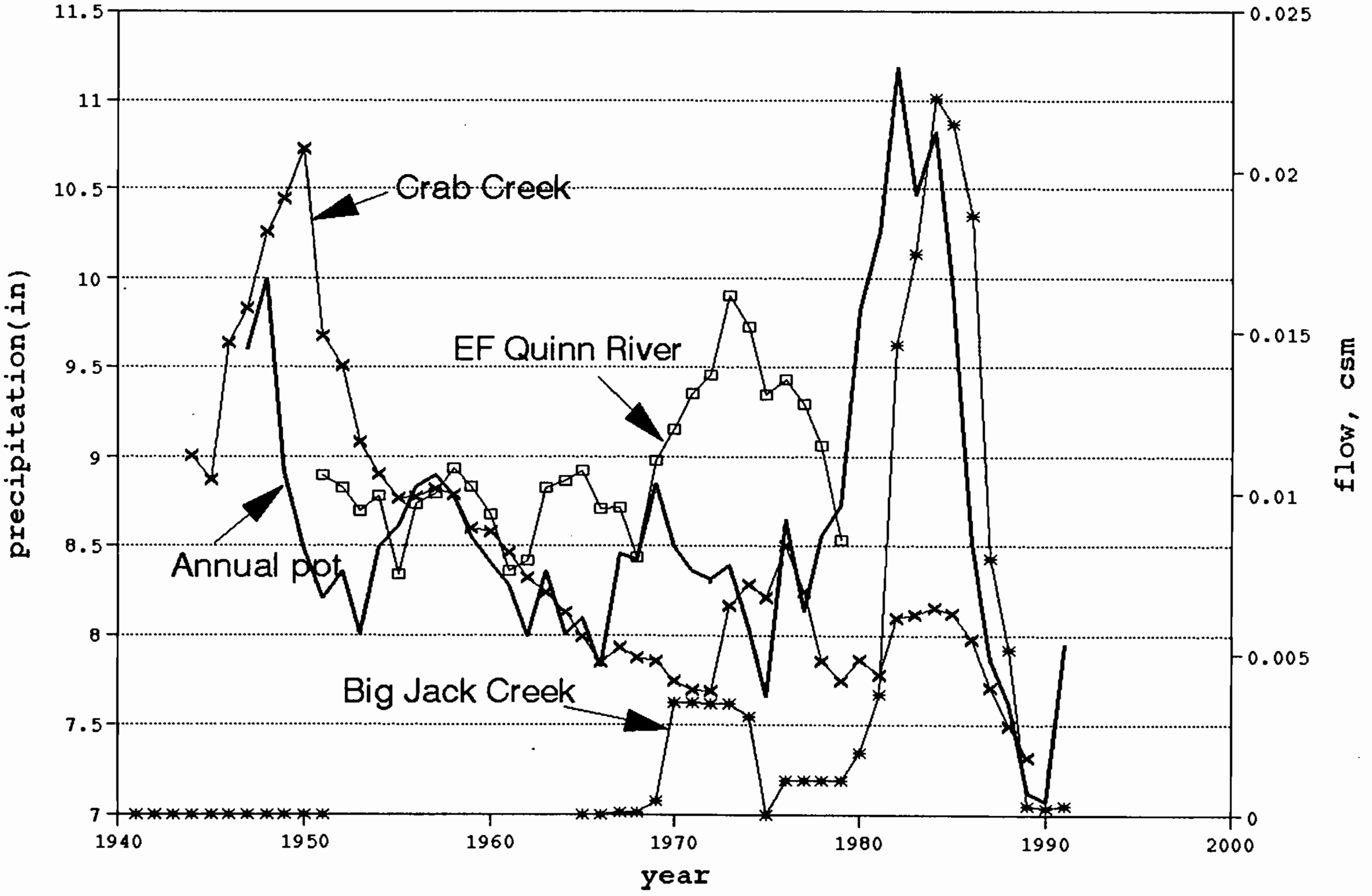
Annual and winter precipitation for Zone 1 had a very high degree of correlation. They were in very good agreement in trends and patterns over the study period from the early 1940s to the end of the period of study (1993). Winter precipitation was about 50% of the annual precipitation in quantity. Summer precipitation for the

Zone 1 had no significant relationship with the annual or winter precipitation, and did not show any significant correlation with summer low-flows. Because of this, summer precipitation was not included in the presentation. Spring and Fall precipitation were also not included in the discussion due to their insignificant effect upon summer low-flows.

Summer low-flows did not behave like precipitation for Zone 1. There was a lot of variation in summer low-flows, quantitatively as well as trend and pattern wise. So summer low-flows for Zone 1 were examined in two sub groups. The first subgroup included watersheds having lower summer low-flows in this zone (Figure 4). It included the Big Jack Creek near Burneau, Idaho, East Fork Quinn River in northern Nevada and Crab Creek in eastern Washington.

Big Jack Creek had the lowest summer low-flows for most of the record period. For many years of the record, it had zero lowest summer low-flow. The data for the 1940's showed a very dry period, with many consecutive years of lowest summer low-flows of zero or close to zero. This stream showed no significant correlation with annual precipitation for the watershed for the period during the mid 1940's that was the second wettest (precipitation wise) of the record for Zone 1. However, it did follow the relatively small wet period of the early 1970's and the wettest period of the

Figure 4: Annual precipitation and summer low flows (Zone 1, 0-10 in)



record during the mid 1980's, with a lag period of about one to two years.

East Fork Quinn River showed a noticeable positive trend in summer low-flows from the beginning of the record (late 1940's) to the mid 1970's, with shorter cycles of wetter and drier periods. The mid 1970's period was the wettest of the record in the area. From the mid 1970's until the end of the record (around 1980), there was a downward trend in summer low-flow. It showed little similarity in trends and patterns with the zonal precipitation. During the 1950's it showed a better correlation with precipitation with a lag of about one year. During the 1960's and 1970's it had opposite patterns to that of precipitation.

Statistically, it showed insignificant correlation with precipitation. Either there was an increase of lag time between precipitation and response in summer low-flows of about four years for the area, or some major change in the watershed vegetation condition took place during that time. The later possibility seems more reasonable because the lag time in low-flow response is more dependent on the geological nature of the watershed, which does not change in a short period.

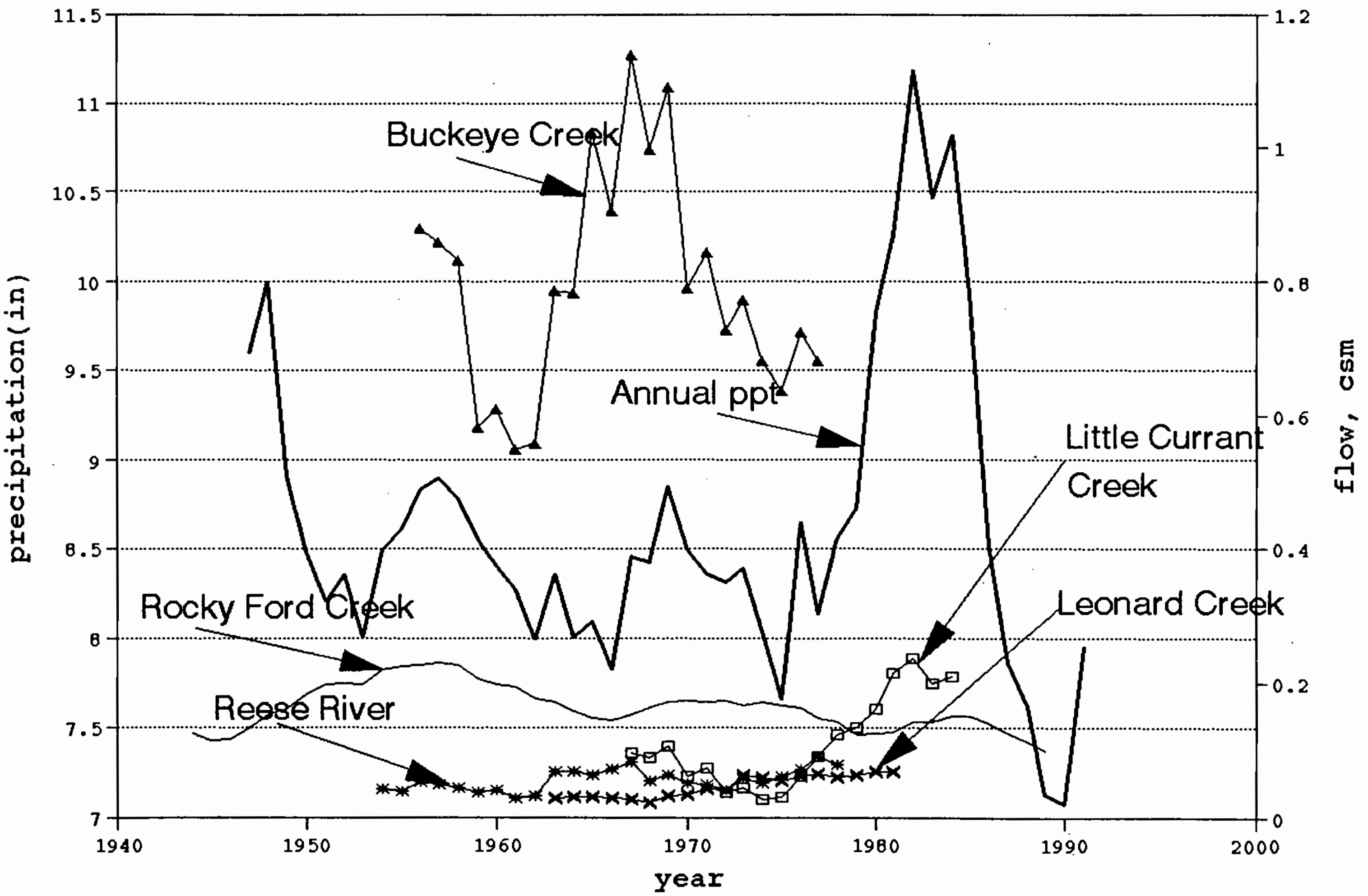
Crab Creek had the longest record of all the streams in Zone 1. Over the period of record, it showed a downward trend in summer low-flow. Generally, it did follow the "noises" of wet and dry spells in precipitation for Zone 1, but with a lesser amplitude every other time it occurred. Summer low-flows were very high during the late 1940's, with a lag of about one year with precipitation in their pattern, then decreasing gradually every year onward until the mid 1970's, when it showed a greater change in trend in summer low-flows as a response to precipitation compared to the mid 1950's and the mid 1980's.

It showed upward scatter in its downward trend with decreasing response during wet precipitation periods. Even the response to the wettest precipitation period of the record, during the mid 1980's, was very low. This could be due to some change in physical nature of the watershed or human made changes on the surface of the watershed. Possibly it could be a gradual increase in the use of ground water from the watershed through pumping for irrigation purposes.

Among the second subgroup in Zone 1 (Figure 5), all five streams showed either positive or no trends over the period of record except Rocky Ford Creek, eastern Washington, which showed a slightly negative trend, and was lesser than Crab Creek in slope. This showed that watershed response in that region of eastern Washington was changing over the period of record.

Of course, precipitation is not the only factor which controls the nature of the summer low-flows. That region

Figure 5: Annual precipitation and summer low flows (zone 1, 0-10 in)



was becoming drier and summer low-flows were decreasing in general. The actual drainage boundary for Rocky Ford Creek is not clear and the contributing area is undoubtedly larger than assumed by the USGS. Therefore, the true nature of the hydrological changes, natural or artificial, cannot be assumed for such watersheds. The negative trends in summer low-flows for both watersheds, which were not supported by the precipitation trends, emphasized the point that water use in that region had increased over the period of record, which could not be accounted for by the information available. These watersheds have very sparse vegetative cover at present.

Gradual decrease of vegetative cover could result in loss of infiltration capabilities of the soil, and hence the storage of water in the mantle of the watershed to support sustained flow during the drier periods. But that seemed less likely in this region. We concluded that an increased uptake of the ground water for agricultural and other uses resulted in a gradual decrease of summer low-flows in the region.

Reese River near Ione, Nevada, showed a positive trend in summer low-flows with an irregular oscillation pattern. Overall, it showed considerable variation in summer low-flows over the period of record with wider cycles. The period around the early 1960's was the driest for the watershed and hence for that region.

Little Currant Creek, central Nevada, had a noticeable upward trend in its summer low-flows for the period of record. It had a higher correlation with precipitation without any lag period. It is a drier and hotter area with high elevation in the middle of the great basin desert. Due to the hot nature of the climate and higher relief of the watershed, no lag time existed in response to the wet or dry cycles of climate. The driest period of the record for the watershed was during the mid 1970's.

Reese River showed stronger similarities in its pattern of wetter and drier episodes with the precipitation cycles in their duration, as well as, intensity with no lag time. The mid 1980's were the wettest years of record for the area.

Leonard Creek, northern Nevada, had a noticeable positive trend in its summer low-flows with a non cyclic pattern. During the early 1960's, it experienced the driest episode of weather, whereas the 2-3 year period around 1980 was the wettest period of the record.

Buckeye Creek, northeastern California, had the highest summer low-flows in Zone 1. It showed a relatively cyclic pattern of dry and wet years, with closer to no trend over the period of record. It showed the strongest correlation with precipitation among all the streams in the Zone 1.

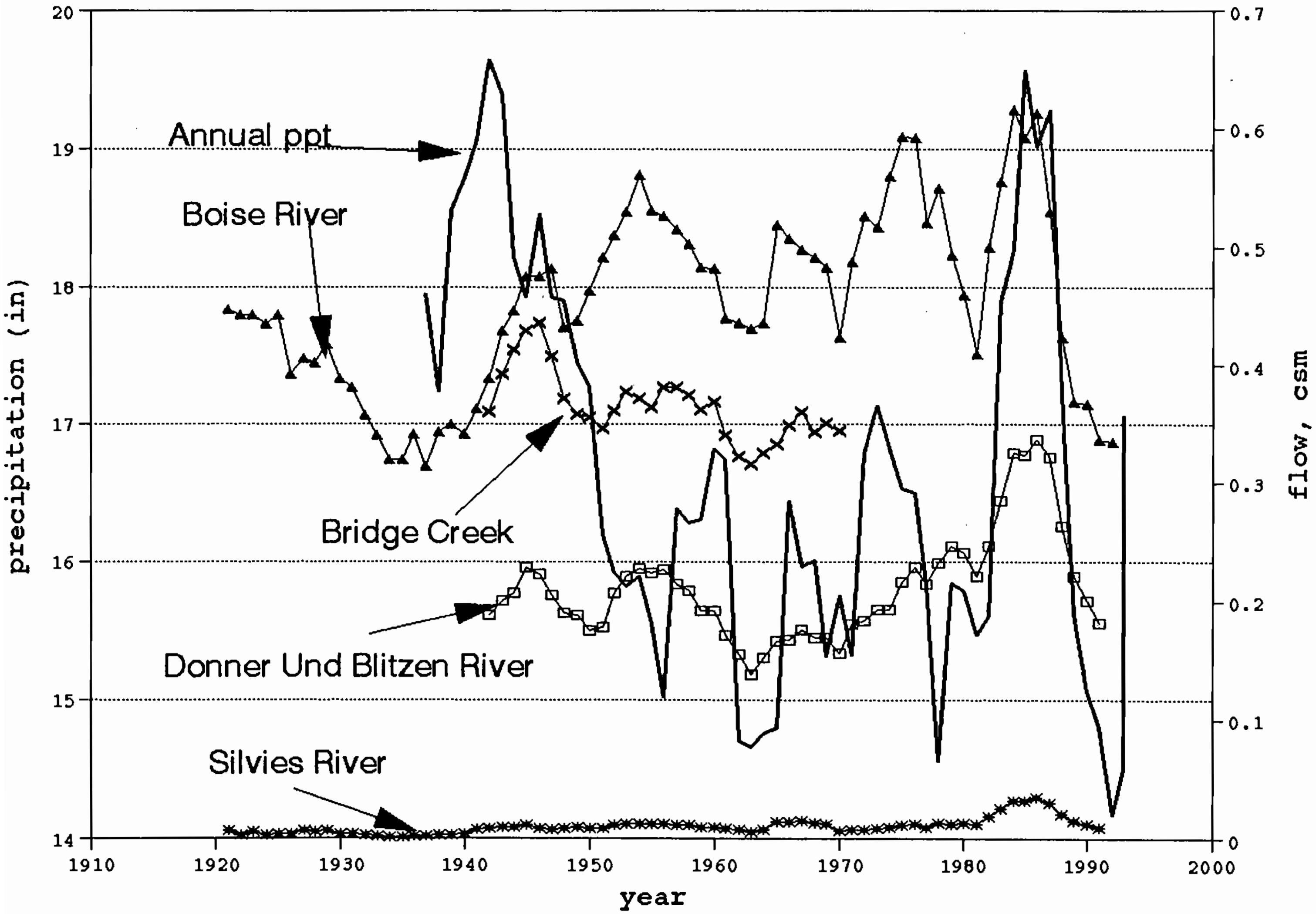
In general, the watersheds which had more vegetative cover or higher watershed relief showed no lag time in their response to precipitation and summer low-flows (e.g., Buckeye creek, Little Currant Creek) compared to about one-to-two years lag time in response for the arid and flatter watersheds (e.g., Crab Creek, Big Jack Creek, etc.). Otherwise, there was no general similarity among the streams in Zone 1 in their trends over the period of record as well as their degrees of response to the precipitation cycles and magnitudes.

Zone 2 (precipitation 10-20 inches)

Annual average precipitation had strong correlation with the winter precipitation for Zone 2. There was clearly a multi-year cycle in the precipitation pattern. The record started after the great drought of the 1930's, which occurred throughout the western United States (Figure 6). There was a very wet period during the late 1930's in Zone 2, followed by a longer period of either drier or closer to average precipitation for about 30 years, with unequal small cycles above and below average precipitation for the period.

If it was to analyze the precipitation record for only those thirty years, one would have a different picture, showing 3-4 years duration cycles of dry and wet periods, with no actual extreme wet or dry periods in the area. With the availability of a relatively longer period of record, it was seen that the period between the late 1940's to the late

Figure 6: Annual precipitation and summer low flows (Zone2, 10-20 in)



1970's was close to the long-term average period in precipitation.

On both sides of this period there were wetter periods of similar intensity and duration. If that was a representation of real patterns of wet cycles in the zone, then the next wet period of similar magnitude for Zone 2 should occur around the end of the first decade of the twenty-first century.

Boise River, Idaho, and Silvies River, Oregon, had the longest records among the study sites in the Zone 2 (Figure 6). Both had quite different summer low-flows per square mile (csm) values. During the 1930's, both rivers experienced the lowest summer low-flows of their records. During the recovery stage from that drought, there was shown a lag period of about 2-3 years for both rivers. This showed that the hydrological drought lasted longer, or at least ended later than the meteorological drought. For the later part of the record, Boise River showed a closer relation between its summer low-flows and zonal precipitation. Response time for the normal conditions, as well as wetter periods of climate, was quicker. The mid 1980's were the wettest period in the area, followed by another severe drought at the end of the record (late 1980's to early 1990's).

Silvies River had quite similar trends and patterns in its summer low-flows to Boise River, except during the late

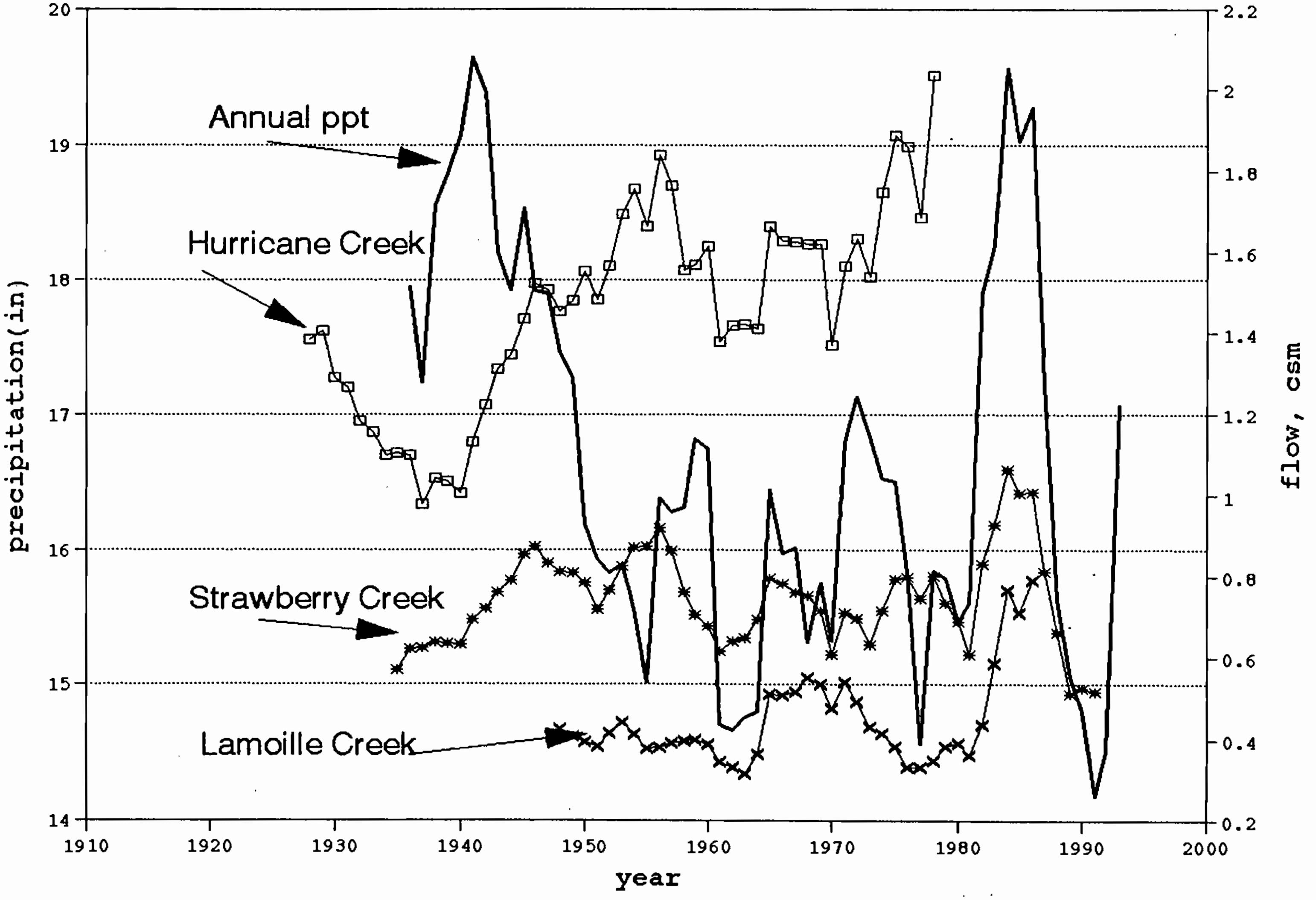
1960's, when it had higher summer low-flow. This is in contrast to the meteorological drought for that period. It followed the wet cycle in precipitation during the 1980's, followed very closely by another hydrological drought at the end of the study period.

Bridge Creek and Donner Und Blitzen River (Figure 6), in the Steens Mountains, Oregon, followed the precipitation cycles and trends very closely for their periods of record. During the 1940's, the response to the precipitation cycle was delayed by about 2-3 years. Responses to the precipitation changes were very positive and clearly noticeable.

Figure (7) shows the other three streams in this precipitation zone. All three had different patterns and trends in their summer low-flows. Lamoille Creek, Nevada, had a shorter record than other streams. Strawberry Creek and Hurricane Creek, Oregon, showed a lag of 1 to 2 years to the wet period of the 1940's. Otherwise, there were opposite trends in summer low-flows and precipitation which could have been due to changes in physical conditions of the watersheds. However, there was not any information to confirm it.

Hurricane Creek followed the oscillation patterns of annual precipitation for the rest of its record, but with a lag of about 2-3 years. Lamoille and Strawberry Creeks

Figure 7: Annual precipitation and summer low flows (Zone 2, 10-20 in)



showed closer resemblance with annual average precipitation than Hurricane Creek for the entire record.

