Characteristics Of Stream Low Flows In Eastern Oregon: Their Relationship With Precipitation And Watershed Parameters

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Characteristics of low flows of nine streams in eastern Oregon were explored using long-term streamflow records. Year-to-year dependence of low flows is highly significant for streams in the Blue Mountain and the southeastern Oregon regions. Low streamflows increased over the period of record for seven of the selected streams. Flow duration curves, flow-date curves and low flow frequency curves were constructed for each stream. Flow per unit area is higher for streams in northeastern Oregon than streams in southeastern Oregon. Forecast equations for streamflow recessions were made for each stream. Forecasts are highly accurate for recession volume and August average flow except for Mill creek and Bridge Creek. Forecasts are poor for the later part of the water year. Even for the later part of the water year, highly accurate results are obtained when forecasts are made for shorter periods (about 40 days). Annual precipitation is fairly well-distributed over the whole year in eastern Oregon with July and August as the driest months. Streams in the Wallowa Mountain and southeastern Oregon regions showed higher trend similarities between summer low flows and precipitation than streams in the Blue Mountain region. Correlations between summer low flows and precipitation were highly significant for the Wallowa Mountain and the southeastern Oregon regions. Correlations

between low flows and watershed parameters, as well as average annual precipitation, were found insignificant for all streams.

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INTRODUCTION

Much of eastern Oregon is typical of semi arid, problematic 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, for 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. Although water quality is the major water management problem, quantity and timing of streamflow are also important and are interrelated with watershed values that should be considered in land use planning (Douglass, 1974).

Hydrological information regarding low streamflows and their relationship with rainfall patterns in eastern Oregon is incomplete. Guidelines for proper land-use policies and practices require a better understanding of climate and streamflow trends. Stream low flow characteristics are highly dependent upon watershed topography, the extent of potential aquifers, climate 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).

Beyond its importance to health and food needs and general survival of the present generation, water also decides much of the future that lies ahead for the next generation. The reason for this is simple: water is a natural resource and an element of the natural environment upon which the economic, social, technological and biological processes are closely related and dependent (Lesaca, 1983). Of particular importance is an assessment of water resources during periods of low flow. In recent years population growth and increasing environmental awareness have stimulated interest in low flow characteristics. Low flows are also significant where reservoir or other storage is limited or absent. An example of the need for low flow data is water resources' information required for the design of waste-treatment plants and planning for the extreme low flow periods which may occur during a drought. A 7-day 10-year low flow ($7Q_{10}$) event is important as the basis for designing most waste-treatment plants.

An ever-increasing demand for fresh water stresses the need for study of streamflow particularly during drought periods. We need a better understanding of streamflow dynamics if we are to more effectively manage our water resources. Surface water forms a major part of our fresh water resource which is important to our needs during water scarce periods. These needs include irrigation, recreation, navigation, municipal and industrial water supply. Qualitatively, low streamflow is important for ecosystem for fish habitat, chemistry and biology in the water courses, etc.

Factors affecting low flows include geometry of the watershed, hydraulics of sub-surface water, vegetation, climate, etc. 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 without rain. Low streamflow periods during the summer season are common.

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).

This study was conducted in order to gain a better understanding of the hydrological characteristics of streamflow in eastern Oregon to help predict seasonal-low streamflow quantities. Equations and graphs are derived to estimate low flows for the study watersheds and similar catchments.

OBJECTIVES

The main objectives of this study were to provide a quantitative overview of streamflow during the summer low and base flow periods, and relate streamflow to annual precipitation in eastern Oregon.

Specific objectives include:

1) identification of low flow characteristics for each selected stream in three regions of eastern Oregon,

2) develop a summer low and base flow forecasting procedure for each gaged watershed and evaluate the procedure,

3) identification of trends and patterns of summer low and base flows in eastern Oregon,

4) identification of trends and patterns of annual precipitation in eastern Oregon,

5) identification of similarities between stream low flow and precipitation trends and

6) determination of relationships between low flows and physical parameters of the watershed.

STUDY AREA

The study area includes portions of northeastern and southeastern Oregon (Fig. 1). Information regarding low flows is not available for all streams in eastern Oregon. Most streams are ungaged, or if they are gaged, flow often is being diverted and regulated upstream from the gaging station. The earliest data available for eastern Oregon is about 1920. The East Fork Wallowa River near Joseph, OR, Hurricane Creek near Joseph, OR, and Bear Creek near Wallowa, OR, are located in the Wallowa Mountain region. Mill Creek near Walla Walla, WA, the South Fork Walla Walla River near Milton, OR, and the Umatilla River near Gibbon, OR, are located in the Blue Mountain region. The Silvies River near Burns, OR, Bridge Creek near Frenchglen, OR, and the Donner Und Blitzen River near Frenchglen, OR, are located in the southeastern Oregon. Areas of both the Blue and Wallowa Mountain ranges consist of irregular ridges, with small sub-ranges.

GEOLOGY OF NORTHEASTERN OREGON

The Blue and Wallowa mountains consist of younger Cenozoic basalt and andesite flows (Baldwin, 1981) with few outcrops of sedimentary rocks. Wallowa batholiths, contrasting with the region, are composed of granitic and strongly metamorphosed sedimentary rocks and volcanics of Mesozoic age. The topography of these mountains varies widely from plateaus to steep rugged terrain. The Blue Mountains have elevations above 8,000 feet. The Wallowa Mountains have elevations of up to 10,000 feet and the most spectacular scenery in the Pacific Northwest, east of Cascades (Johnson and Dart, 1982).

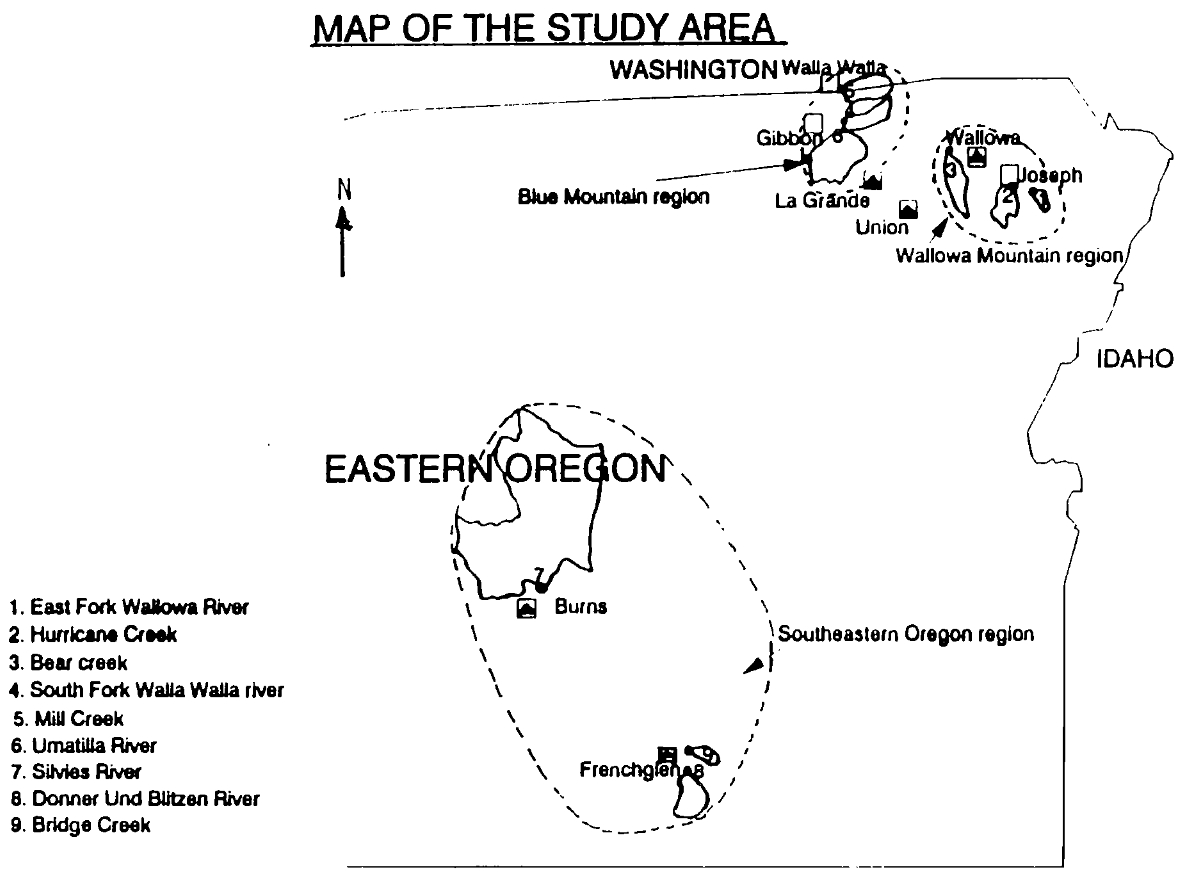

Figure 1. Map of the study area (not drawn to the scale).