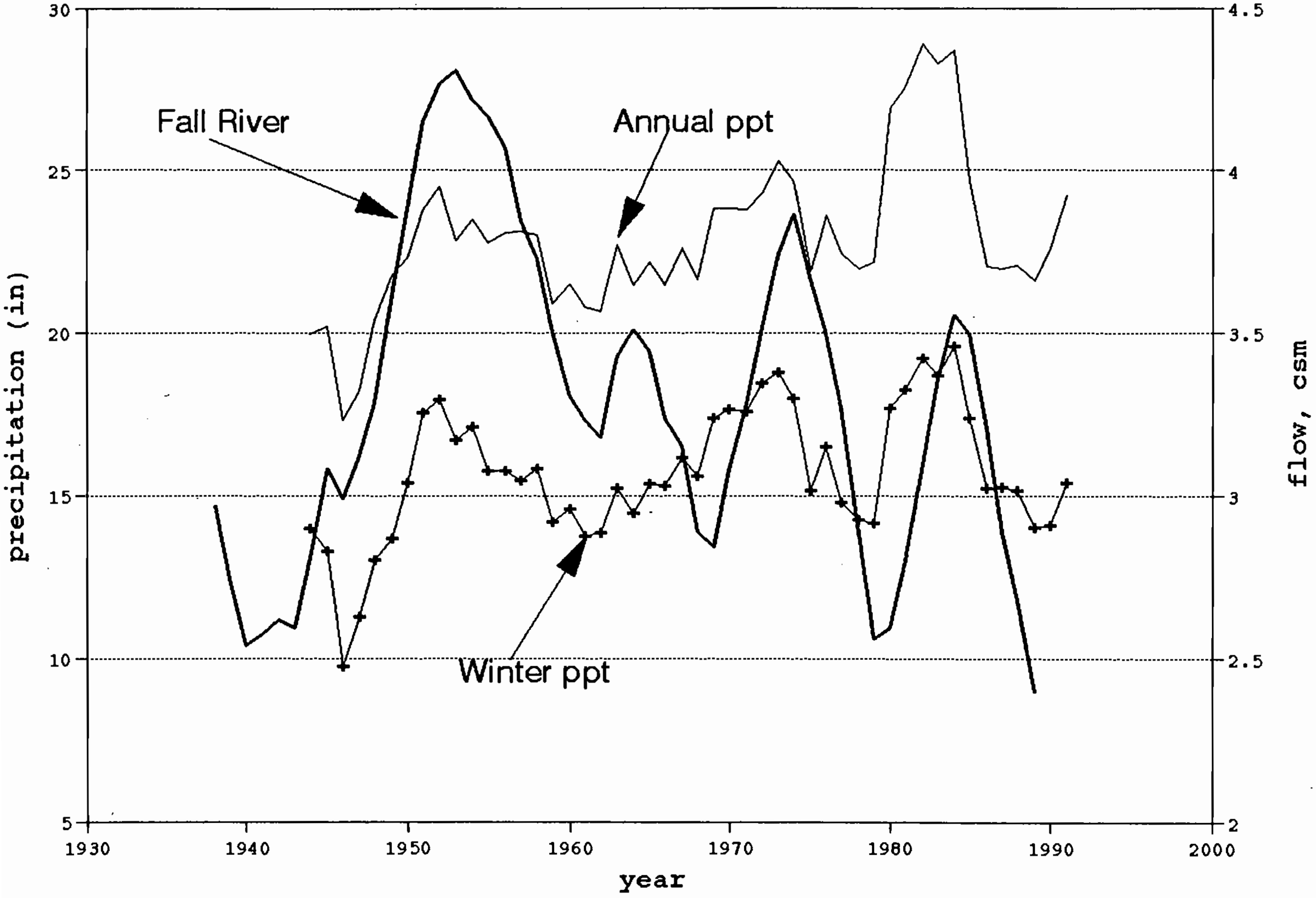
Zone 3 (precipitation 20-30 inches)

Precipitation for the Zone 3 did not show a significant shift in its trend compared to summer low-flows throughout the period of record (Figure 8). There was an overall minor upward trend in annual precipitation. Winter precipitation was a major part of the annual precipitation and it followed the annual precipitation patterns very closely. Summer precipitation was very low and did not follow the patterns in the winter or annual precipitation significantly.

This zone did not have two clearly wet periods like Zone 2. The record period started during the early 1940's, the effect of drought experienced during the 1930's in the area could not be seen. Three relatively wet periods occurred around 1950, the early 1970's, and the mid 1980's (wettest of the three), followed by moderately dry periods of longer duration. There was an upward trend in the precipitation in the zone over the period of the record.

Fall River, near La Pine, Oregon, had the highest summer low-flows(csm) values. Therefore, it was presented in a different Figure (8) in an effort to not mask the trends and patterns of the other streams in Zone 3. Throughout its period of record, it followed the precipitation patterns very closely, although, with

Figure 8:Annual & winter precipitation and summer low flows,(Zone 3, 20-30 in)



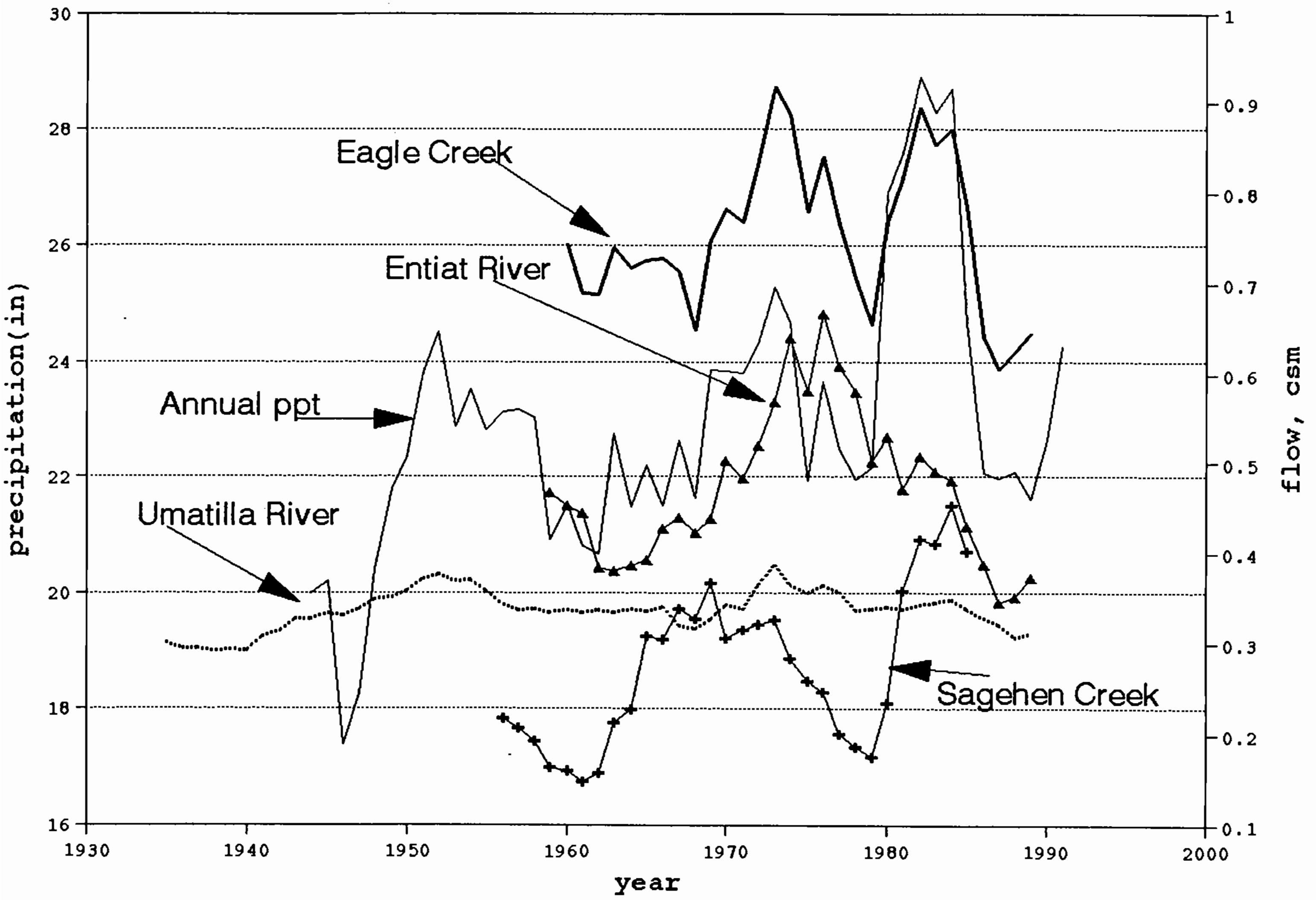
different intensity of response each time. It showed the maximum response to the wet cycle of the late 1940's to the early 1950's and dry cycle in precipitation of the late 1980's. It showed an overall downward trend in summer low-flows after the 1950's.

Eagle Creek, Oregon, followed the precipitation cycles closely during the period of its record with relatively unequal response intensities (Figure 9). It showed maximum summer low-flows in response to the wet period of the mid 1970's, even higher than for the wettest precipitation period of the record during the mid 1980's. Entiat River, Washington, followed the precipitation trend from the mid 1950's to the late 1970's very closely. After that period, it showed an upward movement of summer low-flows in response to precipitation, but its summer low-flows kept on decreasing for the rest of the period in contrast to the wetter precipitation period.

Sagehen Creek, northeastern California, did follow the precipitation trends and patterns very closely for its period of record (Figure 9). Umatilla River, Oregon, had a wetter period during the mid 1950's and the mid 1970's. Until the late 1930's, there was a lingering effect of the great drought of the 1930's for the watershed (Figure 9).

During that period, it had the minimum summer low-flow. This was consistent with a lot of other streams where the hydrological drought lasted a few years longer after the end

Figure 9:Annual precipitation and summer low flows,(Zone 3, 20-30 in)



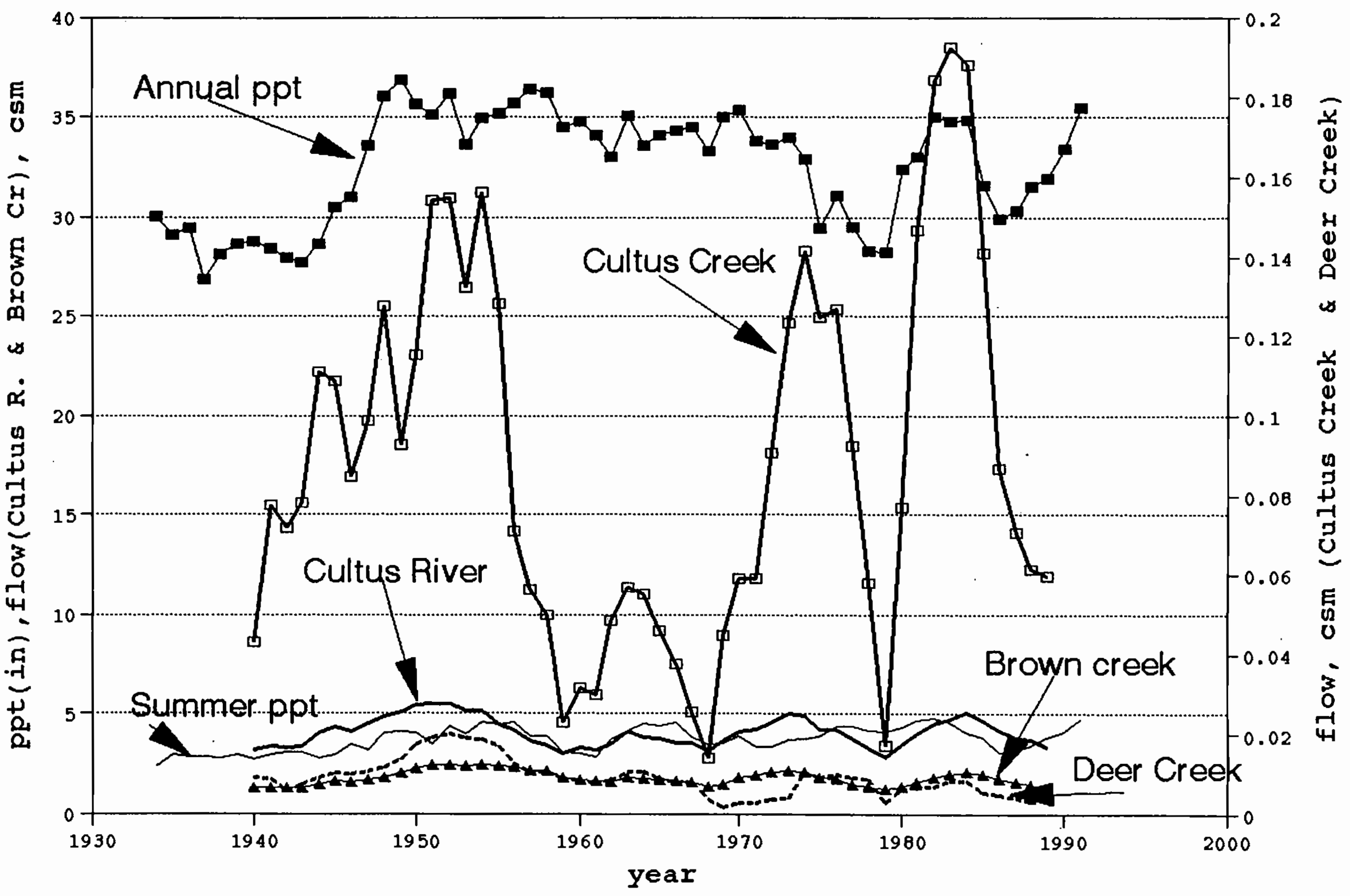
of the meteorological drought. Response to the wetter precipitation period of the mid 1980's was moderate compared to the earlier wet periods. This was followed by a drier period which, by the end of the record, was approaching the drought of the late 1930's in its magnitude by the end of the record.

Zone 4 (precipitation 30-40 inches)

Winter precipitation was about 60% of the annual precipitation for Zone 4. There was not much resemblance between patterns of summer precipitation and annual precipitation. However, there was a close resemblance between the annual and winter precipitation patterns for the entire period of record with the occurrence of dry periods during the 1930's, the mid 1970's, and the mid 1980's. Most of the period between the mid 1940's and the mid 1970's experienced a wetter climate. The driest periods of record occurred during the late 1930's and the late 1970's for the Zone 4 (Figure 10).

Four of the streams in Zone 4 were in the La Pine area of the eastern Cascades, Oregon (Figure 10). These watersheds had a lot of variability in their summer low-flows quantitatively. However, when examined graphically, they had a very high resemblance in the patterns of their summer low-flows. All of them had their summer low-flow

Figure 10:Annual & summer precipitation
and summer low flows, Zone 4 (30-40 in)



trends in good agreement with the precipitation trends for the zone for the entire period of record.

There was no significant upward or downward trend in precipitation. Similarly, all the streams in the area had closer to stationary cycles in their summer low-flows with little different amplitudes in their cycles.

Four of the watersheds in the Zone 4 were in the Coeur d'Alene or surrounding forest areas (Figure 11). All four of them were in agreement with each other in trends and patterns of summer low-flows, as well as magnitudes (csm), except for the St. Joe River, which had a little higher summer low-flows than the other three rivers. When compared to the zonal precipitation trends and patterns, summer low-flows for all rivers showed a very high degree of resemblance with it. Relatively, the period during the early to mid 1950's was the wettest period, and the late 1930's and late 1980's were the driest periods of the record.

Blackwood Creek, northeastern California, had the smallest period of the record in the Zone 4 (about 28 years) (Figure 12). During its recorded period, the summer low-flows in the creek were highly correlated to the precipitation noises above and below normal. Stehekin River, Washington, and South Fork Walla Walla River, Oregon, were also reasonably well agreed with the precipitation noises and overall patterns in precipitation (Figure 12).

Figure 11:Annual & summer precipitation and summer low flows, Zone 4 (30-40 in)

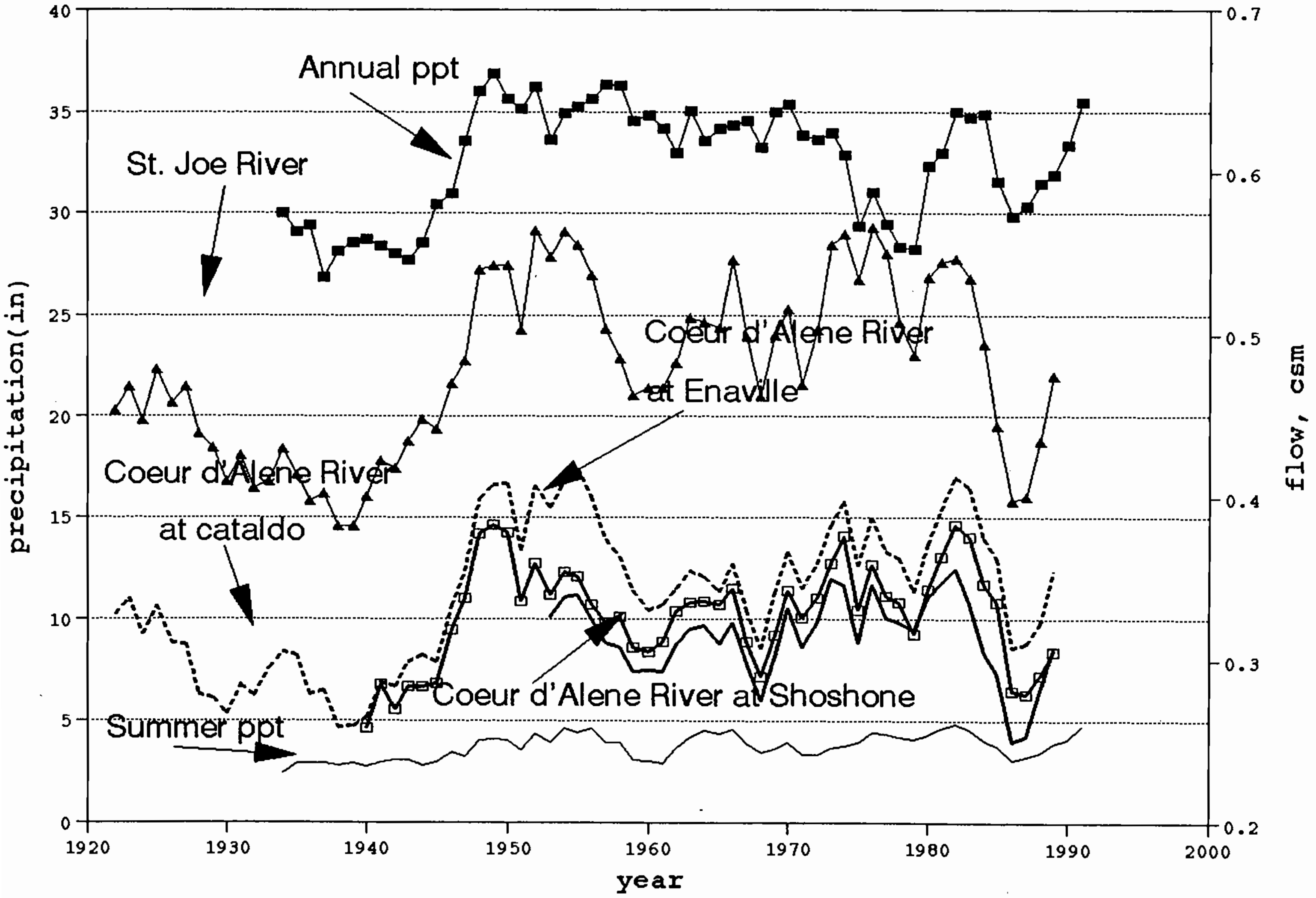
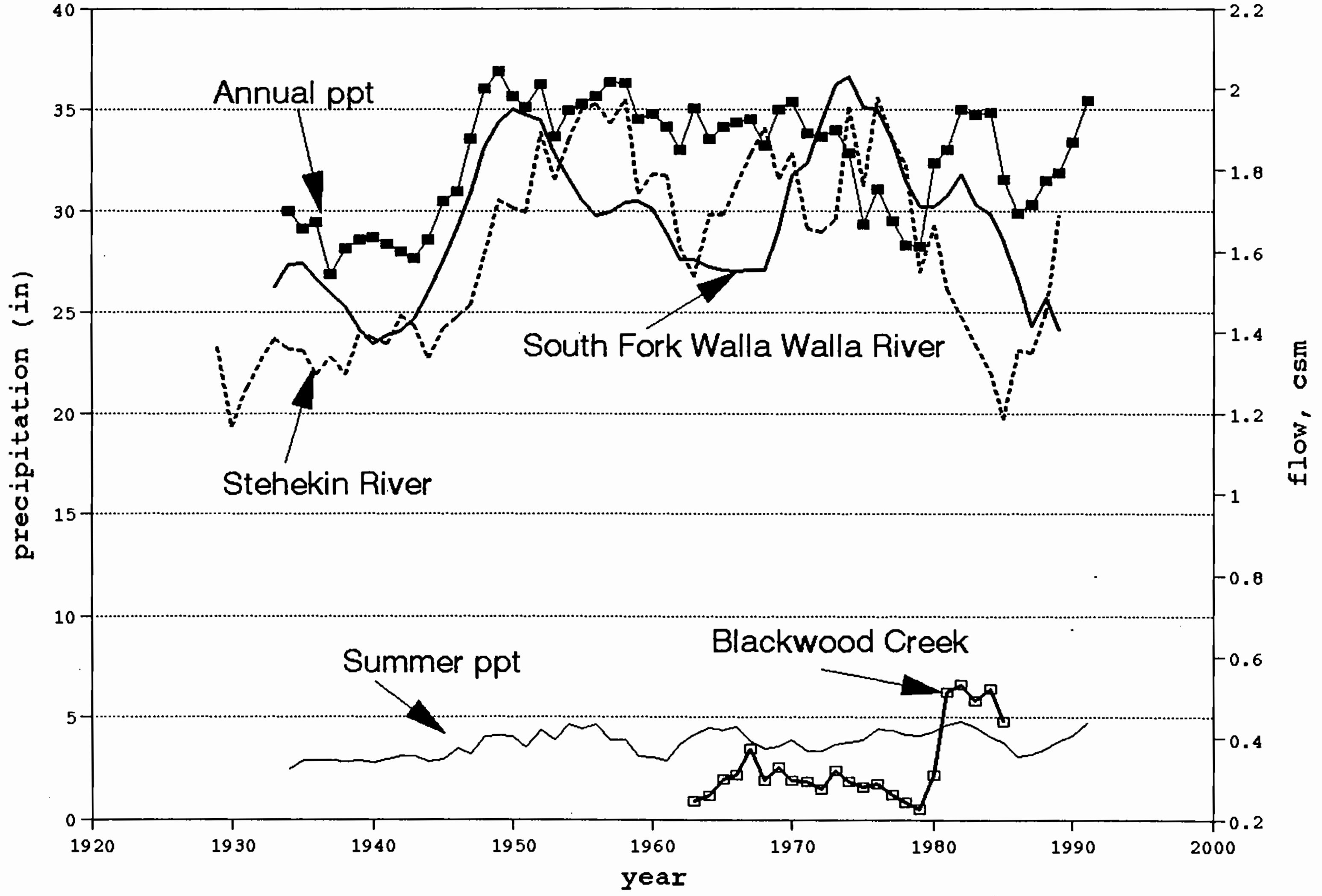


Figure 12:Annual & summer precipitation
and summer low flows, Zone 4 (30-40 in)

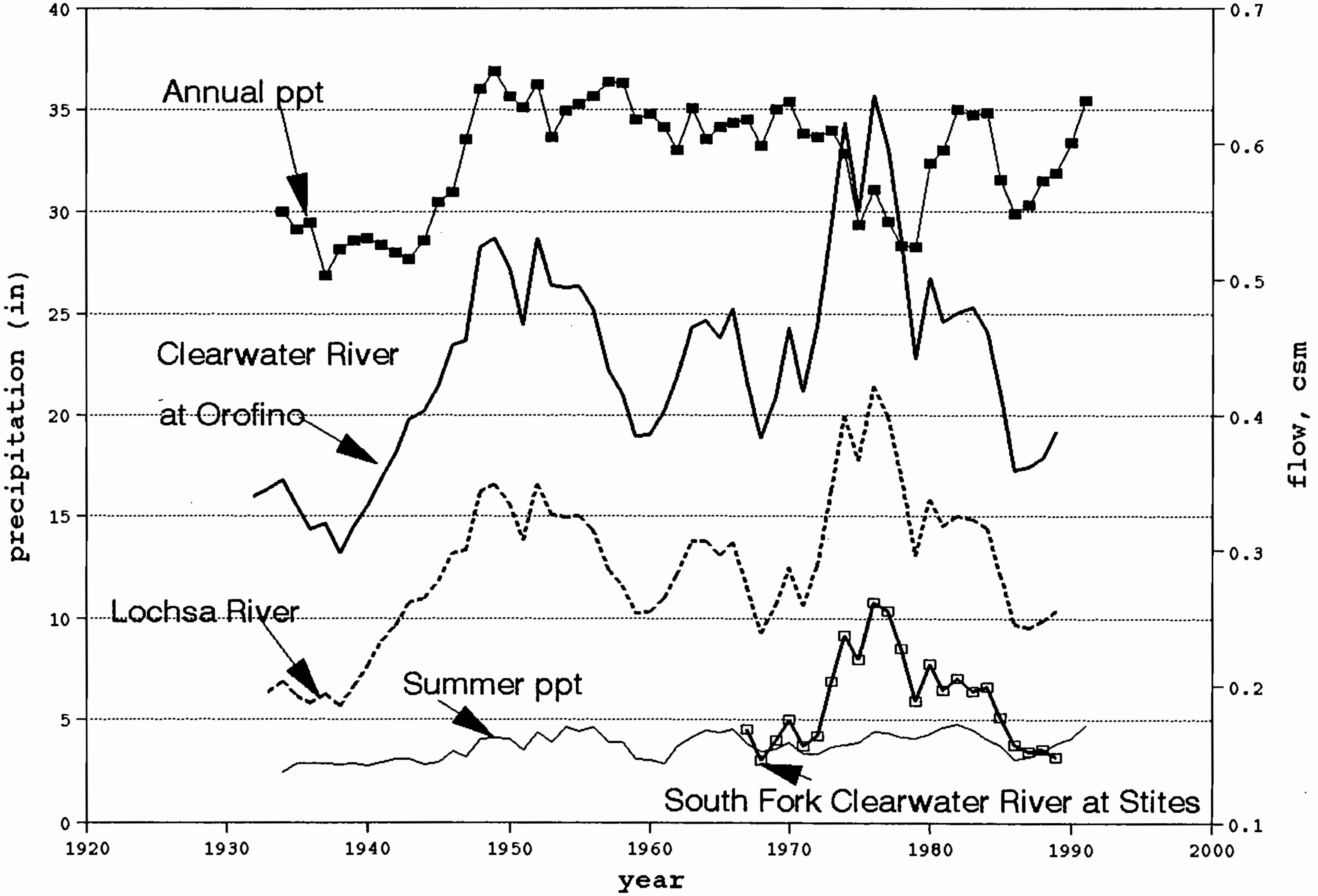


These two also portrayed the pictures of drier periods during the late 1930's and the late 1980's, comparably of similar magnitudes, which were unclear from the precipitation cycles for the zone. Periods from the late 1940's to the early 1950's and the mid 1970's were the wetter periods of the record for both areas.

Three rivers in the Clearwater Forests, Idaho, (Clearwater River at Orofino, South Fork Clearwater River at Stites and Lochsa River near Lowell) were also in good agreement with each other in their trends and patterns of summer low-flows over the period of record (Figure 13). However, their summer low-flowsmagnitudes per square mile (csm) were different. All three rivers had the wettest summer low-flowsperiod during the mid 1970's followed by the wet period of the late 1940's to early 1950's. Summer low flows during the late 1930's were the lowest for the region followed by the periods of the late 1980's, the late 1960's and the late 1950's, respectively.

A wetter period in summer low-flows of the 1970's was not evident in the zonal, annual, and winter precipitation. However, all the rivers in the northern Idaho regions showed a good degree of similarities between the trends and patterns of their summer low-flows and the summer precipitation. There was a higher than average summer precipitation in these areas during the period of the mid 1970's, which could explain the higher than average summer

Figure 13:Annual & summer precipitation and summer low flows, Zone 4 (30-40 in)



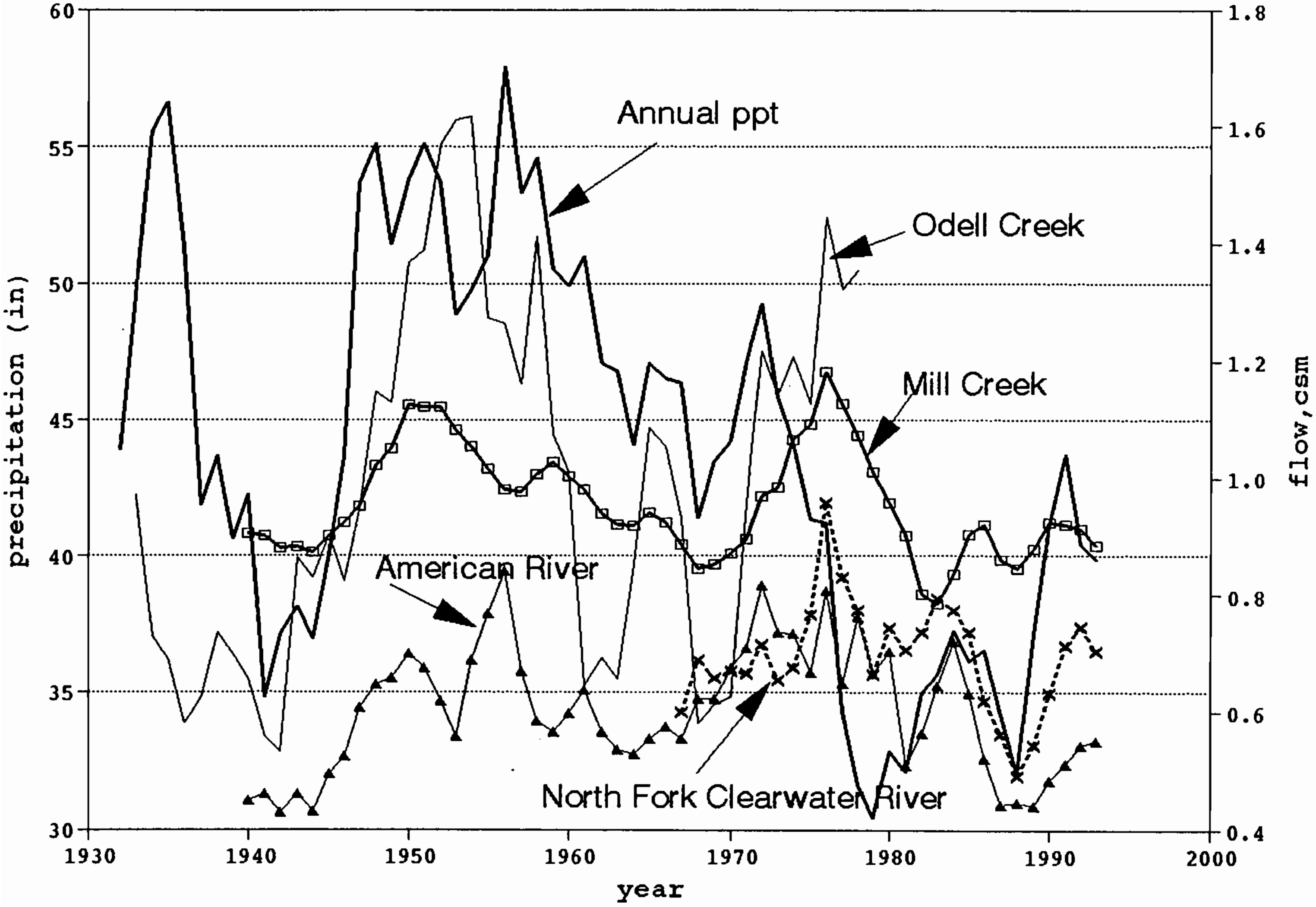
low-flows in the region in spite of the average annual precipitation.

Zone 5 (precipitation $\geq$ 40 inches)

Winter and annual precipitation were again in conformity with each other for Zone 5 for the period of record (Figure 14). Winter precipitation was close to annual precipitation in quantity (about 60% of annual precipitation). Overall, there was a downward trend in precipitation over the period of record with dry periods in the late 1930's to mid 1940's, and then again in the 1980's. A wet period occurred during the mid to late 1930's, and again from the late 1940's to the early 1970's. From the late 1950's to the end of the period of record there was a steeper downward trend in precipitation showing a gradual dry episode. Summer precipitation was relatively very low and did not conform well with the dry or wet periods of the record on the 5-year moving average basis.

Precipitation trend overall for this zone was quite different from the other zones. During the late 1930's to the mid 1940's a drier period was followed by a very wet period during the mid 1950's to the mid 1960's. But, in contrast to the other zones, there was no clear and pronounced wet period during the mid 1980's. There was a downward trend in precipitation for the entire period of record even after including the drought period of the late

Figure 14:Annual precipitation and summer low flows (Zone 5, >=40 in)



1930's. The late 1970's to early 1980's was the driest period.

All four streams/rivers in the zone had tracked with the precipitation patterns, with varying degrees of response to the magnitudinal changes in precipitation (Figure 14). American River, Washington, showed a decreasing summer low-flowstrend after the mid 1950's until the end of the record. It experienced the driest periods in summer low-flows (drought) during the late 1930's to the early 1940's and the late 1980's. This river had the highest degree of resemblance to the annual precipitation with no lag period.

Mill Creek in the Blue Mountains, Oregon, experienced a slightly negative trend over the period of its record, with the mid 1970's being the wettest period of the record. Periods during the late 1930's to the early 1940's, the late 1960's, and the early 1980's were among the driest periods for the area. It had good coincidences in the trends and patterns of its summer low-flows with the zonal precipitation over the period of the record, but with a lag period of about 1-2 years. Also, the responses in magnitudes differed from period to period.

Odell Creek, Oregon, and North Fork Clear Water River, northern Idaho, showed high degrees of resemblance with precipitation for their periods of record. During the study of the 5-year moving averages of summer low-flows and precipitation it was observed on a few occasions that trends and patterns in summer low-flows were completely opposite to those of precipitation. Whereas, for the remainder of the study period, there was a high degree of correlation between both trends.

Due to lack of management history of the watersheds the anomaly in the trends could not be explored. However, by spotting these periods of concern it will now be easier and less time and money consuming to explore the real cause of those differences. With the presence of one or two such periods during which precipitation could not explain the behavior of drier conditions in the region, regression relationships became much less significant.

Correlation between summer low-flow and precipitation

Summer 7-day low-flows were regressed against annual as well as seasonal precipitation for each stream and results were examined. Resulting equations were averaged over all streams in each zone to construct the zonal equations to predict summer low-flows.

Zone 1 (7 watersheds and 8 precipitation stations)

Winter, spring, summer, fall and annual precipitation for each precipitation gauge for each year were extracted from the monthly records. The seasonal and annual precipitation for the individual watersheds were regressed against the annual 7-day summer low-flows for each stream, and their correlations were studied.

Correlation for seasonal and annual precipitation was highly variable within the watersheds and, therefore, the average correlation between stream summer low-flows and precipitation for the zone was found to be not very significant. Correlations between summer low-flows and summer, fall and spring precipitation were found highly insignificant and, hence, not discussed here.

Correlations between summer low-flows and winter and annual precipitation were notable. On the average, the relationships were not statistically significant between summer low-flows and winter and annual precipitation. However, the individual watersheds had varying degrees of relationships. Average r^2 values for the regression between the winter precipitation and summer low-flows for Zone 1 was 21%, with a range of 4% to 51% and a standard deviation of 17%. The average p-value was found to be 0.088, with a range of 0.0002 to 0.234, and the average standard error of y-estimate was 0.075 csm.

Buckeye Creek in northeastern California showed the maximum correlation between winter precipitation and summer low-flows, while, Crab Creek in eastern Washington had the minimum correlation between summer low-flows and winter precipitation. The regression model equation produced by averaging the individual equations for all the watersheds in the zone to predict summer low-flows using winter precipitation is:

$$Q = 0.04+0.07 \text{ (winter precipitation)} \quad (10)$$

where Q=annual summer low-flow.

Although, the relationship between winter precipitation and summer low-flows was significant, its practical use was found limited due to its poor ability to explain the variations in the summer low-flows in Zone 1.

Annual precipitation and summer low-flows for the period of record had maximum correlation for the zone. Average r^2 value was found to be 29%, with a range of 3% to 62% and a standard deviation of 24%. Average p-value for the analysis was 0.114 and the average standard error of y-estimate was 0.07 csm. Like winter precipitation, the maximum correlation between summer low-flows and annual precipitation was shown by Buckeye Creek in the northeastern California and the minimum correlation was shown by Crab Creek in eastern Washington.

The poor correlation between summer low-flows and precipitation for Crab Creek was also shown by the graphical presentation of their 5-year moving averages. Summer low-flows for the stream decreased over the period of record in contrast to precipitation in the area.

The average regression equation for Zone 1 to predict summer low-flows based on annual precipitation was found as:

$$Q = -0.04+0.022 \text{ (annual precipitation)} \quad (11)$$

where Q=annual summer low-flow.

This equation, too, did not have a significant ability to predict the summer low-flows alone for Zone 1 to be of any practical importance.

From the average relationships between summer low-flows and winter and annual precipitation, it was concluded that their usefulness for the practical application was not significant. Individual equations for some streams with very significant relationships between summer low-flows and precipitation may be used for that sub-region. However, there was not enough data to support that conclusion.

Zone 2 (7 watersheds and 7 precipitation stations)

The variation in the regression relationships between precipitation and summer low-flows for the watersheds of Zone 2 was also found very high, making it hard to come up with any good prediction equation for the zone. Fall and spring precipitation had a very insignificant relationship with summer low-flows.

Summer precipitation had very low correlation with summer low-flows compared to the winter and annual precipitation. The average r^2 value was 14% with a range of 2% to 27%, with a standard deviation of 7.4%. The average p-value for the relationship was 0.124 and the average standard error of y-estimate was 0.19 csm.

Average r^2 value for the relationship between winter precipitation and summer low-flows for Zone 2 was found to be 36%, with a range of 7% to 81%, and a standard deviation of 25%. The average p-value for this analysis for Zone 2 was 0.036 and the average standard error of y-estimate was 0.12 csm.

Hurricane Creek in northeastern Oregon showed the maximum correlation between winter precipitation and summer low-flows, while Lamoille Creek in central northern Nevada had minimum correlation between the summer low-flows and winter precipitation. The resulting average regression equation for the relationship between summer low-flows and winter precipitation for Zone 2 was found as:

$$Q = 0.11+0.05\ (\text{winter precipitation}) \qquad (12)$$

where Q=annual summer low-flow.

Annual precipitation and summer low-flows had maximum average correlation for Zone 2 (like Zone 1). Average r^2 value was 45%, with a range of 23% to 67%, and a standard deviation of 22%. The average p-value for the relationship was 0.003 and the average standard error for y-estimate was 0.13 csm.

Like winter precipitation, maximum correlation between summer low-flows and annual precipitation was shown by the Hurricane Creek watershed in the northeastern Oregon and the minimum correlation was shown by the Silvies River in eastern Oregon. The resulting regression equation for the annual precipitation and summer low-flows for Zone 2 was found as:

$$Q = -0.16+0.04\ (\text{annual precipitation}) \quad (13)$$

where Q=annual summer low-flow.

Summer low-flows for the Silvies River showed greater correlation with precipitation at the P-Ranch and Austin stations than precipitation at the John Day station. John Day is just north of the upper catchment boundary of the Silvies River and the station is located at fairly open place at the airport. It did not show any significant relationship with the almost adjacent watershed.

The average regression equation using annual precipitation to predict summer low-flows was highly significant. However, the use of either of these two equations to predict summer low-flows was hampered by their lower capabilities to explain the variations in the summer low-flows.

Zone 3 (5 watersheds and 5 precipitation stations)

Like other zones, fall and spring precipitation did not show any significant correlation with the summer low-flows for Zone 3. Summer precipitation had very low correlations with summer low-flows compared to the winter and annual precipitation. The average r^2 for the regression analysis between summer precipitation and summer low-flows was 12%, ranging from 0.33% to 26%, with a standard deviation of 9%. The average p-value of the relationship was 0.186 and the average standard error of y-estimate was 0.24 csm.

Winter precipitation and summer low-flows had maximum average correlation for Zone 3. Average r^2 value for the regression between winter precipitation and summer 7-day low-flows was 37% ranging from 10% to 58% with a standard deviation of 23%. The average p-value for this analysis for Zone 3 was 0.028 and the average standard error for the y-estimate was 0.21 csm for the winter precipitation.

Sagehen Creek near Truckee River in northeastern California showed the maximum correlation between winter precipitation and summer low-flows while Fall River near La Pine, Oregon had minimum correlation between summer low-flows and winter precipitation. The average equation found by the regression analysis between winter precipitation and summer low-flows for Zone 3 was:

$$Q = 0.66+0.02 \text{ (winter precipitation)} \quad (13)$$

where Q=annual summer low-flow

Average r^2 for the regression between annual precipitation and summer low-flows was 36%, ranging from 8% to 55%, with a standard deviation of 22%. The average p-value for the analyses was 0.024 and the average standard error was 0.21 csm.

Like winter precipitation, maximum correlation between summer low-flows and annual precipitation was found for Sagehen Creek in northeastern California and the minimum correlation was shown for Fall River near La Pine, Oregon. The average regression relation for annual precipitation and summer low-flows was found as:

$$Q = 0.59+0.02 \text{ (annual precipitation)} \quad (14)$$

where Q=annual summer low-flow.

Sagehen Creek and Fall River are both heavily forested watersheds and receive a high amount of precipitation. However, Sagehen Creek watershed is steeper and its hydrological boundaries are definite. It had a clear response to precipitation, probably due to the lack of any inter-basin inflow or out flow and high watershed relief. Hydrological boundaries for Fall River were not very clear. There is probably an inter-basin inflow from nearby lakes located in the adjacent watersheds during the dry periods of the year.

Zone 4 (13 watersheds and 13 precipitation stations)

Fall and spring precipitation had a very insignificant correlation with summer low-flows for almost all the watersheds in the zone. Therefore, they were left out of this discussion. Regression analysis showed marginally better correlations between summer low-flows and summer precipitation than between winter precipitation and summer low-flows for Zone 4. Winter precipitation had the lowest correlations with summer low-flows after fall and spring precipitation.

The average r^2 for the correlation between summer low-flows and summer precipitation is 26%, ranging from 4% to 52%, with a standard deviation of 17%. The average p-value was 0.056 and the average standard error of y-estimate was 0.20 csm. Maximum correlation between summer low-flows and summer precipitation is shown by the Coeur d'Alene River near Prichard in northern Idaho and minimum correlation was shown by the Cultus River near La Pine, Oregon.

Northern parts of Idaho received higher summer precipitation, and summer low-flows are significantly dependent upon the summer precipitation. Inclusion of these northern Idaho watersheds in Zone 4 resulted in high correlations for the summer low-flows and summer precipitation for the zone.

Comparatively, remaining watersheds in Zone 4 (which also receive lower summer precipitation compared to winter and annual precipitation) had low to moderate degrees of correlation between summer low-flows and summer precipitation. The average regression equation resulting for the relationship between summer low-flows and summer precipitation was found as:

$$Q = 0.64+0.05\ (\text{summer precipitation}) \quad (15)$$

where Q=annual summer low-flow.

Winter precipitation and summer low-flows showed an average r^2 value of 24%, ranging from 11% to 41%, with a standard deviation of 10%. The average p-value for this analysis was 0.035 and the average standard error of y-estimate was 0.19 csm. Cultus River near La Pine, Oregon, showed the maximum correlation between winter precipitation and summer low-flows while Stehekin River, eastern Washington, had the minimum correlation between summer low-flows and winter precipitation.

The average regression equation resulting for the relationship between summer low-flows and winter precipitation was given as:

$$Q = 0.41+0.02 \text{ (winter precipitation)} \qquad (16)$$

where Q=annual summer low-flow.

Average r^2 value for the regression relationship between the annual precipitation and summer low-flows was 30%, with a range of 10% to 42%, and a standard deviation of 10%. The average p-value was found to be 0.007 and the average standard error for the y-estimate was 0.2 csm. Maximum correlation between summer low-flows and annual precipitation was shown by the South Fork Clearwater River at Stites in central Idaho and the minimum correlation was shown by Deer Creek near La Pine, Oregon.

The resulting average regression relationship between summer low-flows and annual precipitation for Zone 4 was found as:

$$Q = 0.19+0.02 \text{ (annual precipitation)} \qquad (17)$$

where Q=annual summer low-flow.

There was more than one precipitation station around or close to the watersheds in Idaho included in this zone. The degrees of correlation between the individual precipitation records and the summer low-flows for each watershed were highly variable.

The values shown above were first averaged for individual watersheds on the basis of two, three, or four precipitation stations around that watershed. Stations were decided before the analysis. The zonal regression equation was calculated by averaging the equations for the individual watersheds. Some stations showed a very high degree of correlation and others relatively very low. The ones showing the maximum of correlation with the subject watershed were not always the closest to the watershed.

This happening was similar to the one for the Silvies River and the precipitation stations around the watershed (Burns, John Day, Austin and P-Ranch). No precipitation data from a precipitation station closest to the watershed was excluded from the analysis even though it did not result in a very high correlation with the summer low-flows compared to other precipitation stations. No precipitation data was included in the analysis for a particular watershed because of its better correlation with the summer low-flows of that watershed if it was not already assigned to that watershed and was far away.

These significant relationships between a farther precipitation station than a closer one might be real due to the similarity of storm occurrences at both sites (watershed under study and precipitation station area). This could be checked by the study of wind/storm patterns over both sites, etc. This might have also occurred totally by chance. There was not enough data to confirm such assumptions.

Zone 5 (4 watersheds and 4 precipitation stations)

Like all other zones, fall, and spring precipitation had no role in the behavior of summer low-flows for Zone 5. Therefore, they were not discussed. Regression correlation between summer precipitation and summer low-flows was lower when compared to those for winter and annual precipitation for this zone. The average r^2 for the correlation between summer low-flows and summer precipitation was 12%, with a range of 2% to 34%, and a standard deviation of 13%. The average p-value for the analysis was 0.032 and the average standard error of y-estimate was 0.2 csm.

Maximum correlation between summer low-flows and summer precipitation was shown by North Fork Clearwater near Canyon Ranger Station in central Idaho and minimum correlation was shown by Mill Creek in the Blue Mountains (Oregon and Washington).

Winter precipitation and summer low-flows had an average r^2 value for Zone 5 of 27%, with a range of 13% to 48%, and a standard deviation of 15%. The average p-value for this analysis for the Zone 5 was 0.022 and the average standard error of y-estimate was 0.17 csm. American River in the eastern Cascades of Washington showed the maximum correlation between winter precipitation and summer low-flows, while Mill Creek in the Blue Mountains (Oregon and Washington) had the minimum correlation between summer low-flows and winter precipitation.

Annual precipitation showed better correlation with summer low-flows than winter precipitation. Average r^2 value for regression between the annual precipitation and summer low-flows was 32%, ranging from 11% to 55% with a standard deviation of 18%. The average p-value for the relationship was 0.029 and the average standard error of y-estimate was 0.17 csm.

Maximum correlation between summer low-flows and annual precipitation was shown by the American River, Washington, and the minimum correlation was shown by Mill Creek in the Blue Mountains.

The calculated average regression equations using summer, winter, and annual precipitation, respectively, to predict summer low-flows for Zone 5 were found as:

$$Q = 0.72+0.03 \text{ (summer precipitation)} \tag{18}$$

$$Q = 0.40+0.02 \text{ (winter precipitation)} \tag{19}$$

$$Q = 0.30+0.01 \text{ (annual precipitation)} \tag{20}$$

where Q=annual summer low-flow.

All three relationships were insignificant at the 95% confidence level but significant at a lower prediction level

(90%). Use of these relationships alone to predict summer low-flows will be of no use for most practical purposes because of their poor coefficients of determination for the available data.

The behavior of the Oregon Cascades watersheds was found peculiar in the sense that all five watersheds had at least two different shapes of their annual hydrographs. Fall River showed very little variation in its average daily flows and had a flatter annual hydrograph. Also, the recession limb of the annual hydrographs for these watersheds starts much later in the summer season when compared to most of the watersheds in the study area.

Due to the inclusion of such watersheds in any zone, regression average equations became less significant for their practical use. It was expected that with the inclusion of more watersheds in each zone and exclusion of such watersheds whose watershed boundaries were not very definitive, much better correlations between precipitation and summer low-flows could be established for all the zones.

It was found during the development of the regression model equation for the study area that watershed physical parameters had a strong correlation with extreme summer low-flow. Vegetation and precipitation also had a significant relationship with extreme summer low-flow. Precipitation had a better relationship with the extreme summer low-flows compared to percent vegetative cover. This could be attributed to the lack of adequate data for vegetation cover for all the watersheds studied and differences in the sources of that data. Relatively, precipitation data was collected on a more consistent basis for all the watersheds studied than vegetation cover.

Entire area relationships

Annual summer low-flows for the entire study area (averaged for each year) were regressed against the average annual, winter, and summer precipitation (averaged for each year over the entire period) to examine their correlation. Also, summer low-flows and average precipitation were regressed against time (years). Here is the summary of the resulting relationships.

$$Q = 0.16+0.016\ (\text{annual precipitation}) \qquad (21)$$

$$r^2=31\%,\ S_y=0.11\ \text{csm}$$

$$Q = 0.24+0.022\ (\text{winter precipitation}) \qquad (22)$$

$$r^2=38\%,\ S_y=0.10\ \text{csm}$$

$$Q = 0.56+0.025\ (\text{summer precipitation}) \qquad (23)$$

$$r^2=5\%,\ S_y=0.13\ \text{csm}$$

$$Q = -2.59+0.002\ (\text{Time}) \qquad (24)$$

$$r^2=4\%,\ S_y=0.17\ \text{csm}$$

$$\text{Annual precipitation} = 24.2+0.003\ (\text{Time}) \qquad (25)$$

$$r^2=0.01\%,\ S_y=4.6\ \text{csm}$$

The relationship between winter and summer precipitation was found to be very poor (r^2=2%). Annual summer low-flows for the study area were found significantly related to the average annual and winter precipitation at 95% confidence interval. Correlation was better between summer low-flows and winter precipitation than annual precipitation.

Summer precipitation was found not correlated to the summer low-flows. Winter and annual precipitation were found highly correlated with each other. Whereas, summer precipitation was found uncorrelated with annual and winter precipitation. No trends were found no trends in the annual summer low-flows and precipitation over the period of record.

Recession analysis and summer flow forecast

There is a need to know how much water is going to be available for different uses during the summer low-flow (dry) periods in the semi-arid areas of the PNW. This water is mainly derived from ground water and delayed contribution from soil micropores. To determine the availability of this decreasing water during the summer months of a particular year(s), it was necessary to establish a model equation relating receding summer stream flow to some easily measured variable(s).

This was different from the extreme summer low-flow prediction model equation in the sense that its goal was to forecast the summer low-flow for any desired day during the summer by using the known stream flow of an earlier day. Its intended use was different from the drought prediction model.

The extreme summer low-flow prediction equation gives information about the extreme conditions. In some cases, use of a drought prediction model may not be possible, or difficult, due to the non-availability of some key variables, or not desirable by the user. Recession analysis provided us with the regional, as well as zonal, equations to forecast summer low-flows for a desired date in a year.