Soils of the area are derived from recent volcanic ash (less than 6700 years old) deposited over an older residual soil developed from underlying basalt rock. Both the upper and lower soil horizons are silt loams but with different physical properties. Soils are generally well drained and are up to 1.5 m deep. The hydrology of the area is dominated by snow. Peak runoff from these mountains occurs in May and June because of snowmelt and accounts for about 80% of total annual flow (Fowler et al. 1987). The forest lands in eastern Oregon are under multiple-use management for water, timber, forage, recreation, fish and wildlife.

VEGETATION OF NORTHEASTERN OREGON

Vegetation composition varies with elevation in northeastern Oregon, largely in response to precipitation and temperature. Big sagebrush (*Artemisia tridentata*) occupies the lowest elevations where precipitation generally is lowest. As the elevation and precipitation increases, the vegetation changes to ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*) and Douglas-fir (*Pseudotsuga mensiesii*) and western larch (*Larix occidentalis*). Subalpine fir (*Abies lasiocarpa*), grand fir (*Abies grandis*) and Engelmann spruce (*Picea engelmannii*, occupy higher elevations (Fowler, et al., 1979; Franklin and Dyrness, 1969).

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 causes precipitation. Average annual precipitation is 15.2 inches at the lower elevations and over 55.2 inches at higher elevations. In one area of northeastern Oregon, approximately 80 percent of the total annual precipitation falls between October, 1 and May 31 (Helvey and Tiedemann, 1978).

GEOLOGY OF SOUTHEASTERN OREGON

Southeastern Oregon's highest mountain, Steens Mountain, is a fault block. Fifteen million years ago, layers of basalt gave way under massive pressure caused by the earth's cooling and contracting. Tilting of the fault rock resulted in a rugged east face. This east face climbs one vertical mile from the Alvord desert floor to an elevation of 9733 feet and slopes gently to the valley floor on the west. The lava layers that cap the Steens Mountains are several thousand feet thick and the individual flows are layers 10 to 200 feet thick. About fifteen million years ago, lava erupted from cracks in the ground and spread rapidly across a level plain. Several million years later, the Steens Mountain fault began to lift along a fault below the east rim and along the edge of Catlow valley on the West. The uplift was faster at the east rim, tilting the mountain so that a once level lava flow now forms the gentle slope to the west (BLM, Burns District Office, 1991). Steen Mountains' topography was modified by glaciation that took place 10,000 to 14,000 years ago. Melting of glaciers cut deeply into the basalt, making blocks and canyons at high elevations, called divine canyons. Streams flow within these canyons (personal communication with Geologist, BLM Burns District Office).

Volcanic eruption is the major source of formation of the landscape of the Silvies's catchment. The source of this eruption was at Harney Lake. Most of these flows were tilting toward the basin. The catchments comprised of younger formations which have not been heavily eroded.

Paleo-valleys, about six million years old, were formed by thick layers of welded ash flow. They cooled from top to bottom. The entrapped gas escaped during the process of solidification. Basalt holds more water and is more erodible than welded ash. Ash flow tuff is quite resistant to dissection. There is no evidence of glaciation within the Silvies River drainage basin (Personal communication with Geologist, BLM, Burns District Office, Burns).

VEGETATION OF SOUTHEASTERN OREGON

There are five vegetative zones ranging from Tall Sage to Alpine Tundra on Steens Mountain. Vegetation in the Silvies River includes sagebrush (<u>Artemisia tridentata</u>) and juniper (<u>juniperus</u> <u>macropoda</u>) at lower elevations, changing to ponderosa pine (<u>Pinus</u> <u>ponderosa</u>), lodgepole pine (<u>Pinus</u> <u>contorta</u>), Douglas-fir (<u>Pseudotsuga mensiesii</u>), western larch (<u>Larix</u> <u>occidentalis</u>) etc. as the elevation increases (Franklin and Dyrness, 1969).

PRECIPITATION STATIONS

Precipitation at the following stations was selected for trends analysis (data was obtained from the office of the state climatologist, Corvallis, OR):

Station	Elevation(ft)	Period
1. Union exp. station, OR	2770	1911-1990
2. Wallowa, OR	2920	1903-1988
3. La Grande, OR	2830	1900-1990
4. Burns, OR	4150	1938-1990
5. P-ranch Refuge near Frenchglen, OR	4200	1942-1990

STREAMS IN THE WALLOWA MOUNTAIN REGION

EAST FORK WALLOWA RIVER

The East Fork of the Wallowa River basin is a glaciated valley with steep slopes. The stream channel is the steepest of all the nine streams included in this study. There is much talus on the steep slopes adjacent to the river. The southwest facing slope of the catchment is less vegetated, as compared to the northeast facing slope, probably due to differences in evapotranspiration demands. The channel has large amounts of woody debris, however, due to the high gradient of the stream, debris jams rarely form. Water in the river is less turbid in early summer than in Bear Creek and streams in the southeastern Oregon region. The catchment is densely covered with pine forests. Due to the steepness and narrowness of the catchment and channel, contribution of subsurface water to summer low and base flow is minimal.

HURRICANE CREEK

Hurricane Creek is small compared to Bear Creek but bigger than the East Fork Wallowa River. The basin, densely forested with old growth forests, has less turbid water than Bear Creek in early summer. Woody debris loading appears to be smaller. The catchment is long and narrow, with many glaciers. Its topography is gentler than the East Fork Wallowa River. A fairly extensive floodplain along the stream is expected to store water and contribute to the summer low and base flows with slow release.

BEAR CREEK

At and above the gaging station, there are extensive flood plains next to the channel. It is a large stream,

Table 1. LOCATION OF STREAMS

Name of stream	Long-(Township) Latit(Township)	Area sq.mi	Gage location long/lat	Hydrologic unit/ (period)
East Fork Wallowa River near Joseph, OR	1171000-1171800 (R44E-R45E) 450800-452000 (T21N-T23N)	10.3	451620 1171235	17060105 (1925-1983)
Hurricane Creek near Joseph, OR	1171500-1172000 (R44E) 451000-452000 (T22N-T23N)	29.6	1171730/ 452015	17060105 (1924-1978)
Bear Creek near Wallowa, OR	1172600-1173300 (R42E-R43E) 451500-453200 (T3S-T1S)	68	1173305/ 452015	17060105 (1924-1985)
South Fork Walla Walla River near Milton, OR	1181200-1175700 (R37E-R39E) 454600-455600 (T4N-T5N)	63 (1931-1986)	1181008/ 454948	17070102
Mill Creek near Walla Walla, WA	1181000-1175500 (R37E-R39E) 455600-460300 (T5N-T6N)	59.6	46 00 29 1180703	17070102 (1940-1988)
Umatilla River near Gibbon, OR	1181800-1180000 (R36E-R38E) 453400-454600 (T1N-T3N)	131	1161920/ 454311	17070103 (1933-1987)
Silvies River near Burns, OR	1183730-1191500 (R29E-R31E) 434000-442000 (T21S-T14S)	934	1191035/ 434255	17120002 (1917-1984)
Donner und Blitzen River near Frenchglen, OR	1185400 - 1183500 (R31E-R33E) 423000-424800 (T35S-T32S)	200	1185200/ 424728	17120003 (1938-1986)
Bridge Creek near Frenchglen, OR	1185057-1183600 (R31E-R33E) 424600-425200 (T31S-T32S)	30	1185057/ 425038	17120003 (1938-1971)