Due to the vastness of the study area, as well as high variability in the summer low-flows, recession forecast equations for each zone were constructed along with one general equation for the whole study area. Parameters of equations for each precipitation zone are given in Table 5, along with the associated standard errors.

Parameters of equations for each watershed are given in Appendix 3 (Table 12). Using the slope and intercept of the regression line, flow for a desired nth day Q_n day can be calculated as:

$$Q_n = Q_0 C^n + \sum_{i=0}^{n-1} C_0 C^i + C_0 \qquad (26)$$

where, Q_o is the observed flow on day zero of the forecasted period (starting day of the model), C is the slope of the regression line, C_o is the regression slope intercept, and n is the number of days after day zero (for the detailed description of the equation refer to page 56).

Generally, standard error of Y-estimate decreased with the later start of the recession forecast model (decrease of number of days to predict flow). Values of r^2 were given in the table for the sake of comparison of the significance of different model equations built by starting with a different date. As mentioned earlier in the methodology section, the recession forecast equations were developed by forcing regression intercept through zero. This was done to control the variability of summer low-flows within each zone in order to develop recession forecast models with better predictability.

No pattern was apparent in the level of expected accuracy and the starting date. All the starting dates had high r^2 values with little difference among them. These r^2 values should not be confused with the ones from the test results which were conducted to verify the applicability of these model equations. When actual and predicted recession flows for a test stream were regressed against each other it was only then that comparative significance of each equation was drawn.

One stream from each zone was selected randomly for test purposes. There were not enough streams to sacrifice

Table 5: Parameters of recession forecast model equations for each zone. B0=regression intercept, B1=regression slope, r^2=Coefficient of determination, Sy= Standard error of y-estimate, Sx= standard error of coefficient. Flow for day n will be $Q_n=Q_0B1^n$, Q_0 is the flow on the starting day of the forecast period.

Zone 1	B0	B1	r^2	Sy	Sx
jun1	0	0.974	0.995	0.015	0.003
jun15	0	0.970	0.994	0.013	0.003
jun20	0	0.971	0.992	0.011	0.003
jun25	0	0.971	0.987	0.010	0.004
Zone 2	**B0**	**B1**	r^2	**Sy**	**Sx**
Jun1	0	0.979	0.999	0.070	0.002
jun15	0	0.971	0.999	0.048	0.002
jun20	0	0.968	0.999	0.038	0.002
jun25	0	0.965	0.999	0.033	0.002
Zone 3	**B0**	**B1**	r^2	**Sy**	**Sx**
jun1	0	0.985	0.997	0.063	0.002
jun15	0	0.979	0.998	0.038	0.002
jun20	0	0.977	0.997	0.028	0.002
jun25	0	0.978	0.996	0.025	0.002
Zone 4	**B0**	**B1**	r^2	**Sy**	**Sx**
jun1	0	0.976	0.999	0.055	0.002
jun15	0	0.967	0.999	0.038	0.002
jun20	0	0.965	0.998	0.033	0.082
jun25	0	0.965	0.998	0.031	0.002
Zone 5	**B0**	**B1**	r^2	**Sy**	**Sx**
Jun1	0	0.992	0.990	0.058	0.003
jun15	0	0.981	0.996	0.034	0.002
jun20	0	0.980	0.994	0.027	0.002
jun25	0	0.981	0.991	0.025	0.002

more than one stream in each zone for testing purposes. Testing was merely done to get some idea of the level of prediction accuracies of these equations. The prediction accuracies are found to be maximum for a particular starting date for each watershed (Zeb, 1992).

Four starting dates of June 1, June 15, June 20 and June 25 were selected to cover the range of the best predictive dates for all zones in the study area (determined for each zone during the preliminary analysis of the data) and still be consistent for all the regions. Results of regression runs on test streams in each zone showed very high predictive abilities (high r^2 values) for all four selected dates.

For Zone 1, equation J15 (using June 15 as a starting date) showed the maximum correlation (r^2= 98.3%) between the forecasted and the actual recession summer flows, with least standard error of y-estimate (0.007 csm) (Table 6). Correlation between the actual and the predicted recession flows using equation J25 (June 25th as the starting date) was found minimum (r^2= 96.1%), whereas, equation J1 (using June 1 as the starting date) had the maximum standard error of y-estimate.

There was little difference in the degree of explanation by using either equation during very low summer flows. Using the equation J1, recession flows for a longer period of summer can be forecasted with a little sacrifice of the accuracy.

Zone 1 was comprised of watersheds in the true arid or lower bound of semi-arid environment where annual precipitation is less than 10 inches. Summer precipitation was not a major contributor towards the annual precipitation

Table 6: Results of the level of accuracies using recession forecast models for each zone against test streams. r^2= coefficient of determination, Sy=standard error of y-estimate, Sx=standard error of coefficient.

Zone 1	r^2	**Sy**	**Sx** (Tested on Leonard Creek)
Jun1	0.973	0.011	0.014
Jun15	0.983	0.007	0.014
Jun20	0.975	0.008	0.018
Jun25	0.961	0.009	0.025
Zone 2	r^2	**Sy**	**Sx**
Jun1	0.909	0.610	0.017
Jun15	0.974	0.390	0.013
Jun20	0.982	0.326	0.012
Jun25	0.980	0.314	0.013
Zone 3	r^2	**Sy**	**Sx**
Jun1	0.876	0.324	0.029
Jun15	0.874	0.228	0.036
Jun20	0.876	0.188	0.039
Jun25	0.853	0.165	0.045
Zone 4	r^2	**Sy**	**Sx**
Jun1	0.934	0.235	0.025
Jun15	0.971	0.094	0.020
Jun20	0.976	0.069	0.019
Jun25	0.971	0.063	0.022
Zone 5	r^2	**Sy**	**Sx**
Jun1	0.834	0.611	0.022
Jun15	0.868	0.594	0.035
Jun20	0.863	0.537	0.041
Jun25	0.849	0.433	0.044
Zone 2	r^2	**Sy**	**Sx** (Tested on bridge creek)
Jun1	0.651	0.086	0.147
Jun15	0.446	0.087	0.498
Jun20	0.263	0.097	0.868
Jun25	0.043	0.103	1.502

in this zone. Snowmelt contribution to summer low-flows, if any, did not last long into the summer, and the recession of annual hydrographs started early. This resulted in a best forecast equation with a starting date early in the summer.

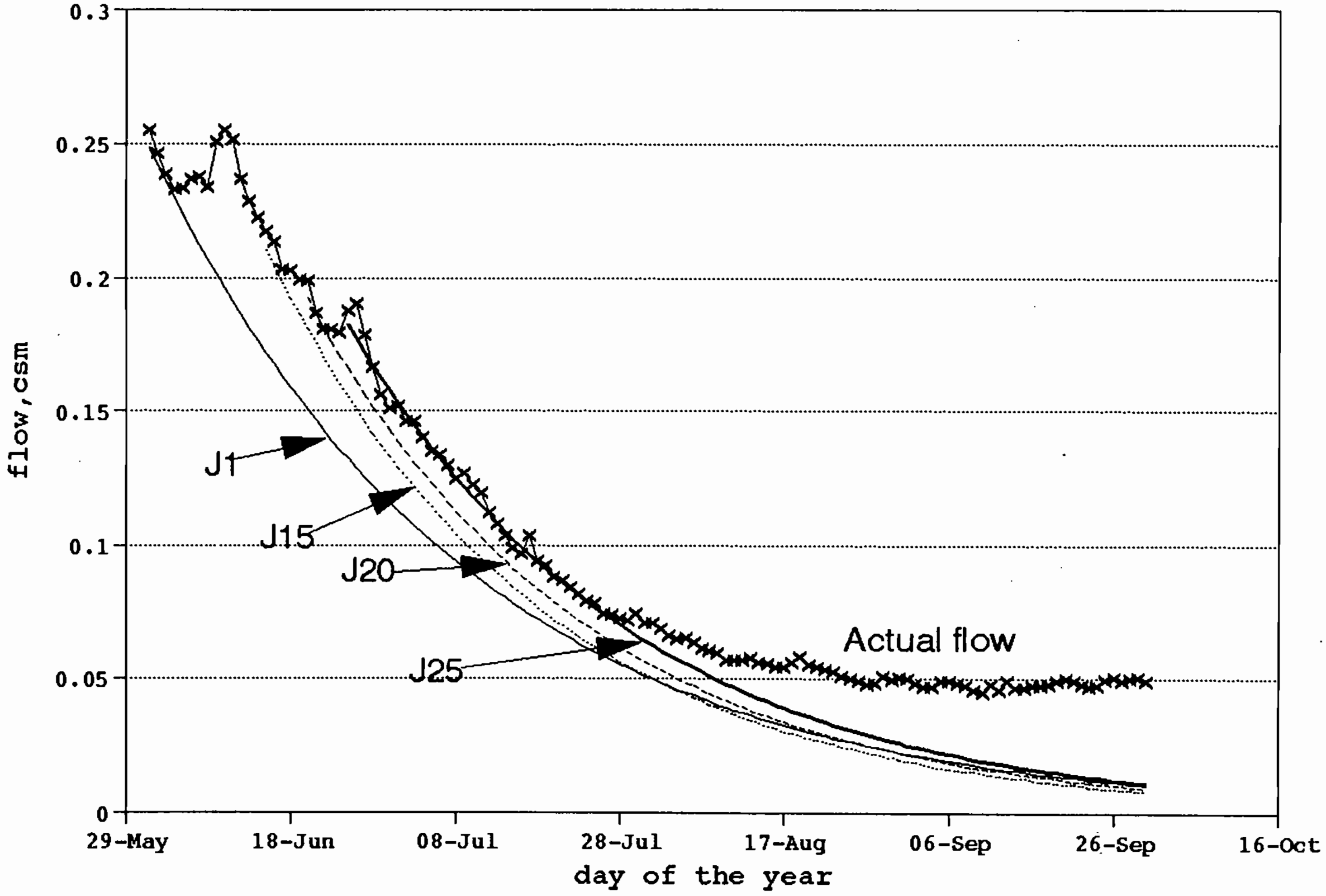
It was considered better for the purpose of its practical application in these areas.

These recession equations were built with no apparent input of summer precipitation. If all the watersheds used to build a zonal model equation had experienced noises of summer precipitation in their recession limbs then forecasted flows will be more accurate for a watershed which experiences similar summer precipitation input. This could be an indirect effect of summer precipitation inputs on recession model equations. However, if the model equations did not incorporate that behavior in them, forecasted flows will be highly inaccurate.

Actual and forecasted flows for Leonard Creek were also plotted (Figure 15). There were several summer precipitation inputs in the actual recession limb of the hydrograph for the Leonard Creek. The forecasted flows were always lower than the actual flows for all equations. Any planning made on the basis of availability of summer low-flows by using these equations will be on the safer side.

For Zone 2, the maximum correlation between forecasted and actual summer flows was shown by using the model equation J20 (using June 20th as the starting date) with r^2 value of 98.2% and a standard error of y-estimate as 0.326 csm. Minimum prediction accuracy was shown by the model equation J1 with r^2 value of 90.9% and a standard error of y-estimate of 0.61 csm.

Figure 15:Actual and forecasted flows
Zone 1, Leonard Creek as Test watershed



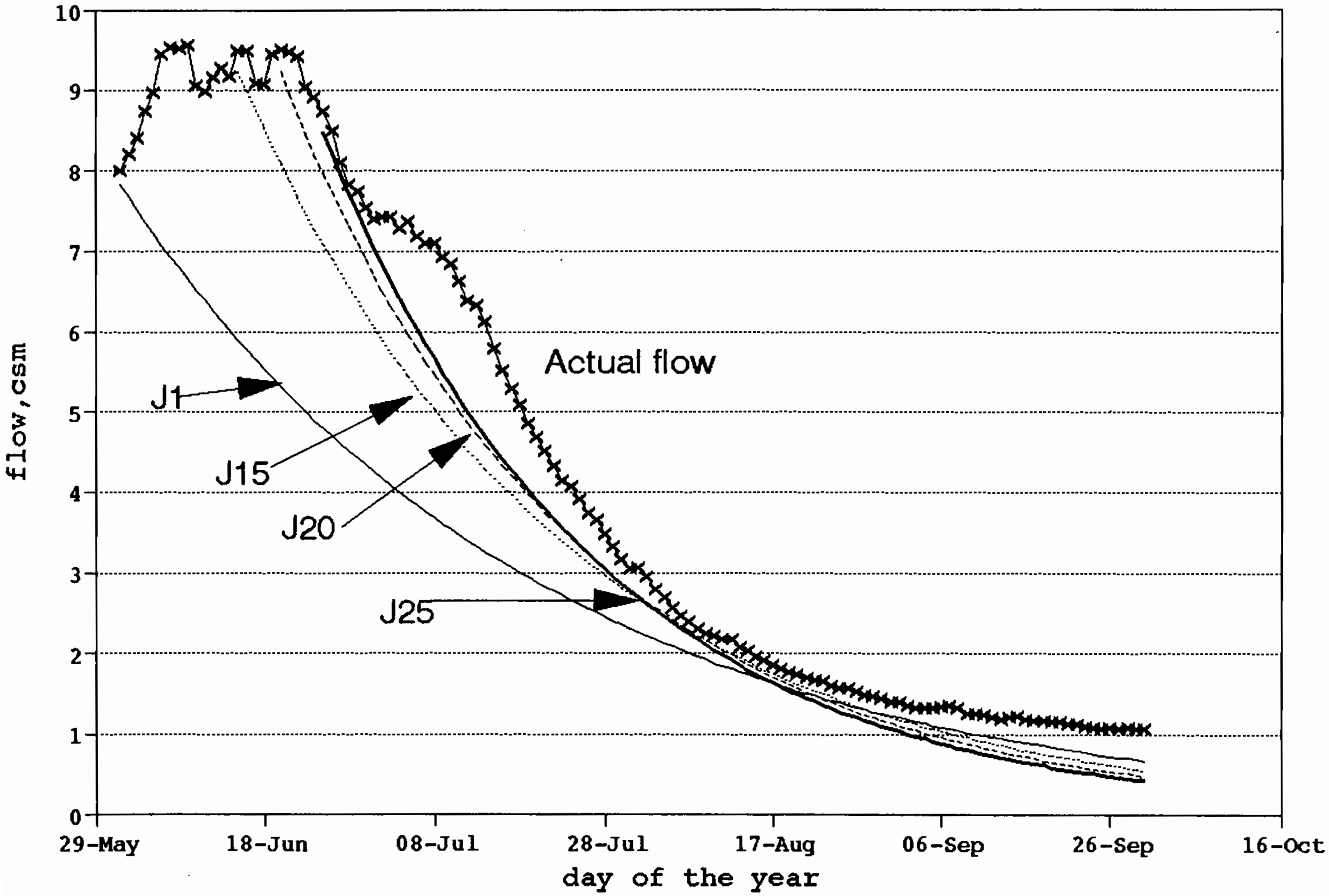
Model equation J25 did not help improve the prediction efficiency. Equations J15, J20, and J25 for Zone 2 did not have much difference in their forecasting abilities. Either of them can be used to forecast flow for the remainder of the water year depending upon the ease or priority of the user.

When actual and forecasted flows were plotted (Figure 16), forecasted flows using equation J1 showed a better fit to the actual flows for the later part of the recession period. It showed lower accuracy in predictions for the entire period of forecast due to the fact that actual flows were augmented during the first and second week of June by summer precipitation inputs.

Using the model Equation J1 for Zone 2 resulted in the poorest correlation between the actual and the forecasted recession summer flows. It was thought that the later snowmelt contribution delayed the peak of the annual hydrograph and start of the recession of flow, thereby resulting in the late settling of the recession limb to a pattern that could be forecasted better by the recession forecast equations. Forecasted flows for the test creek, using model equations for Zone 2 were all lower than actual flows and thereby safer for any planning limited by the availability of the water.

Bridge Creek, among the watersheds included in Zone 2, had distinctive behavior in terms of the shape of its annual

Figure 16: Actual and forecasted flows
Zone 2, Hurrican Cr. as test watershed



hydrograph and recession limb. It had minimum variation in its average daily flows during a year. It is located adjacent to Donner Und Blitzen River in the Steens Mountains, which is a 6-7 times larger watershed than Bridge Creek. However, Bridge Creek had higher summer low-flow (csm) than Donner Und Blitzen River.

It was concluded that Bridge Creek's summer flow is augmented by spring contribution from within the watershed. Otherwise, both watershed have the same geology, similar slopes, aspects, and vegetation. It is a steep watershed and chances of interbasin flow from neighboring watersheds were considered unlikely. This watershed was kept in the prediction model for the sake of reasonable variability in the nature of the streams.

The zonal recession forecast equations are suitable for normal behaving watersheds for their practical application. This was confirmed when Bridge Creek was taken out of the model building watersheds set and used as a test watershed. Although it did not change the prediction equation for Zone 2 drastically, the average forecasting accuracies for the model equations were dropped to very low r^2 values (35.1% compared to 96.1%).

Accuracies of forecasting were lower for the later starting dates. It can be concluded that these model equations to forecast recession flows are applicable only to those watersheds whose response in stream flow is normal

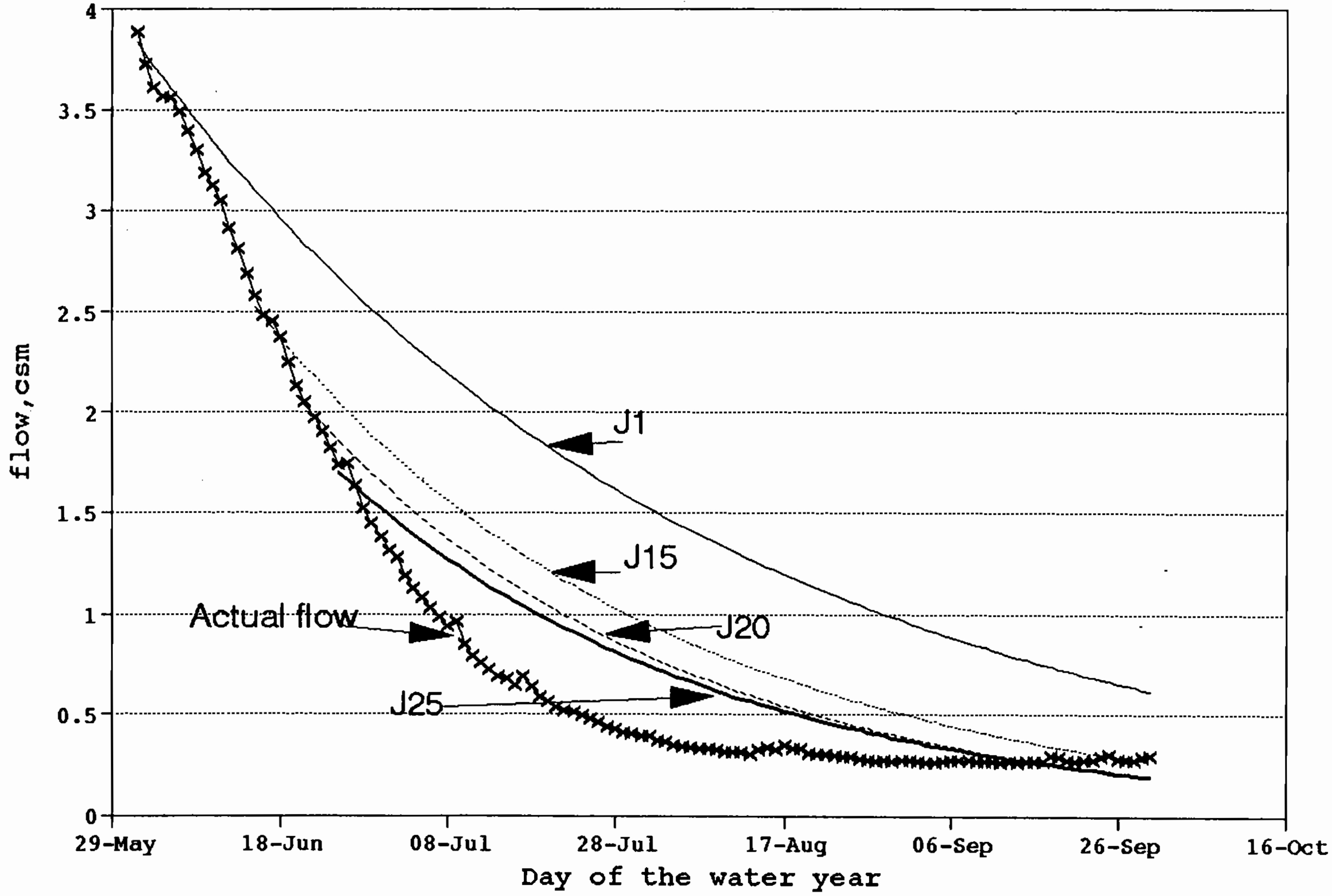
(normal means the behavior shown by the majority of the watersheds with considerable variation in their daily flows over a year and with marked rising and falling limbs of hydrographs), because most of the watersheds used to build the model equations were normal.

Zonal forecast equations should not be used when forecasting recession flow for a watershed whose behavior is different than normal watershed. This creates a limitation with the zonal equations. For such watersheds, individual forecast equations are far better in prediction accuracies (Zeb, 1992).

Zone 3 had lower accuracies in predicting recession flows for the test stream (using all four model equations) compared to those for the first two zones. Model equation J1 showed the best correlation among the four equations, while, equation J25 resulted in the minimum prediction accuracy. The difference in the degrees of correlation using one model equation or the other was not much, and either model equation could be used with comparable accuracy.

However, the plot of actual versus forecasted flows for the test stream revealed a clearer picture (Figure 17). Comparison of prediction accuracies of forecasted flows should be done carefully considering both the r^2 values and their degree of fit with the actual flows for different parts of it. From the graphical fit, it was shown that

Figure 17: Actual and forecasted flows
Zone 3, Sagehen Creek as test watershed



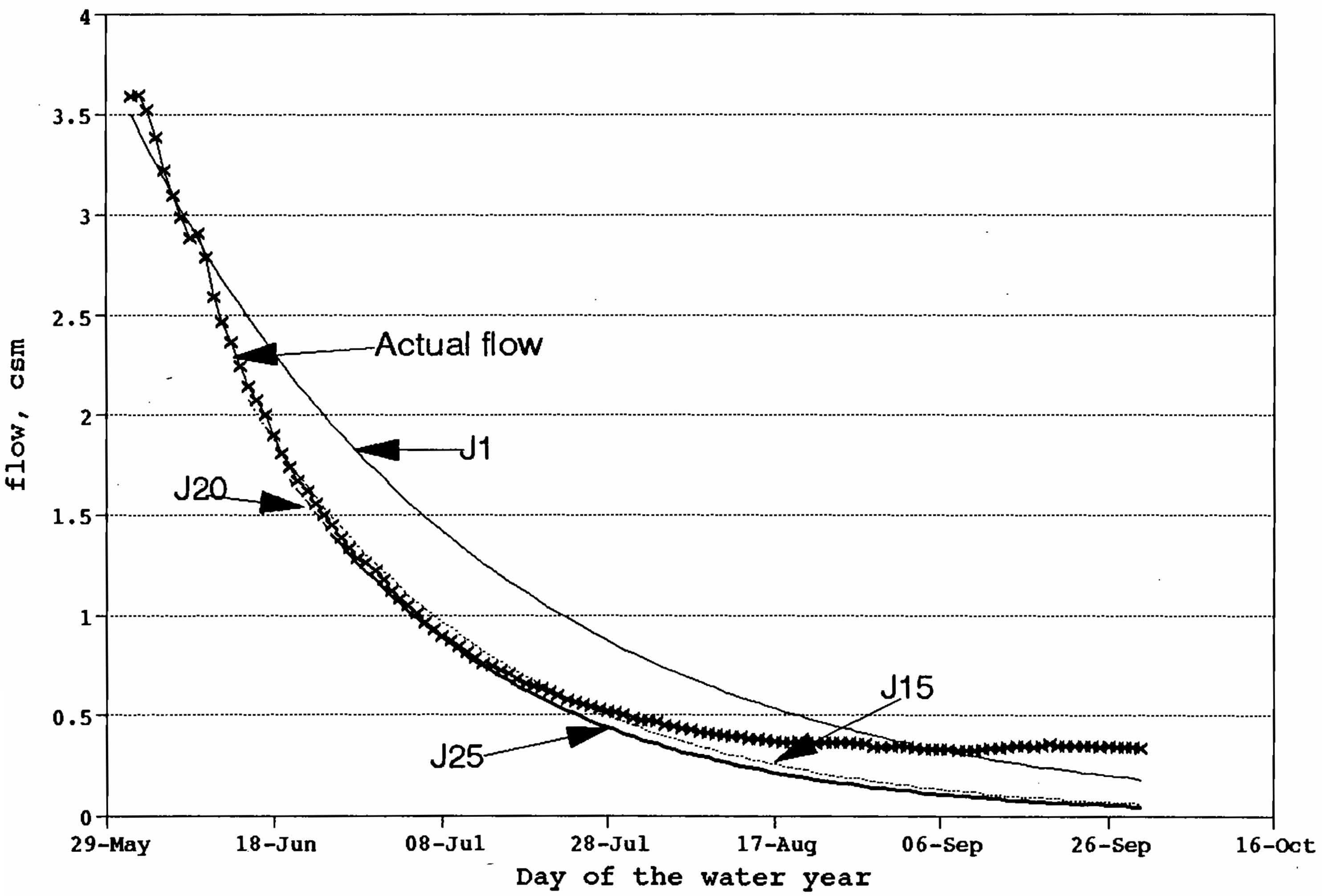
higher level accuracies were achieved through forecasted flows using model equation J25.

All the equations predicted higher flows for most of the recession period. Recession limb was steeper than forecasted flows for the initial period of recession for the Sagehen Creek. Less accurate predictions for Zone 3 can be attributed to the smaller number of streams available for the calculation of zonal model equations.

Recession flows can be predicted with higher accuracies by using model equations J15, J20, and J25 for Zone 4, compared to model equation J1. Model equation J20 showed marginally better efficiency in explaining the recession flows (r^2=97.6%) compared to the other two equations. However, if the user's main interest is only in the prediction of stream flows for the last month and a half of the water year, it is better to use the model equation J1, which seemed better in predicting the first and last part of the recession flows (Figure 18) when compared to all other equations. Better prediction abilities of all the equations for Zone 4 can be partly attributed to the larger number of streams available to construct the model equations.

Zone 5 (with precipitation 40 inches or more) had the minimum prediction accuracies for all of its model equations when compared to the other zones. It had the minimum number of streams, three, in the Zone compared to six, six, four, and twelve for zones 1, 2, 3, and 4, respectively. Still,

Figure 18: Actual and forecasted flows
Zone 4, Coeur d'Alene River, ID



(the extent of relationship between the forecasted and actual flow was quite good. The maximum relationship was shown by the prediction model equation J15 with rof 86.8% and minimum by the model equation J1 with $r^2$of 83.4%.

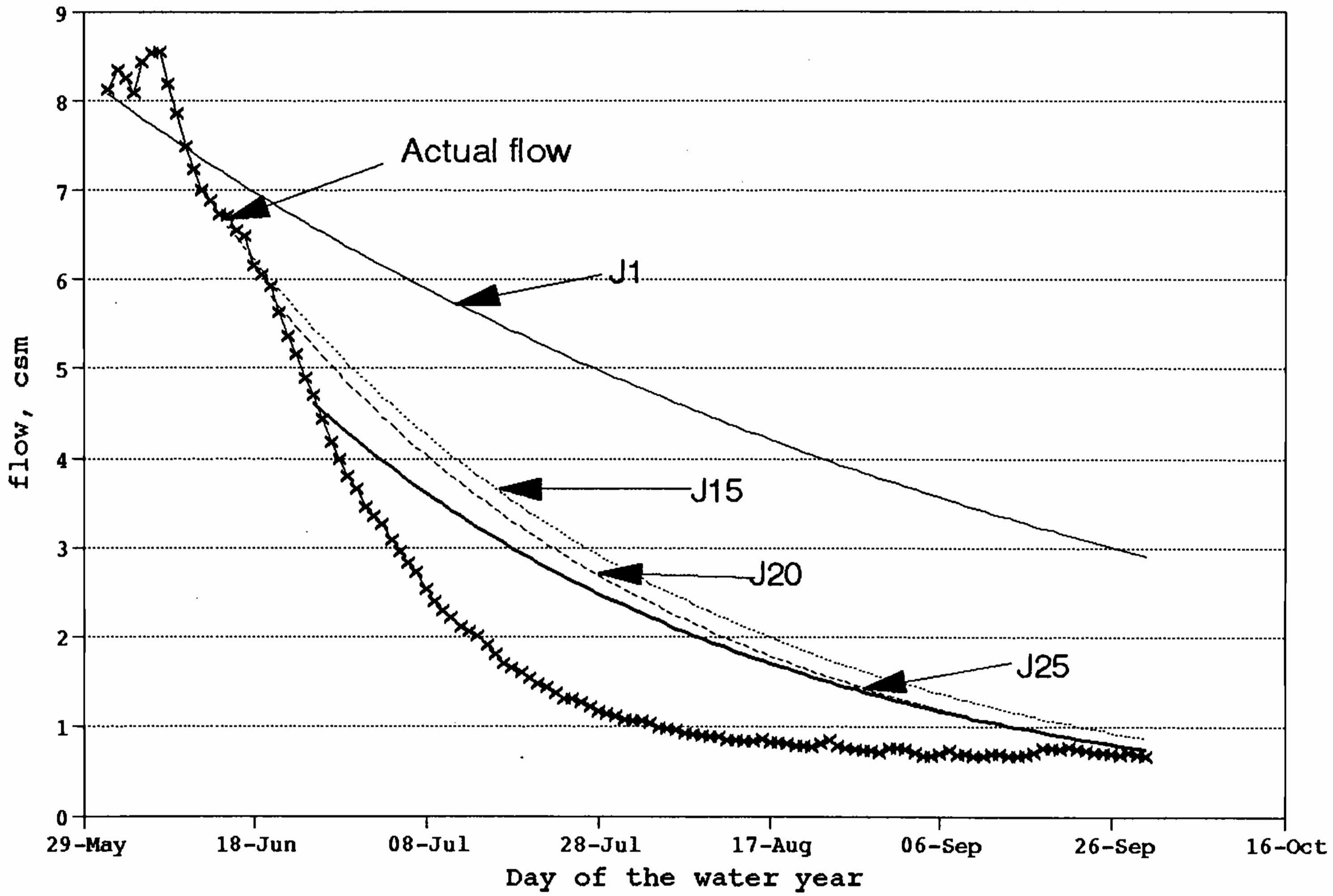
Graphical plotting of forecasted and actual recession flows for the test stream for Zone 5, North Fork Clearwater River at Cataldo, Idaho, revealed that all the prediction equations forecasted higher recession flows compared to the actual flow (Figure 19). Model equation J25, with minimum standard error of estimate (0.433 csm), showed the best fit between forecasted and actual flows for Zone 5.

The prediction accuracies of different equations were expected to be affected by the nature of the test stream's behavior. The level of confidence in the results was impeded by the fact that there was only one test stream in each zone on which to test the model equations. However, the main priority was to develop the best possible forecast model equations from the available data.

It could be expected that a different test watershed in any zone would have shown higher accuracies for a different equation than shown by these test streams. Therefore, it is suggested that a user should use prior knowledge of the watershed location and its general behavior, if possible, for the best suited equation to be used.

Four recession forecast model equations J1, J15, J20, and J25 were developed for the whole study area for four

Figure 19: Actual and forecasted flows
Zone 5, NF Clearwater as test watershed



starting dates of June 1st, June 15th, June 20th, and June 25th, respectively (Table 7). This was done by averaging the equations from all individual streams into a single equation for the entire semi-arid area for each respective date. All the regional model equations showed significant ability to forecast recession flows.

Table 7: Parameters of regional recession forecast model equations for the study area. B0=regression intercept, B1=Regression slope, r^2=coefficient of determination, Sy=standard error of y-estimate (csm), Sx=standard error of coefficient (csm).

	B0	**B1**	**r^2**	**Sy**	**Sx**
June1	0	0.981	0.995	0.048	0.002
Jun15	0	0.974	0.993	0.031	0.002
Jun20	0	0.973	0.989	0.025	0.018
Jun25	0	0.973	0.986	0.023	0.002

All four model equations were tested against five streams, one stream from each zone. Generally, the resulting prediction efficiencies were very high. Most of the r^2 values are above 90%. Values are given in Table 8.

Maximum correlation between forecasted and actual recession summer flows was shown by Hurricane Creek for the model equation J3 (r^2=98.3%). Minimum extent of explanation of variation in the summer low-flows was shown by Sagehen Creek near Truckee River, California, for the model equation J4 (r^2=88.8%).

Table 8: Results of test runs of four regional recession equations on various streams. r^2=coefficient of determination, Sy=standard error of y-estimate (csm), Sx=standard error of coefficient (csm).

Date	**r^2**	**Sy**	**Sx**
Tested on Leonard creek near Denio, Nevada			
June1	0.964	0.012	0.016
Jun15	0.972	0.009	0.018
Jun20	0.968	0.009	0.021
Jun25	0.954	0.010	0.028
Tested on Hurricane Creek, Oregon			
June1	0.915	0.580	0.017
Jun15	0.975	0.386	0.013
Jun20	0.983	0.320	0.012
Jun25	0.980	0.317	0.014
Tested on Sagehen Creek near Truckee River, California			
June1	0.909	0.293	0.026
Jun15	0.911	0.196	0.031
Jun20	0.906	0.166	0.034
Jun25	0.888	0.148	0.040
Tested on Coeur d'Alene River near Cataldo, Idaho			
June1	0.894	0.292	0.030
Jun15	0.937	0.137	0.029
Jun20	0.944	0.105	0.028
Jun25	0.937	0.092	0.032
Tested on North Fork Clearwater River, Idaho			
June1	0.926	0.551	0.020
Jun15	0.920	0.485	0.029
Jun20	0.915	0.442	0.033
Jun25	0.909	0.359	0.037

Forecasted and actual recession flows for all test streams were plotted against time. Graphical plotting showed that the degrees of fit between the forecasted and actual recession flows were either as good as the zonal forecasted flows or better.

Regional equations (for the entire study area) showed higher accuracies in forecasting summer recession flows than zonal model equations for Zone 3 and Zone 5. Forecasting with regional model equation J1 for Leonard Creek was considered better than other equations for the stream and it was a significant improvement over the zonal forecasted recession flows (Figure 20).

Forecasted recession flows for Hurricane Creek using regional model equations were as good as the forecasted flows using zonal equations and even had closer fit to the actual flows for the later part of the recession curve (Figure 21). Forecasting for the Sagehen Creek was comparatively better using regional equations than zonal equations for Zone 3 (Figure 22).

Regional forecasted recession flows for the Coeur d'Alene River at Cataldo were comparable in their accuracies with the forecasted flows using zonal equations for Zone 4 (Figure 23). Zone 4 had the highest number of streams among all zones. Zone 5 had the lowest number of streams for the construction of zonal equations. Regional model equations for the North Fork Clearwater River resulted in highly significant improvement in the forecasted recession flows over the Zone 5 forecast equations (Figure 24).

Comparisons of graphical fit between forecasted and actual flows for both regional and zonal equations suggested that regional models could easily be used for any stream in

Figure 20: Actual and forecasted flows
for study area, Leonard Creek, Nevada

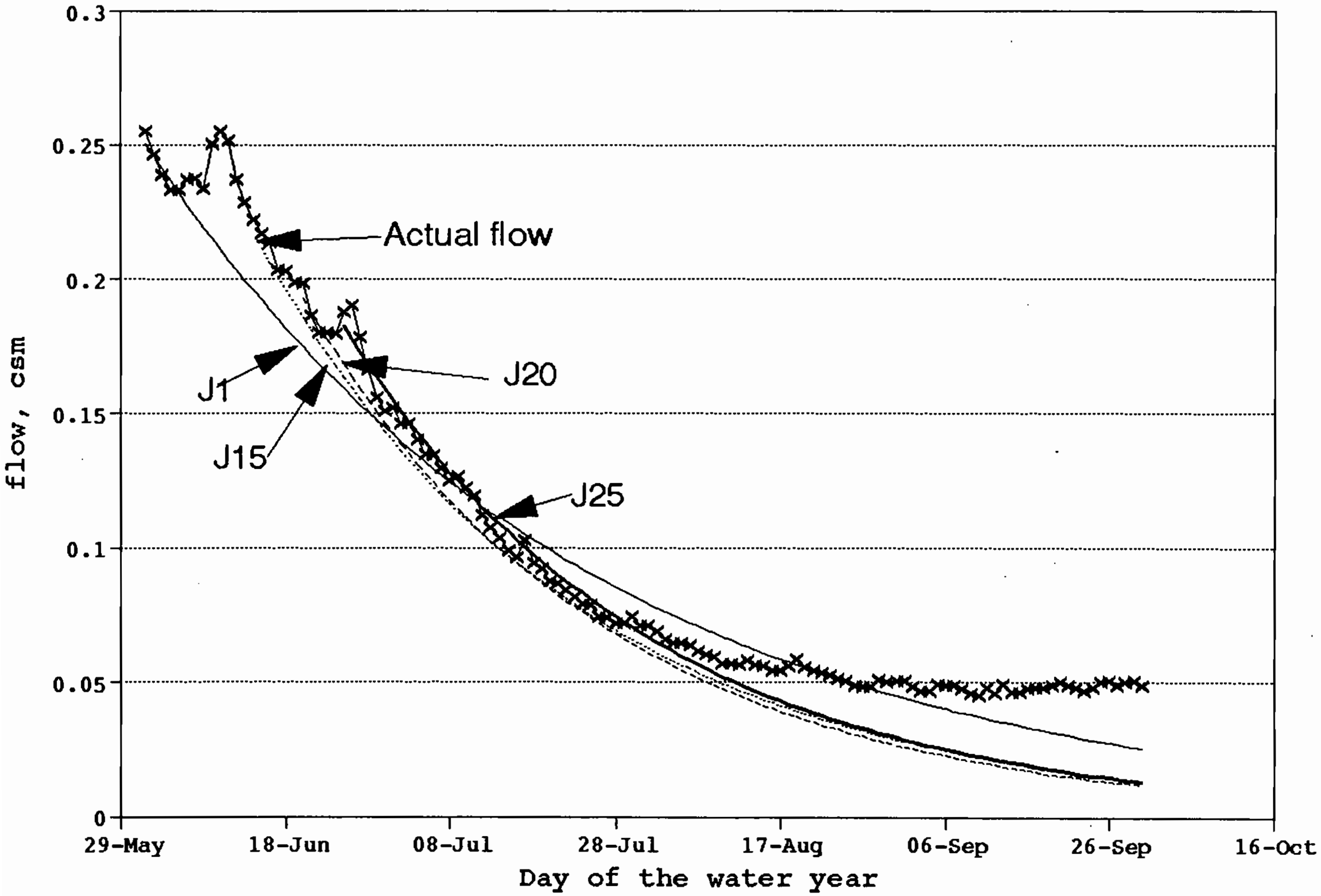


Figure 21: Actual and forecasted flows
for study area, Hurricane Creek, Oregon

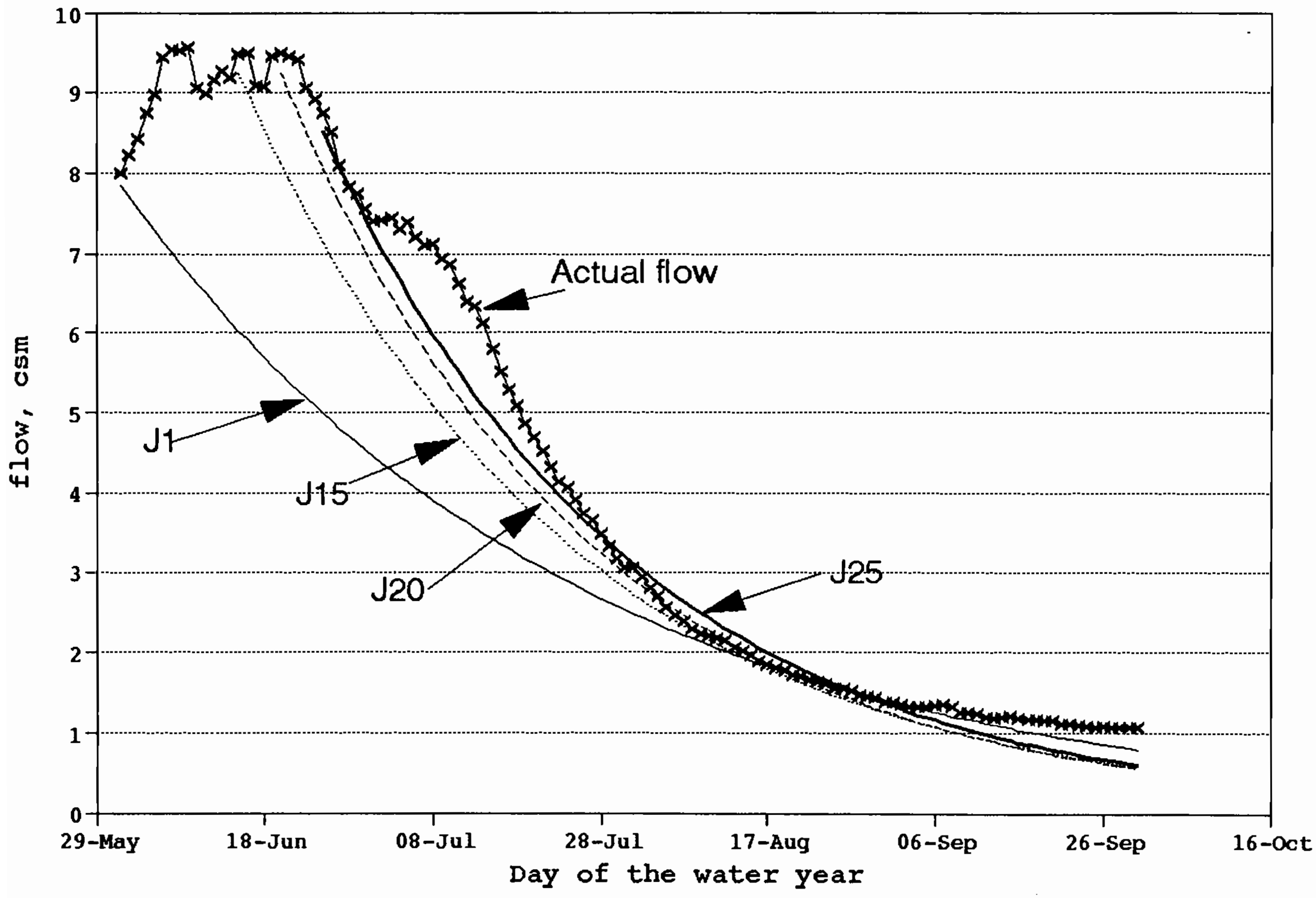


Figure 22: Actual and forecasted flows
for study area, Sagehen Creek, Calif.

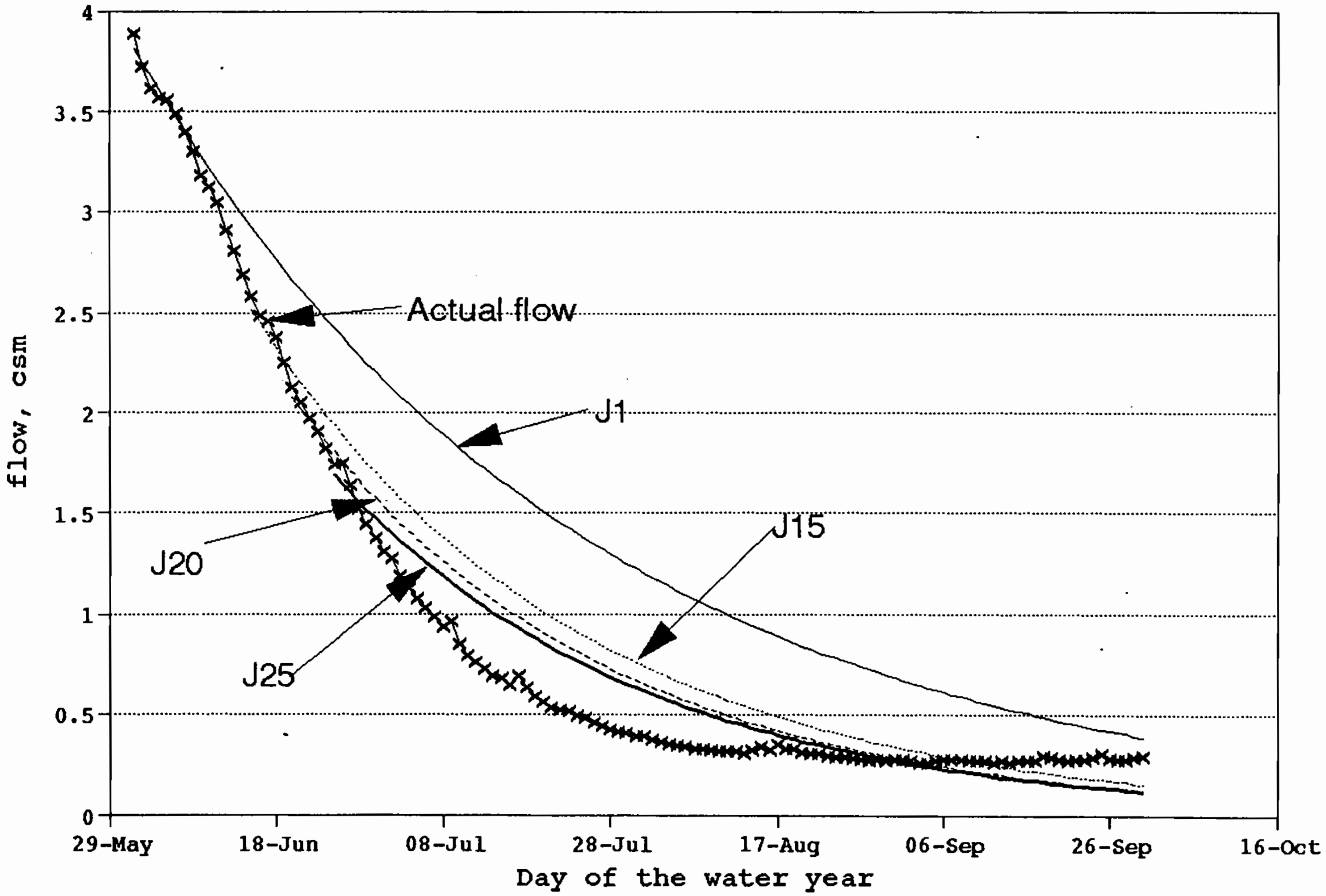


Figure 23: Actual and forecasted flows for study area, Coeur d'Alene River, ID

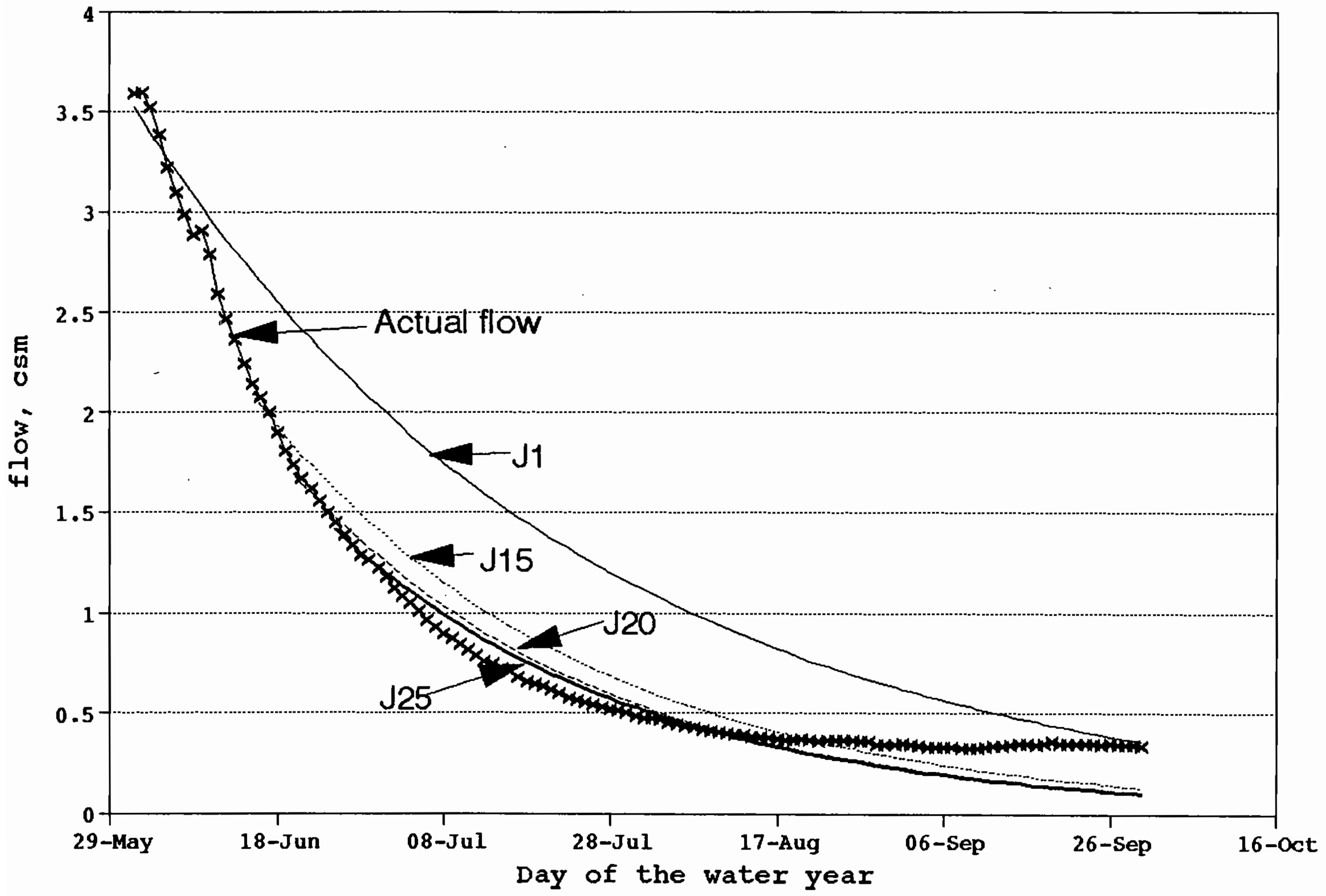
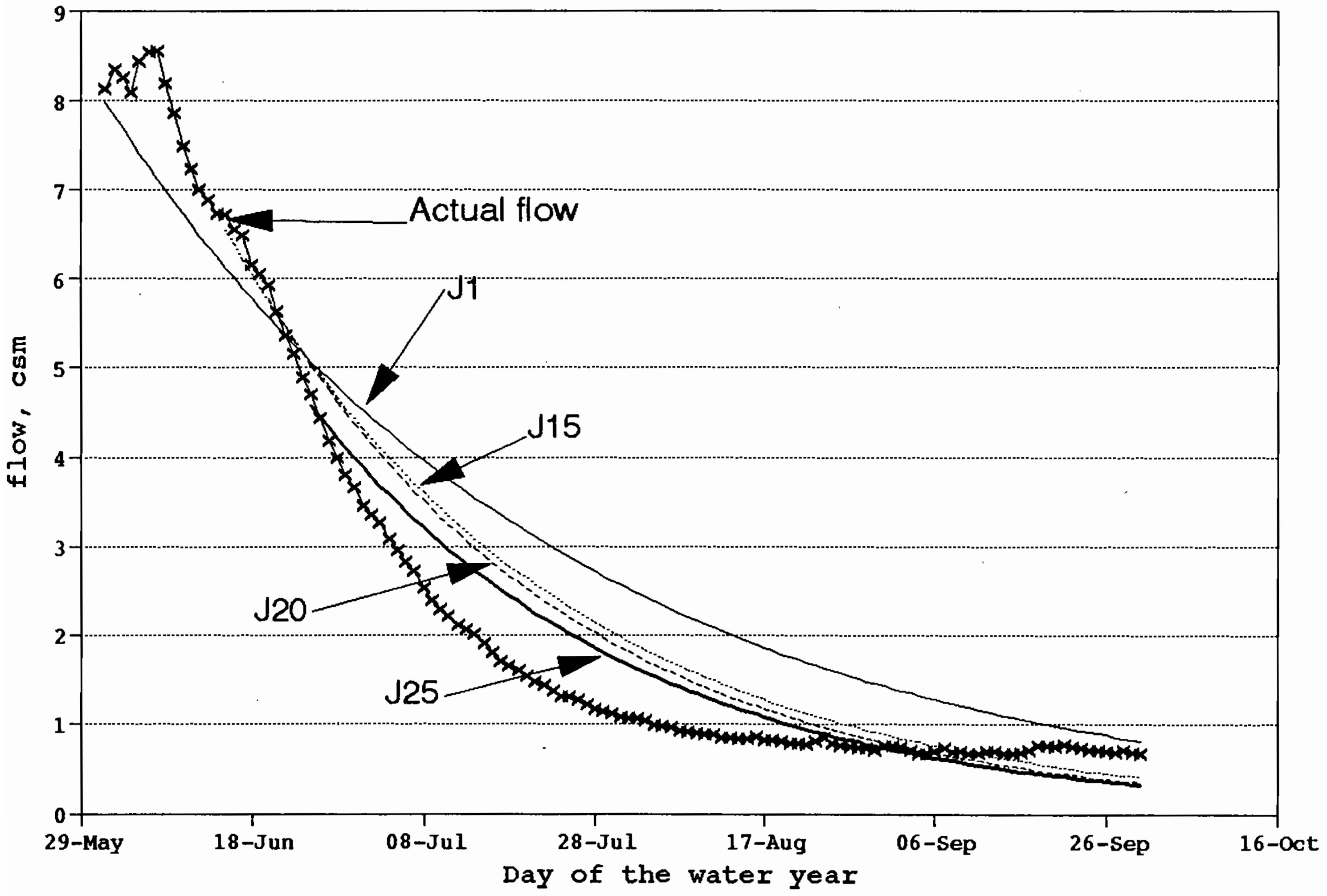