Long= Longitude, Latit= Latitude

approximately 20 miles in length. The stream banks are covered by willow, aspen, lodgepole pine, larch, Douglas -fir and true fir along with open meadows. The water in the stream is more turbid than Hurricane Creek and the East Fork Wallowa River in early summer. The floodplain averages about 500-600 feet wide along the creek, with decreasing width upstream. In the lower stream channel there is a large amount of woody debris. The upper end is relatively free of woody debris (field observation).

STREAMS IN THE BLUE MOUNTAIN REGION

SOUTH FORK WALLA WALLA RIVER

The upper portion of the basin is very steep with exposed mineral soil and little vegetation. The top of its catchment near Tollgate, OR, has scattered patches of grasses and vegetation along the depressions. Near the gaging station and upstream, river banks are well covered with conifer and deciduous vegetation. Less than one half of the catchment is vegetated. Narrow floodplains along the river, combined with bare and steep terrain over half of the watershed are not expected to contribute significantly to sustained low flows. However, water in the river was not very turbid during mid June.

MILL CREEK

Mill Creek basin is protected from all kinds of management, as it supplies the drinking water for the town of Walla Walla, WA. Extensive areas of forest are insect damaged and dying. North facing slopes are densely forested with old-growth pine. South facing slopes are less steep than north facing slopes and are similar to upper portion of catchment of the South Fork Walla Walla River. Overall, about two thirds of the catchment is vegetated. Near the stream gage and upstream, the banks are densely vegetated.

UMATILLA RIVER

The Umatilla River was flowing at a high discharge level in the third week of June and water was not very turbid. The banks and adjoining slopes are heavily covered with the vegetation through most of the visited length of the river catchment. Floodplains are medium in size and not as extensive as along the Bear Creek near Wallowa. The upper portion of the catchment has patchy vegetation. Like the catchment of Mill Creek and the South Fork Walla Walla River, south facing slopes are sparsely vegetated, with vegetation concentrated in the depressions. Above the confluence of the north and the south forks of the river, density of vegetation in the catchment is quite high. Potential for storage of groundwater for sustained summer low and base flows seems moderate.

Throughout this Blue Mountain region, south facing slopes have scattered vegetation. This may be due to greater evapotranspiration on southern slopes during the growing period, particularly during summer.

STREAMS IN THE SOUTHEASTERN OREGON REGION

SILVIES RIVER

The Silvies River above the stream gage flows in a natural canyon. The stream is lined with willow, chokecherries, currants, clematis, sagebrush and wild rose bushes. The stream meanders. There are diversions from the river in three areas onto narrow meadows between Silvies valley and the gage. The water all returns to the stream. More than one half the flow at the gage enters the Silvies River from Emigrant Creek about ten miles above the gage (personal communication with Bill Beal, 1991). The lower portion of the basin is covered with sagebrush and juniper trees. About ten miles above the gaging station is the transition from juniper to ponderosa pine forest. Sagebrush continues, along with other brushes. Fire hazard is common in Silvies's catchment. The lower area near the origin of Cricket Creek is a mosaic of brushes and grass lands. Near the junction of Emigrant and Sawtoothed Creek, vegetation changes markedly from a mixture of ponderosa pine and juniper to a mixture of ponderosa pine, lodgepole pine and choke cherry.

There are many small creeks and springs originating from the meadows and small valleys. Recutting and deepening of the creek beds and small slides were seen in many places. The flow in most of these creeks is small and lower in turbidity than the Silvies River.

The Silvies River near the junction of Myrtle Creek flows with medium discharge levels during summer. On the west side of Highway 395, it has extended flood plains, and meadows covered with grasses and sagebrush. There are numerous small and medium sized valleys in the Silvies' catchment which are expected to have a potential source of sustained summer low and base flows.

DONNER UND BLITZEN RIVER

Most of the lower reach of the Donner und Blitzen River is lined with willows. Vegetation in the lower portion of the watershed is mostly scattered juniper and sagebrush. The major portion of the river flows within a narrow canyon. Outside this canyon there are extensive elevated valleys that can serve as aquifers. Above the gaging station there are fairly wide flood plains, narrowing in the upstream direction. Flood plains are covered with grasses and shrubs. In places, the flood plain is 150 to 200 feet wide. The watershed is mostly comprised of undulating topography with gradually increasing elevation reaching to the high Steens Mountains. The upper catchment of the river is comprised of various extensive flat valleys, grazing lands and meadows. Sagebrush is the dominant vegetation in these valleys. Along the river, the density of juniper trees is greater than the rest of the watershed. These extensive valleys and meadows represent potential storage for subsurface water and are expected to help maintain a higher summer low and base flow.

BRIDGE CREEK

The watershed of Bridge Creek is mostly covered with grasses and shrubs. The upper portion of the catchment supports trees. Along the lower portion of the Bridge Creek, willows line the stream. Juniper/sagebrush is the dominant plant association.

LITERATURE REVIEW

VEGETATION AND STREAMFLOW

WATER YIELD

The fact that removal of forest vegetation increases streamflow has been known since the early 1900's. Research conducted so far has verified this fact. Nearly every study in forest zones has shown an increase in streamflow following forest cutting or a gradual decrease in streamflow as forest regrowth proceeds (Baker, 1986; Hibbert, 1967). In well watered regions, streamflow response is proportional to the reduction in forest cover. The magnitude of increase or decrease depends on climate, topography, vegetation, soils and other environmental factors (Gentry and Parodi, 1980 ; Hibbert, 1967).

In Canada, water yield increased after clear-cut logging over 30% area of a 21.2 mi^2 watershed compared with a control watershed (Cheng, 1989). Hornbeck et al. (1970) also reported an increase in water yield after clear-cutting in New England, where most of the increase occurred during critical low flow months of June through September.

Swank, et al. (1988) studied the long term streamflow records for control and experimental forested watershed 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 demands were usually high. Regrowth of hardwoods brought the streamflow back to pre-harvest levels over the next several years after harvest. Long term experiments showed the striking dependence of streamflow on the type of vegetative cover. Within 25 years, conversion of hardwood to white pine resulted in reduced annual flow by 10 inches, and produced significant reduction in every month of the year (evapotranspiration by hardwoods is less than by pines due to lower leaf area). Conversion from hardwood to grass may also alter streamflow, 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, streamflow increased.

The type and density of vegetative cover affect the percentage of rainfall available as runoff (Bosch et al. 1981; Debussche et al., 1987; Abbas et al., 1987). Forest vegetation is considered to be an efficient regulator of runoff. It increases infiltration, 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 the watershed. A decrease in vegetative cover usually increases water yield. 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. However, they did not try to separate the effects of reduced evapotranspiration and physical basin changes on water yield. Davis (1984) found that conversion of an Arizona chaparral watershed (on gravelly sandy loam derived from granitic material) to grass increased water yield.

Rakhmanov and Opritova (1984) studied the relationship between annual streamflow and forest cover for 72 rivers for the period 1967-76 in Maritime Province of the Soviet far east, which has a monsoon-type climate. They found that annual streamflow increased by 1.67 mm as forest cover increased by one percent. However, the exclusion of ground vegetation and grass cover from such studies may lead to erroneous results and reduces the usefulness of such findings.

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 1977 drought year 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).

In western Oregon after harvesting, although the greatest absolute increases were found during the fall-winter rainy season, the largest relative increases (100-300% of predicted flows) were noticed during the summer (Rothacher, 1970; Harr et al., 1979). Where they have been detected, the relatively large summer increases have tended to diminish quickly as riparian vegetation reestablished (Hicks et al., 1991). In one watershed, measured flows after logging were slightly less than predicted by the prelogging flow relationship (i.e., decreased flow after logging), most likely because of greater consumption of water by newly established phreatophytic riparian vegetation and because of decrease in fog drip in the clear-cut areas (Harr, 1979).

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. They recorded 21% increase in water outflow in the clear-cut plot than in the forested plot during the largest rain-on-snow event of the study. In the snow zone, evapotranspiration is reduced by timber harvesting, resulting in reduced soil moisture depletion during the growing season (with far less deficit than before harvesting). Due to lower deficits, water yield is increased during the spring snow-melt period.

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).

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 United States have been recorded in the Cascade range of Oregon. A 237-acre watershed in the H.J. Andrews Experimental forest was completely clear-cut; 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 streamflow of 57 inches) increased water yield by 6 inches.

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-Dougalas-fir dominant basins than from the watersheds comprised of fir-spruce, lodgepole pine, ponderosa pine and mountain meadow, though receiving same amount of precipitation (Higgins et al., 1989). In general, annual water yields are found to vary roughly proportional to the amount of vegetation removed.

LOW FLOWS

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 streamflow 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.

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, water yield and low flows measured in the subsequent years were higher than before harvesting, although vegetation was still not established.

In areas where precipitation falls primarily as rain, research has shown that removing vegetation can increase late summer streamflow. However, timing is largely dependent on the distribution of precipitation. In Pennsylvania, where the 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 streamflow 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).

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 flows for streams in the Blue Mountains occurred from July to February with 86 percent of low flow events occurred in the months of August (18%), September (37%), and October (31%), covering a range of 0.002-0.323 cfsm.

The source of streamflow 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 to a few 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.

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

AFFECTS OF FIRE AND DISEASES ON STREAMFLOW

Along with management activities, natural calamities such as disease and fire also affect streamflow. Abe and Tani (1985) compared the streamflow and annual water budgets from 1971 to 1982 in paired catchments on the Tatsunokuchiyama experimental forest, in Japan. It is an area of clay loam soil with annual precipitation of about 49 inches and annual mean temperature of 14.3 °C. After the killing of vegetation in the Minamitani catchment (56 acres with 69% cover of 20-year-old Pinus thunbergii) by Bursaphelenchus xylophilus, there was an increase of about 4.4 inches in annual water yield, with base flows (portion of the precipitation that seeps downward into the ground-water aquifer and maintains streamflow during periods of no rain) increasing by 50% in winter and 100% in summer (annual avg.= 70%). The increased flows were attributed to reduced evapotranspiration after pine death.

Doty (1983) analyzed streamflow, water quality and precipitation data for Ohia (Metrosideros polymorpha) forest over Hilo watershed in Hawaii from 1929 to 1980. The catchment underwent a severe loss of the overstory crown component of the vegetation due to dieback of the Ohia forest. Doty was interested to find if the loss of a major portion of the overstory vegetation had any affect on the hydrology of the watershed. He concluded that neither annual streamflows nor peak flows were affected. Increased growth of the understory vegetation and decreased fog-drip were suspected as offsetting the effects of reduced evapotranspiration on streamflow.

A bushfire in the Snowy Mountains region of southeastern New South Wales, Australia, resulted in an increase in runoff for about 4 to 5 years after which watersheds recovered to the conditions prevailing before the fire (Brown, J. A. H., 1972).

In addition to other factors, geology also plays an important role in deciding streamflow patterns, particularly base flows. Reeve and Jones (1984) studied the relationship between salinity and geology in six creeks in southeast Queensland, Australia. They found that those streams that were draining out of rocks which had a greater storage capacity maintained higher base flow.

Much of eastern Oregon 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 streamflow characteristics.

Kauffman, et al. (1983) found significantly greater stream bank erosion and disturbance occurred due to livestock grazing, compared to 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. In eastern Oregon, recovered riparian vegetation and aggrading stream channels appear to improve summer flows (Elmore and Beschta, 1987). No measurements of streamflows were made. Their conclusion is based on field observations and photographs taken before and after treatments. However, it is doubtful that contribution from such a small area (channel bed) could result into 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 removal of juniper trees over the catchment area which are high consumers of water.

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 AND STREAMFLOW

Both rainfall and streamflow 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 gage (Higgins, 1981). In some cases, precipitation may only be measured at a location outside a watershed.

Most often, the explanation for the increase or decrease in streamflow 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 streamflow. Bradley et al. (1987) discovered a significant increase in precipitation over

33mid-latitudes and a concurrent decrease in precipitation over low-latitudes over the last 30-40 years in the northern hemisphere.

Troendle and King (1985) found a strong correlation between estimated increases in flow 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.

Generally, rainfall depth increases with elevation. However, Farmer and Fletcher (1971), while working in central and northcentral Utah, found that the zone that received the greatest depth was not the highest elevation zone.

PRECIPITATION TRENDS

In general, precipitation increases with elevation in northeastern Oregon. Maximum precipitation occurs in May throughout much of the region, except at Wallowa, where November is the wettest month. July is the driest and most variable month at most of the northeastern Oregon stations. Generalization regarding precipitation patterns in eastern Oregon are difficult due to the large spatial variability that exists.

The drought of the 1930's, which was longer in duration than any other in eastern Oregon, was the prominent feature of climate. In most of eastern Oregon, a prevailing downward precipitation trend occurred from the 1890's to about 1930's, and a recovery occurred from 1930's to the early 1970's. For most of the stations, a major part of the recovery occurred in 1930's and 1940's. After that there was no clear trend upward or downward, although interannual fluctuations about the mean have been large (Johnson and Dart, 1982).

DENDROCLIMATOLOGY

Ring widths of trees are sensitive indicators of precipitation variations and can be used to qualitatively construct regional indices of annual precipitation (Graumlich, 1985). 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 streamflows, and annual precipitation. Tree ring chronologies can be used as proxy hydrological records (Cleaveland and Stahle, 1989). For White River, Arkansas, reconstruction of streamflow from tree ring study resulted in good similarity with the gage data. 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 years intervals.

Keen (1937) arrived at an index of the ancient climatic history back to the year 1288 through a study of tree rings in eastern Oregon. He used 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 record 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 in 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 (Nov.-March) totals for Walla Walla for the period 1856 to 1865 are reported to have been above the 1950's average. All of Keen's periods of low tree growth, from his tree-ring calendar agree with reconstructed droughts in Columbia Basin during the early 1740's, late 1750's and 1840's. 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).

STREAMFLOW CHARACTERISTICS

Streamflow characteristics can differ widely over short distances. Annual water yield and annual peak flows increase as elevation and basin precipitation increase.

High natural variability among watersheds in the mountainous snow zone limits the accurate prediction of streamflow characteristics. Basins with predominantly western Larch-Douglas fir forest cover differ from watersheds with forest cover types such as ponderosa pine, mountain meadow, lodgepole pine, fir-spruce. For the catchments with forest cover of western larch-Douglas-fir group, lower peak flows, higher low flows and flatter flow duration curves are characteristics. With maintenance of adequate ground cover over most of the watershed area, low to moderate grazing intensities did not produce significant differences in streamflow characteristics in the Blue Mountains (Higgins et al., 1989).

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). However, in eastern Oregon, some of the minimum flows extend into the middle of April. For low flow prediction methods to be most useful, they should be appropriate for watersheds of all sizes throughout the region.