Figure 24: Actual and forecasted flows
for study area, NF Clearwater River, ID



the study area without sacrificing any prediction ability over zonal models. In some cases, especially, where a smaller number of streams were used in the building of zonal equations, regional model equations resulted in higher accuracies in forecasting of recession flows. A smaller number of streams in a zone resulted in weak model equations.

Among the regional model equations, J1 was considered better for the arid and lower bound of semi-arid areas where summer flow starts receding earlier in the summer. Where recession of stream flows starts later in the summer, other equations were considered better for more accurate forecasting of summer recession flows.

Development of extreme summer low-flow prediction model

Correlation between watershed cover types and extreme summer low-flow

When the extreme summer low-flows for each watershed were plotted graphically it was shown that the range of low-flow was from close to zero to about 4 csm. Most of the streams showed extreme low summer low-flow between 0.5 csm and 1.5 csm. Cultus River above Cultus Creek near La Pine, Oregon, experienced the maximum summer low-flow of about 4 csm followed by Fall River near La Pine, Oregon (both are in the eastern Cascades Oregon). Summer lowest low-flows for

Big Jack Creek, Idaho, Silvies River, Oregon, Cultus and Deer Creeks near La Pine, Oregon, were very low (zero or close to zero).

Vegetation information for most of the Oregon watersheds was obtained for two periods, the early 1970's and the period around 1990. Information was different for both periods in their source agency, techniques used, and classification of information. In general, information on watershed cover was available in the following sub-classes:

area under urban habitation
herbaceous rangelands
pasture lands
barren and clearcut areas
open water areas
wetlands
tundra and alpine forests
shrub and brush rangelands
mixed rangelands
deciduous forests
mixed vegetation and evergreen forests.

During 1990, data was obtained for all fourteen watersheds located in Oregon. However, watershed cover information was procured for twelve watersheds from the aerial photographs taken in the early 1970's. Because different agencies performed the aerial surveys in both instances, differences in the technology, the aerial survey information from 1973 and 1990 were analyzed separately to see their correlation with extreme summer low-flows.

Regression analysis between these sub-classes of watershed cover and extreme summer low-flows for both data sets was carried out. Results indicated that none of these individual watershed covers had any significant correlation with the extreme summer low-flows. Shrub and brush rangelands and mixed vegetation for the data set of 1990 had better correlation with the summer low-flows, though statistically nonsignificant. For the data set of 1973, different sub classes of rangelands, area under urban habitation and deciduous vegetation were found better related to summer low-flows. The resulting r^2 values are shown in Table 9.

Table 9: Results of regression between sub-classes of watershed cover and summer low-flows. r^2= coefficient of determination

Area under	1990	1973
	r^2	r^2
Urban habitation	NA	11
Pasturelands	6.8	9.6
Barren/clearcuts	2	5.2
Herbaceous rangelands	7.2	11
Shrubs and brush rangelands	11.4	10
Mixed rangelands	5.3	16
Open water	3.6	2.3
Wetlands	7	9.6
Snowfield	NA	0.6
Tundra and alpine forests	~0	0.2
Deciduous forests	6.3	10
Mixed vegetation	10.4	NA
Evergreen forests	7.1	8.8

As the individual sub classes did not show any significant relationship with summer low-flows, the data sets were regrouped into five broader classes (Appendix 4, Table 13). It was expected to find more meaningful information about the correlation between the extreme summer low-flows and watershed cover types. The five groups were;

Group 1. Evergreen forests: This group was comprised of the area under conifer forests (G1).

Group 2. This group included the areas under tundra, alpine forest, deciduous and mixed vegetation (G2).

Group 3. Areas under water, wet lands and snowfields (G3).

Group 4. Rangelands: It was comprised of the area under shrubs, brush and mixed rangelands (G4).

Group 5. Area under clearcut, barren lands, pasture lands, and urban habitation (G5).

Here are the results of regression analysis between each group from both data sets and extreme summer low-flows.

1990

Group 1 $Y=0.763-0.001(G1)$ (26)
$r^2=8\%$, $Sy=0.73$, $p=0.331$

Group 2 $Y=0.760-0.043(G2)$ (27)
$r^2=5\%$, $Sy=0.75$, $p=0.464$

Group 3 $Y=0.730-0.018(G3)$ (28)
$r^2=8\%$, $Sy=0.73$, $p=0.325$

Group 4 $Y=0.772-0.006(G4)$ (29)
$r^2=12\%, Sy=0.72, p=0.227$

Group 5 $Y=0.733-0.026(G5)$ (30)
$r^2=4\%, Sy=0.75, p=0.485$

1973

Group 1 $Y=0.676-0.001(G1)$ (31)
$r^2=8\%, Sy=0.003, p=0.35$

Group 2 $Y=0.664-0.029(G2)$ (32)
$r^2=7\%, Sy=0.61, p=0.422$

Group 3 $Y=0.671-0.038(G3)$ (33)
$r^2=12\%, Sy=0.59, p=0.272$

Group 4 $Y=0.727-0.004(G4)$ (34)
$r^2=20\%, Sy=0.56, p=0.146$

Group 5 $Y=0.643-0.048(G5)$ (35)
$r^2=8\%, Sy=0.60, p=0.383$

where,

Y=extreme summer low-flow in cubic feet per second per square mile (csm), r^2=coefficient of determination, Sy=standard error of y-estimate, p=p-value for the regression analysis.

The regression correlations between different watershed covers and extreme summer low-flows in cubic feet per second (cfs) were even poorer than the relationships shown above.

For the watersheds of Oregon and Washington (a total of 19 watersheds), percent forest cover information was calculated. For Oregon watersheds, data from the aerial survey of 1990 was used. Data for the watersheds in eastern Washington was obtained through the stream flow statistics and drainage-basin characteristics for the southwestern and eastern regions, Washington (William and Pearson, 1985). The regression analysis between the percent forest cover and extreme summer low-flows gave the following relationship.

$$Q = 0.0345+0.007\ (\%\text{forest cover}) \qquad (36)$$

where Q=extreme summer low-flow, r^2= 14%, Sy=0.62, p=0.099

The results of all these analyses suggested that there was no significant relationship between different watershed covers and the extreme summer low-flows. The correlations between watershed cover and the extreme summer low-flows were negative, although, statistically non-significant. However, the number of observations in these analyses were small. Therefore, it could not be concluded with higher confidence that these results showed a real pattern of the relationships.

When the number of watersheds was increased from 14 to 19 for the percent forest cover analysis, the r^2 value was significantly improved, which was significant statistically at the 90% confidence interval and relationship was shown positive. Similarly, correlation between the area of a watershed and extreme summer low-flows was insignificant when the analysis was performed for the watersheds in Oregon only. Correlations were shown to be better for the extreme summer low-flows per square mile (csm) than for the actual extreme summer low-flows (cfs).

In the later analysis, area was found very significantly related to the extreme summer low-flows (in cfs) when the analysis was performed for the entire study area (35 watersheds). Correlations were found insignificant between area, as well as other variables used, and the extreme summer low-flows per square mile (csm) for the larger data set. This emphasized further that results based upon a smaller number of observations, even in the hydrological studies where larger sets of data are difficult to obtain, should be examined very carefully. Normally, they are unable to explain the real physical relationship between the tested variables, and sometimes can point in the wrong direction.

Extreme summer low-flow prediction model

Summer low-flow characteristics are different from those of average stream flow. This was verified by regressing annual summer low-flows versus annual average summer flows. Similarly, annual average summer flows were regressed against maximum summer flows for the study watersheds. Correlation between annual summer low-flows and annual average summer flows was not very significant (r^2=48%). Maximum summer flows were found very poorly correlated with average summer flows (r^2=9%). This revealed that the trend and patterns of extreme summer low-flows cannot be predicted precisely on the basis of trends and patterns in average summer flows.

A statistical model to predict the extreme summer low stream flow was constructed for the study area using percent vegetative cover, a number of watershed physical variables, and annual and winter average and minimum precipitation (Appendix 2). To decide which of the watershed variables should be used for the construction of prediction equation(s), they were regressed against each other to determine their multicollinearity (also correlation analysis was performed in the statgraphics computer software).

As expected, perimeter, main channel length, total stream length, number of lower stream orders (1st, 2nd, and 3rd), and watershed length and width were found highly correlated to the watershed area. Similarly, the number of second, third, fourth, and fifth stream orders were found highly correlated with the number of 1st stream orders. The correlation between absolute summer low-flows and summer low-flows per square mile was found very low for the study area.

Also, pairs of watershed length and width, watershed slope and main channel slope, and maximum watershed elevation and end point elevation were all found highly correlated with each other. Annual minimum precipitation was correlated more with the winter minimum precipitation than the annual average precipitation. Gauge elevation and annual minimum and winter minimum precipitation were also found significantly related to each other.

With the advance in technology and availability of sophisticated computer softwares, there is a diversity of options for regression analyses. However, there is no unique way to find a good subset of independent variables for a regression model. It is important to understand the options being used for their subjective use and interpretation to search for the good sub-set (Neter, et al. 1983).

Frequency histograms for dependent and many independent variables showed that their distributions were not strictly normal. However, it did not mean that data sets were abnormal. Theoretically, non-negative hydrologic variables cannot have normal distribution (Haan, 1977). A smaller number of observations can have a normal distribution for the central part of the distribution and a reasonable approximation to the true distribution. However, a larger number of observations are required when dealing with the extreme ends of a distribution. According to the central limit theorem, distribution of a hydrological random variable will approach normal distribution when independent effects in that variable become very large (Haan, 1977).

Theoretically, dependent and independent variables might have attained normal distribution if there were a larger number of observations. A few of the data transformation techniques were used to normalize the distributions. Distributions for most of the physical watershed parameters were more close to normal with log transformation. The extreme summer low-flows and precipitation variables in square root form were more close to normal distribution. Still, none of the transformations made any of the data distributions strictly normal.

Correlation analysis, frequency histograms, stepwise regression, multiple regression, and regression model selection methods were used to construct the model to forecast extreme summer low-flows. With the use of these tools, particularly step-wise regression analysis, it was easy to decide which of these mutually dependent variables to keep in the model depending upon their effect on the accuracy of the selected model and the difficulty in obtaining them for practical purposes.

A model equation was developed to predict the extreme summer low-flows in the study area. Area was found to be the most significant variable explaining the variation in the summer low-flows. This variable was studied more carefully. When regressed against summer low-flows individually, it had a high r^2 value (78.9%). Watershed areas of all the watersheds were very variable. There were roughly two clusters of data sets regarding area. More than half of the watersheds ranged from more than five square miles to less than 400 square miles.

A second cluster of data lies between 700 and a little over 1300 square miles. There was one watershed which was 5530 square miles. This one large watershed had a great positive effect upon the regression fit. When regression was performed without this watershed in the data set, r^2 dropped down to 51.35%. This one data point could not be considered as outlier in the strict sense. It may be representing the real fit or any bound of the fitting confidence.

However, without a few other data points in that range, it was impossible to know reality. Therefore, it was excluded from the analysis even though it had such a significant effect on the results. It was thought unrealistic that one data point out of thirty-six would suggest something significantly different from the rest.

The actual importance of these equations depends upon their ability to predict summer low-flows for an unobserved stream or a group of streams. Data set was not enough to split it into two halves for the model building and testing procedure. In the preliminary data analysis five watersheds were selected, one in each precipitation zone, to test the accuracy of the model. These five watersheds, selected by stratified sampling, were not used in the model building process.

The main objective was to construct a best possible prediction equation with the available data set. It was decided to use all the available data set to construct the final model equation. In the earlier part of this section it was shown how the number of observations play an important role in determining the outcome of an analysis for smaller data samples. Therefore, it was decided to use all the data set available for better predicting ability of the final model.

Testing on small sub-sampling is critical when it is unknown whether the selected variables are of the correct length/size and if the methodology in constructing the model was correct. However, most of the variables selected were unchangeable in this study. It was considered less likely that the methodology in constructing the model was incorrect. Therefore, concentration was focussed on building the strongest possible model. It would have been better to have a larger data set, that could have been splitted in halves for model build-up and subsequent verification of the model.

With the inclusion of one such independent variable that was significantly related to another independent variable, accuracy of the model increased. This variable was able to explain additional variation in the summer low-flows. However, the regression parameters were unreal and signs were also changed. This was the case with area and main channel length. Both were found highly correlated to each other, and were found highly correlated to extreme summer low-flows (positively).

When area was selected as the first independent variable, main channel length became insignificant. Later, with the presence of the annual minimum precipitation or the end point elevation in the model, it became very significant for the explanation of the remainder of the variation in the dependent variable. However, the regression coefficient for main channel length was now found to be negative, opposite to the actual relationship.

The resulting model is considered statistically acceptable in terms of inference to mean response or predicting a new observation within the region of observations. The parameters for each variable are not the real indicator of their individual influence on the significance of prediction (Neter, et al., 1983). It was due to the mutual interaction of these correlated independent variables that changed their parameters so much. Also, the resulting model will be strictly limited to the bounds of the response surface.

It was a very tedious job to know exactly which of the independent variables were more significant when combined with the other variables without affecting the regression parameters of each other unreasonably. Of the mutually correlated variables, one which was more significantly related to the dependent variable, and easier to obtain, was selected for further analysis to be included in the final model.

The final model constructed to predict the extreme summer low-flows is:

$$Q_{eslf} = -299.65+7.63\ (P)+0.02\ (EPE)+9.85\ (WSW) \qquad (37)$$

Where,

Q_{eslf}= Extreme summer low-flow, cfs

P = Annual minimum precipitation, inches

EPE= Watershed end point elevation, feet

WSW= Average watershed width, miles

The R^2 (coefficient of multiple determination) for the selected model is 79% and adjusted R^2 (adjusted coefficient of multiple determination) is 77%. Standard error of the model is 66.64, which is considered well within the range for similar studies. Regression coefficients for all the variables selected in the final model are highly significant. F-statistics for the model is 38.88.

All the variables in the final model are easily obtainable. Average watershed width and end point elevation can be obtained from topographic maps of the watershed. Annual minimum precipitation (minimum of about thirty years) for the watershed can be obtained from the closest precipitation gauge(s) data. Annual minimum precipitation is better correlated to the extreme summer low-flows and easier to obtain than forest cover information.

A better method to obtain annual minimum precipitation would be to calculate the average annual precipitation for the target watershed from the isohyetal map(s). Most of the areas are covered by isohyetal maps. Then, relate the watershed average precipitation so obtained with the average annual precipitation for the nearby precipitation station(s). Finally, use this relationship to calculate the annual minimum precipitation for the watershed from the annual minimum precipitation of the nearby precipitation station(s).

Watershed average width was found most significantly related to the extreme summer low-flows. Watershed area was the second most significant variable related to the extreme summer low-flows. However, with the inclusion of watershed average width in the model, watershed area, and other watershed size variables were insignificant.

Watershed average width was able to explain 61.1% of the variation in the extreme summer low-flows. With the inclusion of annual minimum precipitation in the model, accuracy of prediction of the model increased to 71%. The final selected model, with the inclusion of watershed end point elevation, was able to explain 79% of the variability in the extreme summer low-flows. The regression coefficients of all the selected independent variables were highly significant. All three independent variables in the model are uncorrelated to each other.

Another extreme summer low-flow prediction model using the proper transformations on the variables is presented in Appendix 5. Both models are very close to each other in their prediction accuracies. The standard error for the model using transformed data is much smaller. However, the standard error using transformed data should not be compared with the standard error using normal data. Plotting of residuals, which is a good indicator of the significance of the prediction ability of a model, showed that both models had similar scatter in their residuals.

SUMMARY AND CONCLUSIONS

For the better management of the semi-arid areas, knowledge of climate, occurrence of drought and drought responses to the climatic and physical changes is very important. Semi-arid areas of the PNW are typical of such areas having patterns of wet and dry periods alternatively with varying widths (Graumlich, 1985, Keen, 1938). It is believed that with a better knowledge about the trends and patterns of drought occurrences in the semi-arid areas and a better ability to predict, resources management planning can be done properly.

Summer low-flows are very sensitive to various climatic, geologic and topographic variables. The objective was to gain a better understanding of the hydrologic characteristics of summer low-flows (drought) in the semi-arid areas by studying long-term trends in summer low-flows, and to determine whether there is any exploitable relationship between summer low-flows and some of the climatic and physical watershed variables.

Thirty-eight gauged watersheds with natural and continuous daily stream flow records of close to thirty years or more were selected in the semi-arid areas of five western states (Oregon, Washington, Idaho, Nevada and California). A few watersheds which had a little less than thirty years of gauged record were included in the study because of the scarcity of the gauged streams in those vicinities. On the average, the study covers the data from the mid 1930's to 1992. Thirty-six precipitation stations in or around those selected watersheds were chosen for the study (on average covering from 1940-1992).

A period of thirty years was considered reasonable to be unaffected by the average climatic cycles in the study area. Also, statistically, a satisfactory measurement of population parameters is believed to be reasonably achieved by having number of observations of thirty or more.

Seven-day moving averages of daily flows per square mile for the summer months of June, July and August were extracted for each year. The lowest of the 7-day summer flows were selected as the summer low-flows. Precipitation data from selected stations was found statistically significantly related to the actual watershed precipitation, however, lower in magnitude.

Watershed cover information for the watersheds in Oregon was obtained for two periods, 1973 and 1990. Topographic variables for all the watersheds were measured from the U.S.G.S topographic maps.

Long-term natural data were required for these long-term studies. The amount and kind of data available for the study area was barely enough to conduct meaningful research. The quality of the available data to study the trends and patterns, along with other characteristics of low-flows, was speculated to be fair to poor, because the level of maintenance of stream gauges was found to be not very efficient in the selected watersheds.

Due to relative low priority of stream low-flow research compared to peak flows in the past, there may not have been much concern about the accurate measurement of flows during drier periods. Some of the stream gauges visited were not very well maintained (e.g., at many places the structures (rectangle, etc.) made to calibrate stream flows were not in very good condition).

During the field observation of precipitation stations and selected watersheds, it was noted that the degree of closeness of actual location of the precipitation gauges with respect to the selected watersheds varied from place to place. The actual location of a precipitation gauge related to the surroundings like houses, hedges, trees, hills etc., was also variable. Most of the precipitation gauges were located at proper places, while some were found at locations where there were some physical obstructions expected to result in lesser catch than the actual precipitation.

Summer low-flows are relatively hard to measure. Stream gauges need to be very carefully maintained and calibrated for the measurement of flows during droughts and a better network of stream flow and precipitation gauges is needed. Measurement of annual low-flows are potentially more affected by a relatively small inaccuracy in the gauge than average or higher stream flows.

It is reported in the literature that it is difficult to understand low-flow behavior based upon the knowledge of average stream flows. The relationships between different summer flows were studied for the study area. The average summer low-flows were better correlated (r^2=95.4%) with the minimum summer low-flows compared to the maximum summer low-flows (r^2=61%). However, summer low-flows were moderately explained by the average summer flows (r^2=48%), and very poorly explained by the maximum summer flows (r^2=9%).

One can argue that this moderate relationship could be partly due to the inaccuracies inherent in the measurement of low stream flows. On the other hand these inaccuracies in the low-flows can be believed to be consistent over the period of record. The inability to understand droughts from the knowledge of average conditions, therefore, is a reality.

Low-flows are found difficult to understand from the study of some simple variables which are normally considered good predictor for high flow. Summer low-flows had high variation from one watershed to the other. Within the study area, different zones showed different trends and pattern in precipitation over the period of record, but significant similarities within each zone. This pointed out that the generalization about climatic trends based on a few scattered observations can be erroneous.

Caution should be made in taken sweeping generalization about climatic trends and pattern in the study area or for that matter any area based on limited information. Ground water interflow, nature of soil, aspect, nature of snowpack, vegetation, slope, presence of micropore and macropore, inter-basin flow in some areas, geology of the area, etc., all may play big roles in the timing and quantity of stream summer low-flows.

All the summer low-flow data was tested for its dependence on the previous year's low-flows. Most of the data was found independent of the previous year's condition. Some of the watersheds showed statistically significant correlation between summer low-flows of successive years. However, coefficients of determination (R^2), which explained the variation in the summer low-flows, were low. Distribution of the summer low-flows was not strictly normal. But the majority of the streams had closer to the normal distribution.

No significant trends in summer low-flows were found for the majority of the selected streams. A few showed significantly positive or negative trends, however. Slopes of the regression lines were very close to zero for all the streams. It was concluded that, in general, there were no significant trends in the summer low-flows in the area of study within the time period of this data set.

The study area was divided into five zones on the basis of annual average precipitation. Zone 1 included those areas which receive less than 10 inches of precipitation. Areas which receive precipitation between 10 and 20 inches were included in Zone 2. Similarly, areas with 20 to 30 inches, 30 to 40 inches, and over 40 inches of precipitation were classified as Zone 3, 4, and 5, respectively.

Graphical study of precipitation and summer low-flow trends and patterns revealed the decade wise behavior of stream summer low-flows and precipitation. Regression analyses showed only the resulting relationship for the entire period of study. However, graphical plotting showed that the trends were either positive, negative or close to stationary over different periods for different streams. The trends in precipitation were shown more or less stationary for Zone 1, 2, and 4 on a long-term basis. Whereas, trends were significantly upward (Zone 3) and downward (Zone 5) for the period of record.

It can be concluded that different zones behave differently to different climatic episodes. Construction of stream flow record, or at least summer low-flows, from precipitation or tree ring chronologies needs more care in evaluating their relationships. A highly significant relationship was not found between summer low-flows and precipitation for the study area as a whole. Although, for many localities, statistical relationships between summer low-flows and precipitation were found highly significant.