Studies on precipitation fluctuations over a region (Bradley, 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. Chang and Boyer (1977) estimated the lowest 7-day streamflow ($7Q_{10}$, 10-year return period for lowest 7 day streamflow) from watershed and climatic parameters for twelve Monongahela tributaries in West Virginia. It was 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-squared 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.

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 types, 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, ungaged streams. The standard errors of the estimate, comparing the estimated discharges to the actual discharges, were ± 44 and $\pm 61\%$ in low flow regions, which he 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 percent probability level. Besides F-test, R^2 (coefficient of 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.

Generally, the most important meteorologic and drainage basin characteristics for low flow prediction are drainage area, mean basin elevation, gage 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 streamflow 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 for streamflow in eastern Oregon. Equations for finding the confidence interval for a predicted low flow value can be constructed. These equations will reflect the increase in the variance with decreasing magnitudes of low flows.

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, its tributaries, diversion canals, supply ditches, and storage reservoirs, 2. the unsaturated flow region in the aquifer that transmits water between the water table and the ground surface and the surface water conveyance system and 3. the saturated flow region that acts as 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-Seytoux, 1982).

Glaciers, the frozen reservoirs of water, affect streamflow 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 streamflow during otherwise low flow periods (Fountain and Tangborn, 1985). Snow packs in mountainous areas are important for sustained streamflow. 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 availability of the wind. 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).

RECURRENCE INTERVAL

Frequency curves of hydrologic data commonly relate the magnitude of the event to the recurrence interval or return period. The recurrence interval is the reciprocal of the probability when the population consists of annual events. The low flow recurrence interval of a particular event is the average number of years between the occurrence of this event and the next lesser magnitude event. The recurrence interval does not suggest that flows of that magnitude will occur on a regular basis (Williams and Pearson, 1985). Several parameters can be selected to estimate the probabilities of minimum flows at different times of the year. Weibull's formula is most widely used when graphically fitting the magnitudes to recurrence intervals. As given by Riggs (1985) the following formula will be used in this study:

$T_r = 1/p = (n+1)/m$ where,

T_r = recurrence interval in years

P = probability of an exceedence in any one Year

n= number of items in the sample

m= order number of the individual in the sample array.

METHODOLOGY

This study was conducted in order to gain a better understanding of the hydrologic characteristics of stream low flows in eastern Oregon. The main objectives of this study were to provide a quantitative overview of streamflow during the summer low and base flow periods, and to determine the relationship between low flows and precipitation and physical characteristics of the watershed. For comparison, annual low flows are also analyzed. To accomplish this task, the following steps were taken:

1) streams with long, natural and continuous data were selected,

2) such physical watershed parameters were selected or developed which have relations to low flows,

3) monthly precipitation data were obtained for the selected watersheds for a fairly long period (> 30 years),

4) the best techniques to effectively evaluate the relationship of the derived parameters with low flow regimes were selected and used and

5) predictive equations for different periods of summer low flows were developed using recession analysis from the first half of the available data for each stream. These equations were tested against low streamflow data from second half of the available data for each stream.

The software packages used to analyze the data, graphic presentation and writing of thesis include Quattro Pro, Statgraphics, Harvard Graphics and Word Perfect.

Precipitation in the valleys (where the precipitation gages are located), is definitely lower than in the adjacent mountains. It is assumed that precipitation in the valleys has a consistent relationship with precipitation on the mountains. For the purpose of comparison between stream low flows and precipitation, we were looking more into trends rather than absolute precipitation. The presence of spatial variability in precipitation within a region was also noted. But it is assumed that spatial variability in terms of annual total precipitation within a watershed is not sufficient to change the general trends and patterns. Secondly, the point precipitation in the valley is considered as reasonably representative of the region as far as the trends of wet and drought periods are concerned.

Watersheds were delineated by topographic divides on U.S.Geological Survey topographic maps (1:250,000) above gaging stations. The following parameters were used as means of describing the relationship of low flows and watershed parameters:

-watershed area
-length of watershed perimeter
-watershed relief
-average basin slope
-form factor
-main channel slope
-main channel length
-circulatory ratio
-watershed length
-area under floodplains which may serve as a source for sustained stream low flows.

The two criteria used to select a stream for analysis included a minimum record of 30 years, and no diversion or regulation of water upstream.

Nine streams in eastern Oregon were selected- three each in Blue Mountains, Wallowa Mountains and southeastern Oregon. These were the only streams in eastern Oregon that met the criteria. Then precipitation data was collected for the selected regions from stations with the criteria of a minimum continuous record of 30 years and proximity to the study area. A field visit was made of the study area to look particularly into the kind and extent of floodplains next to the streams and the vegetation conditions.

Year-to-year dependence analysis and time series trend analysis were conducted to find their degree of independence and increase or decrease in the low streamflows over the years of record for each station. Summer low flows were of particular interest, the water year, Oct. 1 - Sep. 30 was used in this analysis. Stream low flow characteristics were analyzed by constructing flow duration curves, flow date curves and low flow frequency curves. Recession analysis for each stream was performed to predict streamflow recessions during summer low flows. Stream low flow trends were analyzed using 5-year moving averages, departure from the mean and cumulative departures from the mean for annual, August, September and October low flows over the period of record. Annual low flows were included in the analysis to better understand the low flow characteristics throughout the year, and to compare with summer low flows. Low streamflows were correlated with precipitation and physical parameters of watersheds.

YEAR-TO-YEAR DEPENDENCE OF MINIMUM FLOWS

Streamflow data is a time series. Each day's flow is dependent upon the preceding day's flow. However, the annual, August, September, and October minimum flows should be fairly independent, random values. Variation in year-to-year minimum flows is related to watershed characteristics and precipitation patterns. Statistical methods commonly used in hydrologic studies are based on the assumption that the observations are independently distributed in time. The occurrence of an event is assumed to be independent of all previous events, which is not always valid for hydrologic time series. However, dependence between hydrologic observations decreases with an increase in the time base (Chow, 1964)

To evaluate the year-to-year dependence, respective minimum flows for annual, August, September and October for each year were used. Each parameter for year X+1 was regressed against year X. Correlation coefficients "r" were noted. A positive correlation coefficient suggested a positive relationship of minimum flows on the previous year's flow. A negative "r" showed a negative dependence of minimum flows on the previous year's minimum flow, and close to zero value of "r" indicated no dependence. The greater is the value for "r", the higher is the correlation. If the correlation is insignificant, each minimum flow is independent of the previous years' minimum flow.

TIME SERIES

Stationary time series have the same means and variances (i.e., the distribution does not change with time). A trend is a smooth motion of the series, or when 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)

TIME SERIES TREND ANALYSIS OF MINIMUM FLOWS

To find out the time series trend for annual, August, September and October minimum flows, minimum flows for each parameter were calculated for each year for all streams. They were simply regressed against time (years) to find the slope of the trend. Positive slope indicated an increase in minimum flows, while negative slope depicted a decrease over the period. No significant changes in minimum flows were shown by slopes very close to zero. The steeper the regression line (slope), the greater the change with the time.

FLOW DURATION CURVE

In a statistical sense, the duration curve is a cumulative frequency curve of a continuous time series, displaying the relative duration of various magnitudes. It is merely an expression of what happened in a particular period. It is not a probability curve because daily discharges are not only serially correlated but their characteristics change throughout the year. It is used to graphically display the variability of flow or the dependability of low flows (Riggs, 1985). The slope of the duration curve depends heavily on the observation period used in the analysis. The mean daily data yields a much steeper curve than annual data as the latter tend to group and smooth off the variations in the shorter-interval daily data (Chow, 1964). These curves help indicate the availability of streamflow and are useful for investigating problems of water supply, power development, waste disposal and administration of water rights. The curve shows the discharges that were equalled or exceeded for specified percentages of time for each station for its period of record.

A flow duration curve for each stream was constructed using the daily flows. Frequencies of flow for each discharge class, usually consisting of 5 cfs intervals, were calculated from daily flows. Class intervals were kept the same except for the first and last classes. Frequencies were converted to percentages, which indicated the percent of time the stream was at that flow for the period of record. The percentages were accumulated starting with the frequency for the highest discharge class. The accumulated values were plotted against discharge on a log normal graph (Fig. 2). Any point on the duration curve shows the percentage of time (during the period used) that the discharge equalled the indicated value. The flow duration curve describes the general behavior of the stream. The flatter portion of the curve indicates the occurrence of stable flows over a long period, while the steeper portion of the curve depicts changing flows. Log-normal graphs of duration curves show the steep and flat portions more clearly.

FLOW DATE CURVE

Flow date curves were prepared for each of the streams based on daily flows averaged over the whole period of record. Total streamflow volume for the entire water year was calculated, from which percent of flow passing by each day was calculated and plotted against water year to get the flow date curve (Fig. 3). Flatter portions of the curve at the ends represent low flows extended over low flow period, which do not contribute much toward the total amount of flow. Peak flow period,

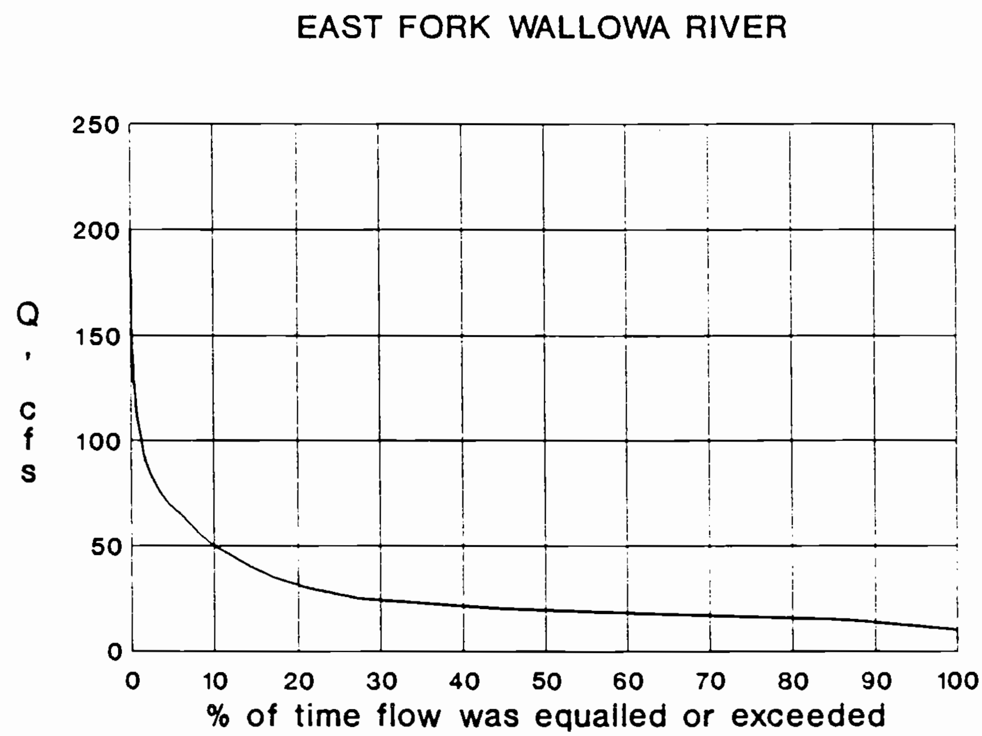

Figure 2. Flow duration curve for the East Fork Wallowa River, Oregon

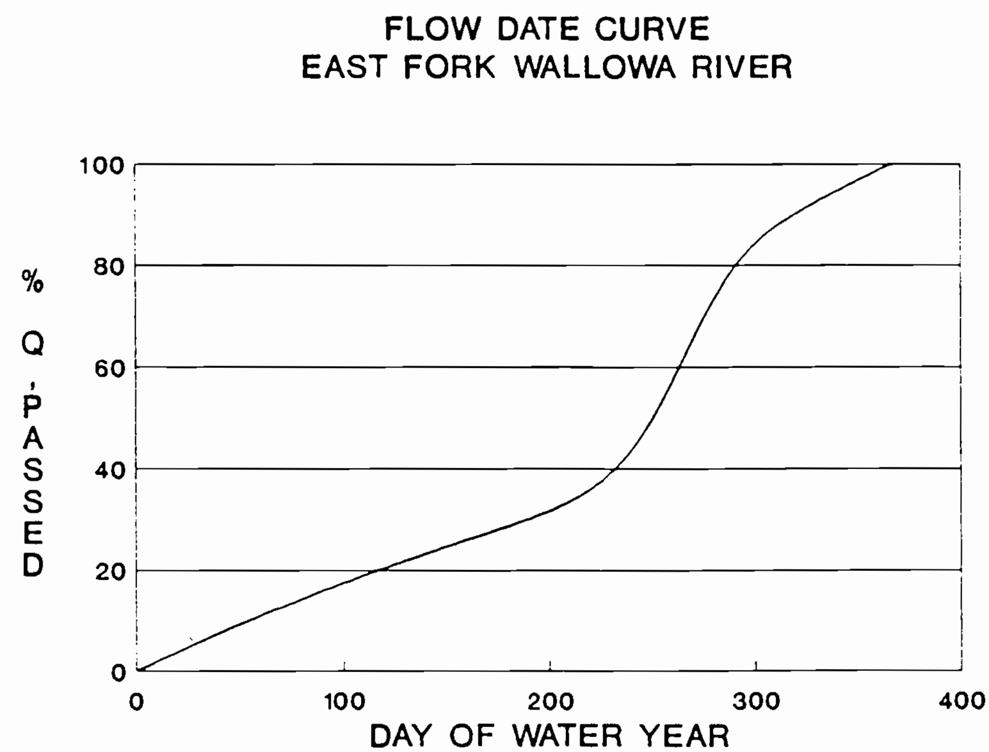

Figure 3. Flow date curve for the East Fork Wallowa River, Oregon.

by comparison, is for a shorter period of time, but has a high percentage contribution towards the total annual flow. Flow date curve is helpful in understanding the flow regimes throughout the year and the availability of a particular flow level during critical periods.

FLOW FREQUENCY CURVE

For relative frequency distribution, probability distribution or just distribution of flow, probability interpretation is valid only if the data used are random. Daily mean flow of a stream is closely related to the flows of the previous day. The distribution of daily means is not one to which the probability interpretation strictly applies. Probability, in the concept of frequency distribution, is defined as relative frequency (Riggs, 1985). To establish the probability of occurrence, frequencies of occurrence are essential. Low flow frequency analysis is helpful when assigning probability of occurrence or return interval to low flow events of varying magnitudes. The length of the return interval depends upon the length of the available data. The longer the record, the more accurate is the frequency curve. Flatter curves indicate less variability in minimum flows with differing return intervals. High variability is associated with the differing return intervals if the slope of the curve is steep.

Annual, August, September and October minimum flows, as well as 7-and 30-day average minimum flows were selected for low flow frequency analysis. Minimum flows for these parameters for each year were calculated.

The following are the most commonly used formuli when calculating frequencies:

Weibull formula $T_r = (n+1)/m$

California formula $T_r = n/m$

Foster formula $T_r = 2n/(2m-1)$

Exceedence formula $T_r = n/(m-1)$

where, T_r is return period in years, m is plotting position and n is number of observations. The Weibull formula was used for this analysis because it does not tend to overestimate or underestimate the true probability for extreme events (Wanielista, 1990). Usually at least 25 data points are needed when using this formula. When using the Weibull formula, low flow days are ordered in ascending order. The plotting position is then converted to a less than or equal to probability. Finally, the return period (T_r) is calculated and plotted against precipitation or low streamflow values to get frequency curves. When plotted on a log-normal scale, the frequency curves were upward-concave for each parameter (Fig. 4). If the return interval of 100 cfs is 15 years, then the annual minimum discharge will be less than 100 cfs at intervals averaging 15 years in length, with a probability of 1/15 that the minimum discharge in any one year will be less than 100 cfs (Riggs. 1985, p-66,72).