In some sub-regions, a lag period of one to two years between precipitation and summer low-flows was found. Precipitation trends and patterns were different in different zones. Zone 1 and Zone 2 had higher resemblance among their precipitation patterns. The early to mid 1980's was shown to be the wettest period of records for Zones 1, 2 and 3. For Zone 5 it was a drier period, and for Zone 4 it was an average wet period.

Summer low-flows were variable in their trends and patterns within each zone. The degrees of similarities between summer low-flows and precipitation were also varying from watershed to watershed. Watersheds with higher relief and, perhaps, higher vegetative cover had efficient response in their summer low-flows to the precipitation changes. Flatter and larger watersheds showed a lag of 1-2 years in their recovery from the drought periods.

Watersheds in the Blue Mountains, eastern Oregon, seemed to have higher storage capability of moisture in their mantle or in the snow packs to dampen the effects of annual variation in climate. Precipitation for Zone 4 did not show any significant upward or downward trend. The resemblance between precipitation and summer low-flows for the majority of the watersheds in the zone was very high.

Summer low-flows generally followed the wet and dry episodes of the climate closely. The precipitation trend for Zone 5 was found downward, overall. The period between the mid 1950's to early 1960's was the wettest for the zone. Summer low-flows followed the precipitation trends significantly in Zone 5.

Similarity of magnitudes, trends, and patterns between summer low-flows within each zone were found higher for the higher precipitation zones compared to the lower precipitation zones. The drought of the 1930's was shown by all the zones where data records were available. All the zones, except Zone 5, showed the early to mid 1980's as one of the wettest periods. This wet period was followed by drought from the late 1980's to the end of the period of record. For the majority of sites studied, this latest drought period was approaching the severeness in its magnitude that was comparable to the drought period of the 1930's.

The graphical examination of the summer low-flows and precipitation behavior over the period of record revealed that droughts of 10-15% below average occur more frequently with a return interval of 10 to 20 years. There is a pattern of alternate dry and wet periods. Wet periods are followed by the dry periods of relatively similar magnitude. A 50-55 year return interval of major drought in the area, similar in magnitude to that of the 1930's which was about

20% below average low-flow conditions, is common. The pattern of the occurrence of major droughts of such magnitude in the study area seem in conformity with the major drought occurrence in the western Great Plains (Meko, 1982).

However, it is inferred that generalization of the wet and dry trends and patterns for a larger scale of area are misleading. Precipitation patterns and trends were found to be different in different zones. Storm patterns may differ even in the adjacent watersheds and at different altitudes within a large watershed. Zoning of the study area on the basis of precipitation seemed more appropriate for the study of climatic behavior. Precipitation patterns and trends within each zone showed a high degree of agreement. Summer low-flow trends and patterns are not controlled by precipitation alone. Therefore, reconstruction of stream flow, or at least summer low-flows, from a few scattered observations over a large region should be avoided.

Correlation between summer low-flows and precipitation were analyzed by regressing annual summer low-flows against annual and seasonal precipitation. Correlations between summer low-flows and spring and fall precipitation were found highly insignificant for all zones. Correlations between summer precipitation and summer low-flows were found very low compared to the winter and annual precipitation, except for Zone 4. Eight of the fourteen watersheds in Zone

4 were located in north central Idaho. Summer precipitation was found to be a significant part of the annual precipitation for that area. Summer low-flows in those watersheds were correlated better with the summer precipitation compared to other zones.

Winter and annual precipitation were found more significantly related to the summer low-flows for Zone 3, 4, and 5 when compared to Zone 1 and 2. However, the variation in summer low-flows among the watersheds within zones did effect the forecasting abilities of zonal model equations. For some individual watersheds, r^2 between summer low-flows and precipitation was found as high as 80%. But for the average equation for the zones, it was always less than 50%. It was concluded that annual precipitation is one of the major controlling factors for summer low-flows for the normal behaving watersheds.

Recession analyses were performed on individual streams in each zone and resulting equations were averaged for each zone. Building of a recession forecast model was performed by forcing regression intercept through origin. This resulted in a high degree of forecasting ability of the equations for all the streams with variable summer low-flows.

Four model equations for four different starting dates in summer (June 1, June 15, June 20 and June 25) were made for each zone, as well as for the study area as a whole.

Forecasting abilities of resulting equations were generally very high for all equations. For drier regions, equations using an earlier start date were more accurate than the later start date. Model equations were best suited to forecast recession flows for normal behaving watersheds.

Those watersheds which have major springs contributing to their flows, or those which have higher carry over of moisture from one year to the next, and lesser variation in their flows over the year, were less predictable using these equations. Recession forecast equations for those zones which had a higher number of watersheds were generally more accurate in their predictions of summer low-flows.

Regional recession forecast equations were also built using all the watersheds available. These resulting equations were tested against five randomly selected streams. Recession forecast equations were found strong in predicting recession flows for normal behaving watersheds. They were found as good as the zonal equations or, in some cases, better than the zonal equations.

For those zones which had the fewest number of watersheds available to use in the model building process, the prediction accuracies of the zonal models were lower compared to the regional equations. It was concluded that, for practical purposes, the regional equations are more useful for predicting recession flows compared to the zonal equations, unless a zonal equation is considered better by the user for a particular reason.

Vegetation information for the two periods of 1973 (twelve watersheds) and 1990 (fourteen watersheds) were analyzed separately. None of the eleven sub-classes of watershed cover appeared significantly related to summer low-flows. Among these, mixed vegetation, rangelands, deciduous vegetation, and area under urban habitation showed marginally better correlation with summer low-flows.

Broader grouping of the vegetation information did not help find any significant relationship between watershed cover types and summer low-flows. Rangeland cover type appeared to be explaining the variability in the summer low-flows better than all other classes for both data sets. However, statistically, the correlations were insignificant at 95% confidence level.

Many studies in hydrology are conducted with a comparable number of watershed observations and have made a useful contribution towards the understanding of natural processes. From that perspective these results should be considered reliable. But the experience from the later analyses showed that results shown by using a small number of observations may sometimes be misleading.

For the construction of a forecast model for the extreme summer low-flows, various independent variables were obtained. These included watershed physical parameters and precipitation. They were tested for their muticollinearity first. They were also regressed against summer low-flows individually to note their partial effect upon the summer low-flows.

Annual minimum precipitation was found better correlated with summer low-flows than percent vegetative cover. This could be due partly to the data collection errors for the percent vegetative cover. Data for fourteen watersheds was calculated from aerial survey information. Data from the other five watersheds was calculated from the USGS published statistics of stream flow data for Washington. Estimates about percent vegetative cover were made from the field observations for the remaining nineteen watersheds.

However, the pattern of significance of relationships between summer low-flows and several independent variables was more or less similar even when regressions were performed by excluding the estimated percent vegetative cover data. Precipitation showed better correlation than the percent vegetative cover with the summer low-flows.

Instead of the average annual or average winter precipitation, minimum values of annual and winter precipitation were found more significantly related to summer low-flows. In the future, studies in similar areas should examine the relationship between summer low-flows and minimum annual and winter precipitation carefully. Overall, summer precipitation was found inefficient in explaining the summer low-flow behavior.

Most of the variables used to construct the summer low-flow prediction model were not normally distributed. The data set was not a randomly selected one. Proper transformations of skewed dependent and several independent variables were performed. Effects of influential observations, as well as natural and transformed data sets, on the resulting model were carefully studied. The final model equation was constructed based upon the knowledge of the physical relationships between different independent and dependent variables.

The final model to predict summer low stream flows was constructed using watershed average width, annual minimum precipitation, and watershed end point elevation as the independent variables. The model is highly significant in explaining the variation in summer low-flows. In the final model, no two mutually correlated independent variables were selected. This lowered the model prediction ability to some extent. However, a higher reliability is attributed in this model due to easily understandable physical relationships between dependent and independent variables. It can be used for a broader response surface. Where excessive care is needed in planning a resource management project, it is suggested that the lower bounds of the confidence should be used.

It is believed that this study will lead toward positive direction for future research on summer low-flows in semi-arid areas. Some of the directions indicated in this effort need careful review and better data sets to take them to the next level of acceptance. A denser network of stream and precipitation gauges is strongly recommended in the study area. Also, an efficient maintenance of these gauges is very important for the accurate measurements, particularly during drier periods. A study of the precise relationships between different vegetative cover types and extreme summer low-flows with a larger data set is needed.

LITERATURE CITED

Abbas, S. H. and M. Hanif. 1987. Effect of Watershed Management operations on run off and sediment release in Hazara. Pakistan Journal of Forestry 37(2):89-98.

Alley, William M. 1985. The palmer drought severity index as a measure of hydrologic drought. Water Resources Bulletin, American Water Resources Association, 21(1):105-114.

Baker, Malchus B. Jr. 1986. Effects of Ponderosa pine treatments on water yield in Arizona. Water Resources Research 22(1):67-73.

Berris, S. N. and R. Dennis Harr. 1987. Comparative snow accumulation and melt during rainfall in forested and clear-cut plots in the Western Cascades of Oregon. Water Resources research 23(1):135-142.

Blasing, T. J.; D. W. Stahle and D. N. Duvick. 1988. Tree ring-based reconstruction of annual precipitation in the south-central United States from 1750 to 1980. The American Geophysical Union, paper no.7W4882:163-171.

Bosch, J. M. and J.D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Jour. of Hydrology 55:3-23.

Bradley, R. S. 1976. Seasonal precipitation fluctuations in the western United States during the late nineteenth century. Monthly weather review, 104(5):501-512.

Bradley, R. S.; H. F. Diaz; J. K. Eischeid; P. D. Jones; P. M. Kelly and C. M. Goodess. 1987. Precipitation fluctuations over northern Hemisphere land areas since the mid 19th century. Science 237(4811):171-175.

Brown, H. E. 1972. Evaluating watershed management alternatives. In: Transactions of the American Society of Civil Engineers 137:911-912.

Calder, I. R. 1986. The influence of land use on water yield in upland areas of the U.K. Journal of Hydrology, Netherlands 88(3/4):201-211.

Campbell, J. C. 1971. Prediction of seasonal-low stream flow quantities. WRRI-10. Water Resources Research Institute, Oregon State University Corvallis, OR, 16p.

Campbell, Alan J.; Roy C. Sidle and H. A. Froehlich. 1982. Prediction of peakflows for culvert design on small watersheds in Oregon. WRRI-74. Water Resources Research Institute, Oregon State University Corvallis, 96p.

Carter, H. G. 1935. Climatic trend in the Pacific Northwest. Monthly Weather Review, January, 1935:19-23.

Chang, Mingteh and Douglas G.Boyer 1977. Estimates of low flows using watershed and climate parameters. Water Resources Research 13(6):997-1001.

Chang, Tio J. 1990. Effects of drought on stream flow characteristics. Journal of Irrigation and Drainage Engineering, 116(3):332-341.

Chang, Tiao J. and Jennifer R. Stenson, 1990. Is it realistic to define a 100-year drought for water management? Water Resources Bulletin, American Water Resources Association, 26(5):823-829.

Cheng, J. D. 1989. Stream flow changes after clear-cut logging of a pine-beetle-infested watershed in southern British Columbia, Canada. Water Resources Research 25(3):449-456.

Chow, Ven Te. 1964. Handbook of applied hydrology. A compendium of water-resources technology. Published by Mcgraw-Hill book company, 29 chapters.

Cleaveland, Malcolm K. and David W. Stahle. 1989. Tree ring analysis of surplus and deficit runoff in the White River, Arkansas. Water Resources Research 25(6):1391-1401.

Croft, A. R. 1948. Water loss by stream surface evaporation and transpiration by riparian vegetation. Transactions, American Geophysical Union, 29(2):235-239.

Davis, E. A. 1984. Conversion of Arizona chaparral to grass increases water yield and nitrate loss. Water Resources Research 20(11:1643-1649.

Davis, Wendell E. and Arthur W. Sampson. 1936. Experiment in correlation of tree-growth rings and precipitation cycles. American Geophysical Union Trans. 1936:493-496.

Debussche, M.; S. Rambal and J. Lepart. 1987. Land-use changes in the wet mediterranean region: Assessment of hydrological effects. In: Forestry Abstracts, 1988. SD1 F58 49(7):no.4906.

Douglass, J. E. and W. T. Swank. 1975. Effect of management practices on water quality and quantity. USDA Forest Service, Coweeta Hydrological Laboratory, North Carolina, Northeastern Forest Experiment Station. General Technical Report N.E. 13:1-13.

Dracup, John. A., Kil Seong Lee and Edwin G. Paulson, Jr. 1980. On the definition of droughts. Water Resources Research 16(2):297-302.

Fowler, W.B.; J. D. Helvey and E. N. Felix. 1987. Hydrologic and climatic changes in three small watersheds after timber harvest. USDA Forest Service PNW Research Station, Research Paper PNW-RP-379, 13p.

Gentry, A. H. and J. Lopez-Parodi 1980. Deforestation and increased flooding of the Upper Amazon Peru, Ecuador. American Association for the Advancement of Science, 210(4476):1354-1356.

Golding, Douglas L. and Robert H. Swanson. 1986. Snow distribution patterns in clearings and adjacent forest. Water Resources Research 13(13):1931-1940.

Graumlich, Lisa. 1985. Long-term records of temperature and precipitation in the Pacific North-West derived from tree rings. Dissertation presented to University of Washington, Seattle, Washington, in partial fulfilment of the requirements for the degree of Doctor of Philosophy:1-82.

Grizzel, Jeffrey D. 1993. Municipal water source turbidities following timber harvest and road construction in western Oregon. Thesis presented to Oregon State University, Corvallis, Oregon, in partial fulfilment of the requirrements for the degree of Master of Science.

Haan, Charles T. 1977. Statistical methods in Hydrology. The Iowa State University press/ Ames, 15 chapters.

Hammett, K. M. 1985. Low-flow frequency analysis for streams in West-Central Florida. USGS Water-Resources Investigations Report 84-4299.

Hardman, George and Orvis E. Reil. 1936. The relationship between tree-growth and stream runoff in the Truckee River Basin, California-Neveda. The University of Nevada, Agri. Eperim. station, Bulletin no. 141.

Harenberg, W. A.; M. L. Jones; I. O'Dell; T. S. Brennan and A.K. Lehmann. 1991. Water resources data, Idaho, water year 1991. Volume 2. Upper Columbia River Basin and

Snake River Basin below King Hill. USGS water-data report ID-91-2

Harlow, William M. and Ellwoods S. Harrar. 1941. Textbook of dendrology. Covering the important forest trees of the United States and Canada. McGraw-Hill book company, Inc.

Harr, R. D.; Al Levno and Rosewell Merseeau. 1982. Stream flow changes after logging 130-year old Douglas fir in two small watersheds. American geophysical union, paper no. 2W0253:637-644.

Harr, R. D. 1986. Effects of clearcutting on rain-on-snow runoff in Western Oregon: A new look at old studies. Water Resources Research 22(7):1095-1100.

Harrold, Steven A. 1990. Drought-simply global climatic change? Journal of Agron. Educ., 19(1):119-121.

Hibbert, A. R. 1967. Forest treatment effects on water yield. In Forest Hydrology proceedings of a NSF Advanced Science Seminar. Sopper, W.E. and H.W. Lull (eds.), Pergaman press, Oxford:527-543.

Hibbert, A. R. 1969. Water yield changes after converting a forested catchment to grass. Water Resources Research, 5(3):634-640.

Hibbert, Alden R. 1983. Water yield improvement by vegetation management on western rangelands. Water resources bulletin, 19(3), American Water resources association, 19(3):375-81.

Hicks, Brendan J.; Robert L. Beschta and R. Dennis Harr. 1991. Long-term changes in stream flow following logging in western Oregon and associated fisheries implications. Water Resources Bulletin, American Water Resources Association 27(2):217-226.

Higgins, Roger J. 1981. Use and modification of a simple rainfall-runoff model for wet tropical catchments. Water Resources Research 17(2):423-427.

Higgins, D. A.; A. R. Tiedemann; T. M. Quigley and D. B. Marx. 1989. Stream flow characteristics of small watersheds in the Blue Mountains of Oregon. Water Resources Bulletin, American Water Resources Association 25(6):1131-1149.

Hornbeck, J. W.; R. S. Pierce and C. A. Federer. 1970. Stream flow changes after forest clearing in New England. Water Resources Research 6(4):1124-1131.

Hornbeck, James W. 1975. Stream flow response to forest cutting and revegetation. Water Resources Bulletin, American Water Resources Association, 11(6):1257-1260.

Hubbard, L. E.; T. A. Herrett; R. L. Kraus; G. P. Ruppert and M.L. Courts. 1992. Water resources data Oregon, water year 1992. USGS water data-report OR-92-1.

Hydrosphere Inc. 1993. HYDRODATA volume 5.3. USGS daily values West 2. 1002 Walnut, suite 200 Boulder, Colorado 80302.

Johnson, E. A. and H. G. Meginnis. 1960. Effect of altering forest vegetation on low-flows of small streams. IAHS publication number 51, pp:257-266.

Joseph, E. S. 1970. Frequency of design drought. Water resources Research, 6(4):1199-1201.

Karl, Thomas R. 1983. Some spatial characteristics of drought duration in the United States. Journal of Climate and Applied Meteorology, 22:1356-1366.

Kauffman, J. B.; W. C. Krueger and M. Vavra. 1983. Impacts of cattle on stream banks in northeastern Oregon. Journal of Range Management 36(6):683-685.

Keen, F. P. 1937. Climatic cycles in eastern Oregon as indicated by tree rings. Monthly Weather Review 65(5), W.B. 1210:175-189.

Lee, K. W.; G .W. Kapple and D.R. Dawdy. 1975. Rainfall runoff relation for redwood Creek, above Orik, California. USDI Geological Survey. Open file report, 14p.

Lee, Fred N. 1985. Analysis of the low-flow characteristics of streams in Louisiana. USGS Water Resources Tech. Report 35, 41p.

Loague, Keith M. and Allan Freeze R. 1985. A comparison of rainfall-runoff modeling techniques on small upland catchments. Water Resources Research 21(2):229-248.

Lynch, James A.; W. E. Sopper and D. B. Partridge. 1976. Changes in stream flow following partial clearcutting on a forested watershed. In: Proceedings of the national symposium on watersheds in transition.

American Water Resources Association and Colorado State University:313-320.

Manugistics, Inc. 1992. STATGRAPHICS version 7. Statistical graphics system by statistical graphics corporation. 2115 east Jefferson street, Rockville, Maryland 20852.

Meko, David M. 1982. Drought history in the western Great Plains from tree rings. IN: International Symposium on Hydrometeorology, June 13-17. American Water Resources Association, 1983, :321-326.

Miles, M. B; W. D. Wiggins; G. P. Ruppert; R. R. Smith; L. L. Reed and L. E. Hubbard. 1990. Water resources data, Washington, water year 1990. USGS water data-report WA-90-1

Moffatt, Robert L.; Roy E. Wellman and Janice M. Gordon. 1990. Statistical summaries of stream flow data in Oregon: Volume 1-Monthly and annual stream flow , and flow-duration values. USGS open file report 90-118.

Neter, John; William Wassermann and Michael H. Kutner. 1983. Applied linear regression. Published by Richard D. Irwin, Inc. Homewood, Illinois 60430, 15 chapters.

Parrett, Charles; Dave R. Johnson and J.A. Hull. 1989. Estimates of monthly stream flow charactersistics at selcetd sites in the upper Missouri River basin, Montana, base period water year 1937-86. U. S. Geological Survey Water-Resources Investigations Report 89-4082.

Pittock, A. B. 1977. On the causes of local climatic anomalies, with special reference to precipitation in Washington state. Journal of Applied Meteorology, 16:223-230.

Rao, A. Ramachandra and A. Durgunoglu. 1987. Variability in periodicities exhibited by tree ring data. IN: The influence of climate change and climatic variability on the hydrologic regime and water resources. IAHS publication no. 167:133-141.

Riggs, H. C. 1985. Stream flow characteristics -development in water science, ELSEVIER, 22, 249p.

Rothacher, J. 1970. Increase in water yield after clear-cut logging in the Pacific Northwest. Water Resources Research 6(2):653-658.

Stockton, Charles, W. and David M. Meko. 1975. A long-term history of drought occurrence in western United States as inferred from tree rings. Weatherwise, 1975:244-249.

Swank, W. J.; L. W. Swift, jr. and J. E. Douglass. 1988. Forest hydrology and ecology at Coweeta. Ecological study 66:297-312.

Taylor, George H. 1993. Normal annual precipitation. State of Oregon. State Climatologist, Oregon Climate Service, 326 Strand Ag Hall, Oregon State University, Corvallis, Oregon.

Troendle, C. A. and R. M. King. 1985. The effect of timber harvest on the Fool Creek Watershed, 30 years later. USGS Water Resources Research 21(12):1915-1922.

Troendle, Charles A. and Charles F. leaf. 1981. Effects of timber harvest in the snow zone over volume and timing of water yield. Interior west watershed management. David M. Baungartner, compiler and editor. [Symposium, Spokane, Wash., April 8-10, 1980]. 288 p. Cooperative extension, Washington State University, Pullman:232-243.

Wahl, E. W. and T. L. Lawson. 1970. The climate of the mid nineteenth century United States compared to the current normals. Monthly Weather Review, 98(4):259-265. Whipple, William, Jr. 1966. Regional drought frequency analysis. Proceedings of the American Society of Civil Engineers. Journal of the Irrigation and Drainage Division. p:11-31

Welch, R. A. and CRMS_UGA. 1991. CAPTURE version 3.1. R-WEL, Inc. P.O. Box 6206, Athens, GA 30604

Williams J. R. and H. E. Pearson. 1985. Stream flow statistics and drainage-basin charactersitics for the southwestern and eastern regions, Washington. USGS open-file report 84-145-B.

Wyk, D. B. Van. 1987. Some effects of afforestation on stream flow in the Western Cape Province, South Africa. Water SA 13(1):31-36.

Zeb, Aurang. 1992. Characteristics of stream low-flows in eastern Oregon. Their relationship with precipitation and physical watershed parameters. Thesis presented to Oregon State University, Corvallis, Oregon, in partial fulfilment of the requirrements for the degree of Master of Science.

Zecharias Yemane B. and Wilfried Brutsaert. 1988. The influence of basin morphology on groundwater outflow. Water Resources Research 24(10):1645-1650.

APPENDICES

Appendix 1

Table 10: Selected streams/rivers in the study area in each precipitation zone

Name of River/Stream		Area (m^2)
Zone 1 (precipitation from 0-10 inches)		
1.	Big jack Creek near Bruneau, Idaho	253
2.	Little Currant Creek near Currant, Nevada	12.9
3.	Crab Creek at Irby, Washington	1042
4.	East Fork Quinn River near Mcdermitt, Nevada	140
5.	Reese River near Ione, Nevada	53
6.	Buckeye Creek near Bridgeport, California	44.1
7.	Rocky Ford Creek near Ephrata, Washington	12
8.	Leonard Creek near Denio, Nevada	52
Zone 2 (precipitation from 10-20 inches)		
1.	Silvies River near Burns, Oregon	934
2.	Donner Und Blitzen River near Frenchglen	200
3.	Lamoille Creek near Lamoille, Nevada	25
4.	Boise River near Twin Springs, Idaho	835
5.	Strawberry Creek, Oregon	7
6.	Hurricane Creek, Oregon	29.6
7.	Bridge Creek, Oregon	30
Zone 3 (precipitation from 20-30 inches)		
1.	Umatilla River, Oregon	131
2.	Entiat River, Washington	203
3.	Eagle Creek, Oregon	156
4.	Fall River, Oregon	45.1
5.	Sagehen Creek near Truckee River, California	10.5
Zone 4 (precipitation from 30-40 inches)		
1.	Cultus Creek, Oregon	33.2
2.	Deer Creek, Oregon	21.5
3.	South Fork Clearwater River at Stites, Idaho	1150
4.	Blackwood Creek near Tahoe City, California	11.2
5.	Clearwater River at Orofino, Idaho	5580
6.	Coeur d'Alene River at Enaville, Idaho	895
7.	Coeur d'Alene River near Prichard, Idaho	335

Table 10 (continued): Selected streams/rivers in the study area in each precipitation zone

Name of River/Stream	**Area(m^2)**
8. Lochsa River near Lowell, Idaho	1180
9. St. Joe River at Calder, Idaho	1030
10. Stehekin River, Washington	321
11. South Fork Walla Walla River, Oregon	63
12. Cultus River, Oregon	16.5
13. Brown Creek near La Pine, Oregon	21
14. Couer d'Alene River at Cataldo, Idaho	1223
Zone 5 (precipitation 40 inches or more)	
1. American River, Washington	78.9
2. Odell Creek near La Pine, Oregon	39
3. Mill Creek near Walla walla, Washington	59.6
4. North Fork Clearwater River near Canyon Ranger station, Idaho	1360

Appendix 2

Table 11: Watershed physical and precipitation paramteres for the study area.