RECESSION ANALYSIS AND FORECASTING

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 that maintains streamflow during periods of no rain. The hydrograph of streamflow during periods when all discharge is derived from groundwater resource is known as a base-flow recession. A curve that

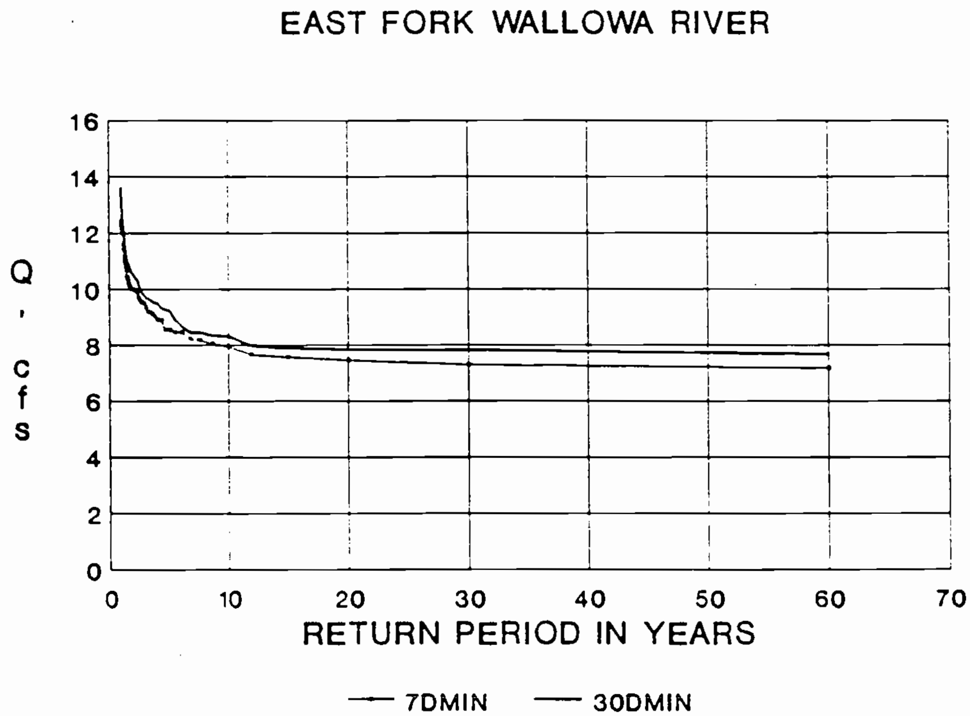

Figure 4. Seven- and 30-day low-flow frequencies for the East Fork Wallowa River.

averages these recessions is the base flow recession curve. Streamflow recession curve equations are derived from theoretical equations for flow in an aquifer, which are of the form

$$Q_t=Q_oK^{-t}$$

where Q_t is the discharge at any instant, Q_o is the discharge at some initial time, K is the recession constant, and t is the time interval between Q_o and Q_t. Also, recession factors can be derived from the slopes of the straight lines being fitted to the plotted points of daily average recession discharges against the daily average recession discharges on the preceding day (Chow, 1964, p. 10-35). These recession factors can be used to derive the recession portion of the hydrograph.

For recession analysis and forecasting summer low flows, the first half of the data set was used to build the forecast model. The second half of the data was used to check the validity of the forecast model. To build the forecast model, the average annual hydrograph for each stream was prepared by averaging the daily flow over the first half of the record, for the water year. For all streams, the peak of this hydrograph occurred from March to May. The position on the recession limb was selected arbitrarily as the inflection of the convex portion of the annual hydrograph to the end of water year. From this recession limb, flow for the day T+1 was regressed against the flow for previous day, day T (Fig. 5). Regression parameters (slope and constant) so obtained were used to forecast streamflow for the day T+1 by using the equation:

$$Q_{t+1}=Q_t(\text{slope})+\text{constant}$$

where, Q_t is the flow for day T

Forecast flow for day T+2 was calculated using the same regression parameters with flow for day T+1 as Q_t, as:

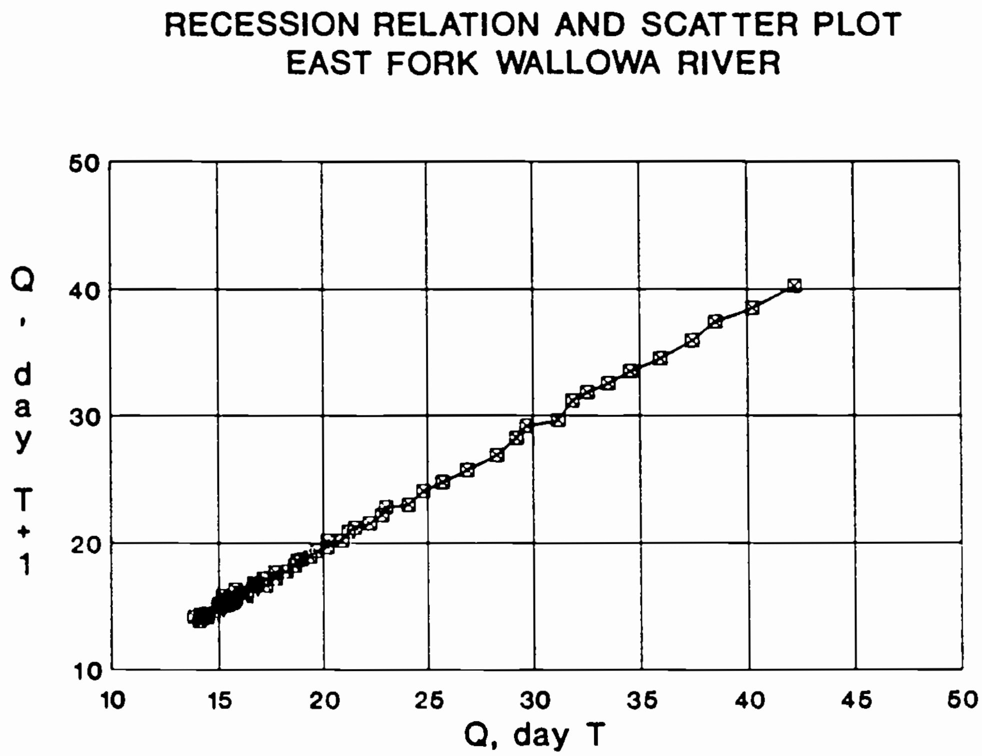

Figure 5. Recession relation and scatter plot for the East Fork Wallowa River, Oregon.