Name of watershed	AREA	PERM	STL	LKA	MNCL
Silvies River, OR	934	218	1099	0	100
Strawberry Creek, OR	7	13	16	0	6
Lochsa River, ID	1180	240	893	0	91
S.F. Clearwater R, ID	1150	205	1064	1	81
N.F.Clearwater R.,ID	1360	188	1352	0	74
Clearwater River, ID	5580	483	4881	1	145
St. Joe River, ID	1030	189	735	0	76
Couer d'Alene River near Prichard, ID	335	94	219	0	41
Couer d'Alene River near Enaville, ID	895	145	698	0	74
Couer d'Alene River at Cataldo, ID	1223	179	910	0	80
Boise River, ID	830	149	644	0	54
Big Jack Creek, ID	253	82	178	0	44
Leonard Creek, NEV	52	31	71	0	13
Reese River, NEV	53	40	65	0	15
Little Currant Creek,NEV	13	14	5	0	5
East Fork Quinn River, NEV	140	71	201	0	26
Lamoille Creek, NEV	25	24	23	0	12
Blackwood Creek, CAL	13	17	15	0	7
Sagehen Creek, CAL	11	13	15	0	5
Buckeye Creek, CAL	44	35	53	0	16
Stehekin River, WA	321	94	378	1	25
Entiat River, WA	203	82	228	0	39
Crab Creek, WA	1042	164	1118	0	94
American River, WA	79	51	100	0	23
Mill Creek, WA	60	40	78	0	14
Umatilla River, OR	131	55	341	0	21
South Fork Walla Walla River, OR	63	44	152	0	20
Hurricane Creek, OR	30	37	64	0	12
Donner Und Blitzen River, OR	200	75	357	0	32
Bridge Creek, OR	30	32	55	0	16
Eagle Creek, OR	156	70	313	0	26
Cultus River, OR	17	20	10	0	9
Cultus Creek, OR	33	27	44	2	11
Odell Creek, OR	39	30	36	6	14
Fall River, OR	45	31	16	0	9
Deer Creek, OR	22	30	31	1	13

Table 11 (continued): Watershed physical and precipitation paramteres for the study area.

Name of watershed	ISTO	SECO	THRO	FTHO	FFTO	SXTO
Silvies River, OR	337	85	14	6	2	1
Strawberry Creek, OR	6	3	1	0	0	0
Lochsa River, ID	428	116	29	3	1	0
S.F. Clearwater R, ID	318	72	15	3	1	0
N.F.Clearwater R., ID	962	167	37	7	1	0
Clearwater River, ID	1466	367	81	11	5	1
St. Joe River, ID	222	49	9	2	1	0
Couer d'Alene River near Prichard, ID	66	17	3	1	0	0
Couer d'Alene River near Enaville, ID	105	26	6	1	0	0
Couer d'Alene River near Cataldo, ID	49	11	4	1	0	0
Boise River, ID	173	41	11	2	1	0
Big Jack Creek, ID	34	8	3	1	0	0
Leonard Creek, NEV	27	8	2	1	0	0
Reese River, NEV	25	7	2	1	0	0
Little Currant Creek, NEV	3	1	0	0	0	0
East Fork Quinn River, NEV	75	14	4	1	0	0
Lamoille Creek, NEV	5	1	0	0	0	0
Blackwood Creek,CAL	7	1	0	0	0	0
Sagehen Creek, CAL	7	1	0	0	0	0
Buckeye Creek, CAL	18	2	1	0	0	0
Stehekin River, WA	163	34	4	1	0	0
Entiat River, WA	95	17	4	1	0	0
Crab Creek, WA	316	62	13	1	0	0
American River, WA	38	6	1	0	0	0
Mill Creek, WA	29	5	1	0	0	0
Umatilla River, OR	42	9	3	1	0	0
South Fork Walla Walla River, OR	23	4	1	0	0	0
Hurricane Creek, OR	13	2	1	0	0	0
Donner Und Blitzen River, OR	111	21	7	1	0	0
Bridge Creek, OR	11	2	1	0	0	0
Eagle Creek, OR	68	11	3	1	0	0
Cultus River, OR	2	1	0	0	0	0
Cultus Creek, OR	13	3	1	0	0	0
Odell Creek, OR	19	1	0	0	0	0
Fall River, OR	4	1	0	0	0	0
Deer Creek, OR	10	3	2	0	0	0

Table 11 (continued): Watershed physical and precipitation paramteres for the study area.

Name of watershed	WSL	WSW	GELE	EPEL	MXEL	MWSL	MCSL
Silvies River, OR	50	26	4195	6070	8563	38	19
Strawberry Creek,OR	5	2	4910	8580	9038	730	595
Lochsa River, ID	71	21	1453	8300	8647	96	75
S.F. Clearwater River, ID	54	26	1300	6700	8860	99	67
N.F. Clearwater River,ID	46	50	1660	7937	7930	3	85
Clearwater River,ID	103	37	991	8300	8887	71	55
St. Joe River, ID	60	19	2172	6610	6838	74	59
Couer d'Alene River Prichard, ID	32	15	2485	5450	5960	94	72
Couer d'Alene River Enaville, ID	42	13	2100	5450	6700	80	45
Couer d'Alene River Cataldo, ID	66	27	2100	5450	6838	51	42
Boise River, ID	42	20	3256	10500	10500	172	134
Big Jack Creek,ID	30	13	2810	6240	6240	113	77
Leonard Creek, NEV	11	7	4331	9397	9397	482	402
Reese River, NEV	12	8	7087	11195	11772	350	282
Little Currant Creek, NEV	5	3	6759	9220	11319	540	510
East Fork Quinn River, NEV	17	11	4725	6989	8137	135	86
Lamoille Creek, NEV	9	3	6267	10926	11352	509	391
Blackwood Creek,CAL	6	3	6201	8629	8878	388	327
Sagehen Creek, CAL	5	3	6332	8767	8767	508	446
Buckeye Creek, CAL	12	5	6923	11844	11844	396	307
Stehekin River, WA	21	23	1099	7382	8511	299	253
Entiat River, WA	31	9	1561	9249	9249	249	196
Crab Creek, WA	76	27	1386	2805	2861	19	15
American River, WA	20	5	2700	6710	7513	200	175
Mill Creek, WA	12	5	1996	6103	6070	333	292
Umatilla River, OR	16	10	1855	5217	5450	215	163
S. Fork Walla Walla River, OR	17	5	2050	5676	5876	219	182
Hurricane Creek, OR	10	4	4500	8416	9833	377	324
Donner Und Blitzen River, OR	23	13	4254	7612	9462	144	104
Bridge Creek, OR	13	3	4185	7251	7251	233	197
Eagle Creek, OR	22	9	2800	8744	9049	274	230
Cultus River, OR	7	3	4450	5939	6303	199	158
Cultus Creek, OR	8	5	4545	6126	6893	203	139
Odell Creek, OR	11	4	4799	8416	8410	316	266
Fall River, OR	8	6	4220	5791	6214	209	168
Deer Creek, OR	11	4	4520	6119	6119	146	127

Table 11 (continued): Watershed physical and precipitation paramteres for the study area.

Name of watershed	CLRT	WSRL	MWSEL	WLRT	ESLF
Silvies River, OR	2	4368	6379	2	0
Strawberry Creek, OR	1	4128	6974	2	3
Lochsa River, ID	2	7194	5050	3	295
S.F. Clearwater River ID	2	7560	5080	2	130
N.F.Clearwater River, ID	1	6270	4795	1	647
Clearwater River, ID	2	7896	4939	3	1036
St. Joe River, ID	2	4666	4505	3	330
Couer d'Alene River near Prichard, ID	1	3475	4223	2	70
Couer d'Alene River at Enaville, ID	1	4600	4400	3	178
Couer d'Alene River at Cataldo, ID	1	4738	4469	2	264
Boise River, ID	1	7244	6878	2	215
Big Jack Creek, ID	1	3430	4525	2	0
Leonard Creek, NEV	1	5066	6864	2	1
Reese River, NEV	2	4685	9430	2	1
Little Currant Creek,NEV	1	4560	9039	1	0
East Fork Quinn River, NEV	2	3412	6431	2	0
Lamoille Creek, NEV	1	5086	8809	3	5
Blackwood Creek, CAL	1	2677	7540	2	2
Sagehen Creek, CAL	1	2435	7550	2	1
Buckeye Creek, CAL	1	4922	9384	3	14
Stehekin River, WA	1	7412	4805	1	312
Entiat River, WA	2	7688	5405	4	67
Crab Creek, WA	1	1475	2124	3	1
American River, WA	2	4813	5107	4	32
Mill Creek, WA	1	4074	4033	2	48
Umatilla River, OR	1	3595	3653	2	35
South Fork Walla Walla River, OR	2	3826	3963	4	81
Hurricane Creek, OR	2	5333	7167	3	24
Donner Und Blitzen River, OR	1	5208	6858	2	24
Bridge Creek, OR	2	3066	5718	4	9
Eagle Creek, OR	2	6249	5925	2	72
Cultus River, OR	1	1853	5377	3	37
Cultus Creek, OR	1	2348	5719	1	0
Odell Creek, OR	1	3611	6605	3	17
Fall River, OR	1	1994	5217	1	91
Deer Creek, OR	2	1599	5320	3	0

Table 11 (continued): Watershed physical and precipitation paramteres for the study area.

Name of watershed	FOR%	PANA	PANM	PWIA	PWIM
Silvies River, OR	84	13	7	7	2
Strawberry Creek, OR	99	17	12	9	4
Lochsa Rivser, ID	96	33	21	17	8
S.F. Clearwater River,ID	93	31	21	15	9
N.F.Clearwater River,ID	97	41	25	24	11
Clearwater River, ID	91	32	21	17	9
St. Joe River, ID	97	35	20	20	10
Couer d'Alene River near Prichard, ID	96	35	23	21	12
Couer d'Alene River at Enaville, ID	94	35	23	21	12
Couer d'Alene River at Cataldo, ID	92	35	23	21	12
Boise River, ID	65	20	9	13	3
Big Jack Creek, ID	3	8	3	4	1
Leonard Creek, NEV	8	9	5	5	2
Reese River, NEV	75	7	2	3	0
Little Currant Creek,NEV	63	7	2	3	0
East Fork Quin River,NEV	15	10	5	4	2
Lamoille Creek, NEV	55	19	11	8	5
Blackwood Creek, CAL	95	32	10	24	5
Sagehen Creek, CAL	96	22	10	16	6
Buckeye Creek, CAL	80	10	3	6	0
Stehekin River, WA	83	35	20	26	13
Entiat River, WA	91	26	16	20	10
Crab Creek, WA	3	9	5	5	2
American River, WA	91	48	27	35	17
Mill Creek, WA	87	41	31	25	15
Umatilla River, OR	98	28	19	17	8
South Fork Walla Walla River, OR	90	35	25	21	12
Hurricane Creek, OR	67	19	12	9	5
Donner Und Blitzen River, OR	21	12	7	6	2
Bridge Creek, OR	13	12	7	6	2
Eagle Creek, OR	93	22	10	14	10
Cultus River, OR	100	35	14	24	5
Cultus Creek, OR	95	35	14	24	5
Odell Creek, OR	87	48	18	34	8
Fall River, OR	96	21	10	14	3
Deer Creek, OR	98	35	14	24	5

Table 11 (continued): Watershed physical and precipitation paramteres for the study area

AREA=Watershed area, square miles
PERM=Watershed perimeter, miles
STRL=total perennial stream length, miles
LKA=Lake area, square miles
MNCL=Main channel length, miles
ISTO=Number of first order streams
SECO=Number of second order streams
THRO=Number of third order streams
FTHO=Number of fourth order streams
FFTO=Number of fifth order streams
SXTO=Number of sixth order streams
WSL=Watershed length, miles
WSW=Watershed average width, miles
GELE=Gage elevation, feet
EPEL=End point elevation, feet
MXEL=Watershed maximum elevation, feet
MWSL=Mean watershed slope, feet per mile
MCSL= Main channel slope, feet per mile
CLRT=Circulatory ratio
WSRL=Watershed relief, feet
MWSEL=Mean watershed elevation
WLRT=Watershed length and width ratio
ESLF=Extreme summer low flows, cfs
FOR%=Percent forest cover
PANA=Average annual precipitation, inches
PANM=Minimum annual precipitation, inches
PWIA=Average winter precipitation, inches
PWIM=Minimum winter precipitation, inches

Appendix 3

Table 12: Recession forecast model parameters for individual watersheds for four statrting dates of June 1, 15, 20 and 25. B0=regression intercept, B1=regression slope, Sey= standard error of y-estimate, Sex=standard error of coefficient

Name of watershed	B0	B1	R^2	Sey	Sex
Zone 1 (June 1)					
Big jack Creek, Idaho	0	0.975	0.988	0.000	0.004
Little Currant Creek, Nevada	0	0.973	0.998	0.013	0.003
Crab Creek. Washington	0	0.984	0.987	0.001	0.005
East Fork Quinn River,Nevada	0	0.960	0.999	0.002	0.002
Reese River, Nevada	0	0.964	0.999	0.007	0.002
Buckeye Creek, California	0	0.988	0.998	0.066	0.002
Zone 1 (June 15)					
Big jack Creek, Idaho	0	0.976	0.975	0.000	0.006
Little Currant Creek, Nevada	0	0.970	0.997	0.011	0.003
Crab Creek. Washington	0	0.981	0.999	0.000	0.001
East Fork Quinn River,Nevada	0	0.952	0.998	0.001	0.003
Reese River, Nevada	0	0.956	0.999	0.004	0.002
Buckeye Creek, California	0	0.983	0.998	0.059	0.002
Zone 1 (June 20)					
Big jack Creek, Idaho	0	0.979	0.962	0.000	0.006
Little Currant Creek, Nevada	0	0.966	0.995	0.011	0.004
Crab Creek. Washington	0	0.982	0.999	0.000	0.001
East Fork Quinn River,Nevada	0	0.955	0.997	0.001	0.003
Reese River, Nevada	0	0.961	0.998	0.004	0.003
Buckeye Creek, California	0	0.979	0.998	0.051	0.002
Zone 1 (June 25)					
Big jack Creek, Idaho	0	0.985	0.939	0.000	0.006
Little Currant Creek,Nevada	0	0.966	0.992	0.011	0.005
Crab Creek. Washington	0	0.984	0.999	0.000	0.001
East Fork Quinn River,Nevada	0	0.958	0.996	0.001	0.004
Reese River, Nevada	0	0.958	0.996	0.001	0.004
Buckeye Creek, California	0	0.977	0.998	0.046	0.002
Zone 2 (June 1)					
Silvies River, Oregon	0	0.958	0.999	0.001	0.001
Donner Und Blitzen River	0	0.975	0.998	0.021	0.003
Lamoille Creek, Nevada	0	0.986	0.999	0.133	0.002
Boise River, Idaho	0	0.981	0.999	0.039	0.002
Strawberry Creek, Oregon	0	0.984	0.999	0.082	0.002
Bridge Creek, Oregon	0	0.995	0.961	0.010	0.002
Zone 2 (June 15)					
Silvies River, Oregon	0	0.957	0.999	0.001	0.001
Donner Und Blitzen River	0	0.971	0.999	0.010	0.002
Lamoille Creek, Nevada	0	0.975	0.999	0.103	0.003

Table 12 (continued): Recession forecast model parameters for individual watersheds for four statrting dates of June 1, 15, 20 and 25. B0=regression intercept, B1=regression slope, Sey= standard error of y-estimate, Sex=standard error of coefficient

Name of watershed	B0	B1	R^2	Sey	Sex
Boise River, Idaho	0	0.970	0.999	0.023	0.001
Strawberry Creek, Oregon	0	0.972	0.999	0.052	0.002
Bridge Creek, Oregon	0	0.998	0.867	0.006	0.001
Zone 2 (June 20)					
Silvies River, Oregon	0	0.961	0.999	0.001	0.002
Donner Und Blitzen River	0	0.968	0.999	0.008	0.002
Lamoille Creek, Nevada	0	0.967	0.999	0.090	0.003
Boise River, Idaho	0	0.965	0.999	0.018	0.001
Strawberry Creek, Oregon	0	0.967	0.999	0.038	0.001
Bridge Creek, Oregon	0	0.999	0.798	0.005	0.001
Zone 2 (June 25)					
Silvies River, Oregon	0	0.961	0.999	0.001	0.002
Donner Und Blitzen River	0	0.969	0.999	0.008	0.002
Lamoille Creek, Nevada	0	0.960	0.999	0.080	0.003
Boise River, Idaho	0	0.963	0.999	0.016	0.001
Strawberry Creek, Oregon	0	0.963	0.999	0.025	0.001
Bridge Creek, Oregon	0	0.999	0.768	0.003	0.001
Zone 3 (June 1)					
Umatilla River, Oregon	0	0.973	0.993	0.042	0.004
Entiat River, Washington	0	0.985	0.998	0.120	0.003
Eagle Creek, Oregon	0	0.983	0.999	0.089	0.002
Fall River, Oregon	0	0.999	0.998	0.002	0.000
Zone 3 (June 15)					
Umatilla River, Oregon	0	0.971	0.995	0.018	0.003
Entiat River, Washington	0	0.974	0.999	0.072	0.002
Eagle Creek, Oregon	0	0.973	0.999	0.060	0.002
Fall River, Oregon	0	0.999	0.998	0.002	0.000
Zone 3 (June 20)					
Umatilla River, Oregon	0	0.977	0.992	0.017	0.003
Entiat River, Washington	0	0.966	0.999	0.046	0.002
Eagle Creek, Oregon	0	0.966	0.999	0.046	0.002
Fall River, Oregon	0	0.999	0.998	0.002	0.000
Zone 3 (June 25)					
Umatilla River, Oregon	0	0.982	0.989	0.015	0.003
Entiat River, Washington	0	0.967	0.999	0.040	0.002
Eagle Creek, Oregon	0	0.963	0.999	0.043	0.002
Fall River, Oregon	0	0.999	0.998	0.003	0.000
Zone 4 (June 1)					
Cultus Creek, Oregon	0	0.981	0.999	0.019	0.001
Deer Creek, Oregon	0	0.957	0.999	0.007	0.002
South Fork Clearwater, Idaho	0	0.977	0.999	0.030	0.002
Blackwood Creek, California	0	0.974	0.998	0.161	0.003
Clearwater River, Idaho	0	0.976	0.999	0.052	0.002
Coeur d'Alene River at					

Table 12 (continued): Recession forecast model parameters for individual watersheds for four statrting dates of June 1, 15, 20 and 25. B0=regression intercept, B1=regression slope, Sey= standard error of y-estimate, Sex=standard error of coefficient

Name of watershed	B0	B1	R^2	Sey	Sex
Enaville, Idaho	0	0.966	0.999	0.018	0.001
Coeu d'Alene River near Prichard, Idaho	0	0.961	0.999	0.023	0.002
Lochsa River, Idaho	0	0.974	0.999	0.070	0.002
St. Joe River, Idaho	0	0.970	0.999	0.035	0.001
Stehekin River, Washington	0	0.988	0.998	0.202	0.002
South Fork Walla Walla River, Oregon	0	0.989	0.997	0.034	0.001
Cultus River, Oregon	0	0.999	0.995	0.012	0.000
<u>Zone 4 (June 15)</u>					
Cultus Creek, Oregon	0	0.968	0.999	0.008	0.001
Deer Creek, Oregon	0	0.935	0.999	0.001	0.001
South Fork Clearwater, Idaho	0	0.964	0.999	0.020	0.002
Blackwood Creek, California	0	0.960	0.997	0.139	0.004
Clearwater River, Idaho	0	0.960	0.999	0.030	0.002
Coeur d'Alene River at Enaville, Idaho	0	0.967	0.999	0.012	0.001
Coeu d'Alene River near Prichard, Idaho	0	0.966	0.999	0.014	0.002
Lochsa River, Idaho	0	0.958	0.999	0.037	0.001
St. Joe River, Idaho	0	0.961	0.999	0.017	0.001
Stehekin River, Washington	0	0.981	0.999	0.138	0.002
South Fork Walla Walla River, Oregon	0	0.991	0.996	0.023	0.001
Cultus River, Oregon	0	0.999	0.996	0.011	0.000
<u>Zone 4 (June 20)</u>					
Cultus Creek, Oregon	0	0.964	0.999	0.006	0.001
Deer Creek, Oregon	0	0.932	0.999	0.001	0.001
South Fork Clearwater, Idaho	0	0.959	0.998	0.018	0.003
Blackwood Creek, California	0	0.953	0.996	0.129	0.004
Clearwater River, Idaho	0	0.952	0.999	0.022	0.002
Coeur d'Alene River at Enaville, Idaho	0	0.968	0.999	0.011	0.001
Coeu d'Alene River near Prichard, Idaho	0	0.970	0.998	0.012	0.002
Lochsa River, Idaho	0	0.952	0.999	0.025	0.001
St. Joe River, Idaho	0	0.961	0.999	0.016	0.961
Stehekin River, Washington	0	0.980	0.999	0.127	0.002
South Fork Walla Walla River, Oregon	0	0.993	0.995	0.020	0.001
Cultus River, Oregon	0	0.999	0.996	0.011	0.000
<u>Zone 4 (June 25)</u>					
Cultus Creek, Oregon	0	0.960	0.999	0.005	0.001
Deer Creek, Oregon	0	0.928	0.999	0.001	0.001

Table 12 (continued): Recession forecast model parameters for individual watersheds for four statrting dates of June 1, 15, 20 and 25. B0=regression intercept, B1=regression slope, Sey= standard error of y-estimate, Sex=standard error of coefficient

Name of watershed	B0	B1	R^2	Sey	Sex
South Fork Clearwater, Idaho	0	0.960	0.998	0.017	0.003
Blackwood Creek, California	0	0.952	0.994	0.131	0.006
Clearwater River, Idaho	0	0.950	0.999	0.020	0.002
Coeur d'Alene River at Enaville, Idaho	0	0.971	0.999	0.010	0.002
Coeu d'Alene River near Prichard, Idaho	0	0.973	0.998	0.012	0.002
Lochsa River, Idaho	0	0.951	0.999	0.023	0.001
St. Joe River, Idaho	0	0.964	0.999	0.015	0.001
Stehekin River, Washington	0	0.982	0.999	0.112	0.002
South Fork Walla Walla River, Oregon	0	0.994	0.993	0.017	0.001
Cultus River, Oregon	0	0.999	0.996	0.011	0.000
Zone 5 (June 1)					
American River, Washington	0	0.999	0.983	0.103	0.002
Odell Creek, Oregon	0	0.990	0.999	0.030	0.001
Mill Creek, Washington	0	0.986	0.987	0.039	0.004
Zone 5 (June 15)					
American River, Washington	0	0.974	0.999	0.062	0.002
Odell Creek, Oregon	0	0.984	0.999	0.020	0.001
Mill Creek, Washington	0	0.986	0.989	0.019	0.003
Zone 5 (June 20)					
American River, Washington	0	0.967	0.999	0.042	0.001
Odell Creek Oregon	0	0.983	0.999	0.020	0.001
Mill Creek, Washington	0	0.989	0.982	0.018	0.003
Zone 5 (June25)					
American River, Washington	0	0.970	0.999	0.038	0.001
Odell Creek, Oregon	0	0.983	0.999	0.018	0.001
Mill Creek, Washington	0	0.992	0.974	0.018	0.003

Appendix 4

Table 13: Watershed cover type information for the watersheds in Oregon for the periods of 1973 and 1990 (areas in square miles)

1990

Name of watershed	Group1	Group2	Group3	Group4	Group5
Strawberry Creek	6.95	0.00	0.05	0.00	0.00
Eagle Creek	145.0	7.54	0.00	0.38	3.09
Hurricane Creek	19.79	9.57	0.00	0.00	0.25
Umatilla River	127.8	50.00	0.00	0.00	3.15
South Fork Walla Walla River	56.85	0.00	0.00	2.76	3.39
Cultus River	16.50	0.00	0.00	0.00	0.00
Cultus Creek	31.60	0.00	1.60	0.00	0.00
Fall River	43.49	0.00	0.00	0.00	1.61
Deer Creek	21.14	0.00	0.36	0.00	0.00
Brown Creek	17.66	0.00	0.00	0.00	3.34
Odell Creek	33.98	0.00	5.02	0.00	0.00
Silvies River	780.06	2.40	44.23	84.90	22.36
Donner Und Blitzen River	41.20	8.75	0.00	150.05	0.00
Bridge Creek	3.91	2.55	0.00	23.24	0.00

1973

Name of watershed	Group1	Group2	Group3	Group4	Group5
Strawberry Creek	6.97	0.00	0.03	0.00	0.00
Eagle Creek	144.80	7.19	0.44	3.57	0.00
Hurricane Creek	21.70	7.77	0.03	0.00	0.10
Umatilla River	105.62	0.00	0.00	25.20	0.18
South Fork Walla Walla River	56.28	0.00	0.00	6.59	0.13
Fall River	44.52	0.00	0.00	0.00	0.58
Deer Creek	20.67	0.00	0.83	0.00	0.00
Brown Creek	20.96	0.00	0.02	0.00	0.01
Odell Creek	32.05	0.00	6.40	0.00	0.54
Silvies River	732.85	16.91	18.58	153.54	12.12
Donner Und Blitzen River	23.36	0.00	0.07	176.52	0.06
Bridge Creek	3.94	0.00	0.00	25.76	0.00

Appendix 5

The extreme summer low-flow prediction model using the properly transformed variables is given below:

$$SQRT(Q)_{eslf}=24.83+3.63*SQRT(P)+4.66*Log(WSW)+0.001178*(EPE)$$

where,

Q_{eslf}=Extreme summer low-flow, cfs

P = Annual minimum precipitation, inches

EPE= Watershed end point elevation (longitudinal), feet

WSW= Average watershed width, miles

Regression coefficients are highly significant. F-staistics for the model is 31.12, R^2=75.1%, Adjusted R^2=72.7 and standard error is 3.42.