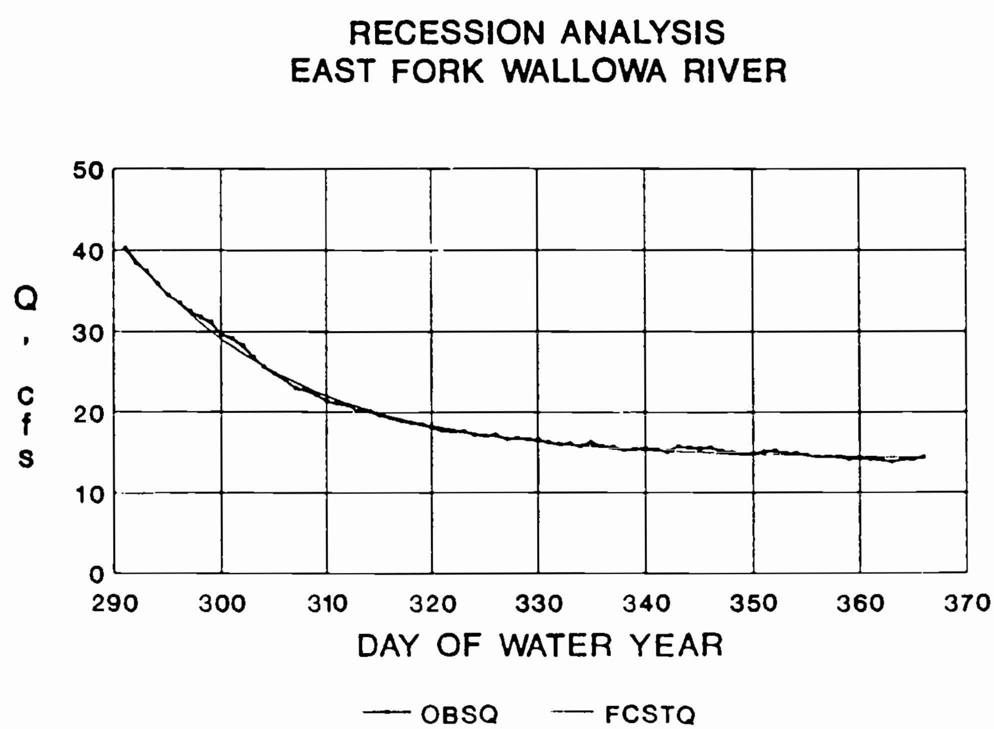

Figure 6. Observed and forecasted recession curves for the East Fork Wallowa River, Oregon.

$$Q_{(t+2)} = Q_{(t+1)}\text{slope}+\text{constant}$$

This procedure was repeated through the end of water year in order to get the forecast flow for each day (Widner, 1991). This forecast flow was compared with average actual flow for that period, and their degree of similarity was noted. The whole procedure was repeated several times with different starting dates to get the best fit lines for actual average and forecast flows. The date which gave the best fit was selected as the model for that stream (Fig. 6). The general form of the model equation is derived as follow:

$$Q_{(day\ 1)} = Q_oC+C_o$$

$$Q_{(day\ 2)} = \{Q_oC+C_o\}C+C_o = Q_oC^2+CC_o+C_o$$

$$Q_{(day\ 3)} = \{Q_oC^2+CC_o+C_o\}C+C_o = Q_oC^3+C_2C_o+C_oC+C_o$$

This results into the general shape of the equation as:

$$Q_n = Q_oC^n+\sum_{i=1}^{n-1}C_oC^i$$

where, Q_o is the observed flow on day zero of the forecast period, C is the regression slope constant, C_o is the regression slope intercept, n is the number of the day after day zero and Q^n is the forecasted flow for the nth day.

In order to test the validity of the forecast model, it was used to forecast daily streamflows for each year of the second half of the data, starting from the same date that was used to develop the model.

Four parameters were selected to test the model; these included recession volume (total flow over the whole recession limb), August, September and last 7 day average flows. These four parameters were calculated for each year for the observed and forecasted periods. The same was done for the first half of the data. Each forecasted parameter for each year was compared with the respective observed parameter. If the forecasted flows were similar to the observed flows, the model was considered accurate. If the trends showed poor similarity with one another, the model was considered to be inaccurate. If the forecast was good for recession volume yet decreased in its validity for the later part of the water year, forecasts for some of the parameters were made with the observed flow on a later date (the day just before that parameter). This is done to find the usefulness of models for shorter forecasts for the later parameters, using the same equation.

To study the improvement of the forecast model over the prediction made by long term mean of model building period, average and forecast errors were calculated for all selected parameters. Average errors for each parameter was calculated by subtracting observed flow for each year of the second half of the data from the respective long term average of the first half of the data. Forecast error for each parameter was calculated by subtracting observed flow from the forecasted flow for each year. Average errors were graphically compared with forecast errors for each parameter. If the forecast error was closer to zero than the average error, the forecast model is considered accurate. If the forecast and average errors are close to one another, the forecast model did not improve the efficiency of forecasting over average prediction. To find the degree of improvement of the forecast model over using the long term mean as prediction, percent improvements were calculated. Average and forecast errors were averaged for the whole period. The percent improvements are calculated as follows:

$$\% \text{ improvement} = \frac{(\text{Average error} - \text{Forecast error})}{\text{Forecast error}} \times 100$$

Forecast flows for recession volume, average August, average September and average last 7 days of water year were graphically compared with respective observed flows over the years. Disparities between forecast and observed flows were examined.

5-YEAR MOVING AVERAGES

Absolute minimum flows for each parameter- annual, August, September and October flows- were calculated. Long term means for these parameters were calculated. Five-year moving averages were calculated by averaging values for years one through five. The average was recorded at year three. From year two through year six, the average was calculated and recorded at year four, and so on). Five-year moving averages smoothed the curves. They were plotted against the long term mean so as to see long term trends and detect patterns in the minimum flows (Fig. 7).

Similarly, long term mean and 5-year moving averages for regional as well as individual precipitation station were calculated.

CUMULATIVE DEPARTURE FROM MEAN

The cumulative departure for each parameter was calculated first by subtracting individual values for each parameter from the respective long term mean to get the departure from mean for each year. Then, cumulative departure from mean was calculated by adding each years' departure. When plotted against the time interval, the cumulative departure provided a better picture of the

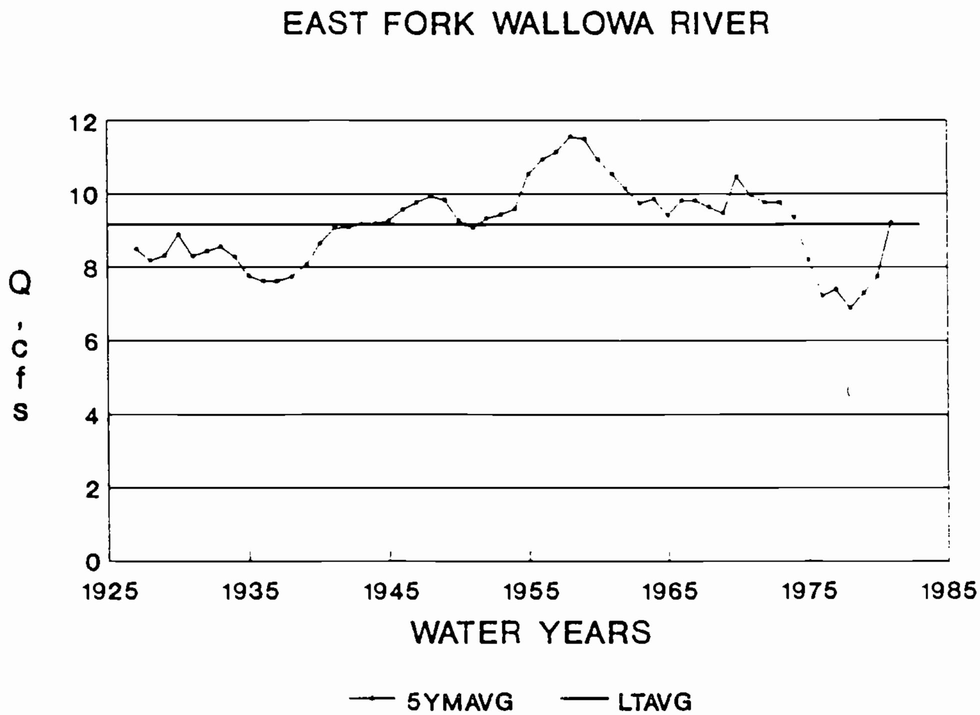

Figure 7. Five-year moving average and long-term mean annual streamflow for the East Fork Wallowa River, Oregon.

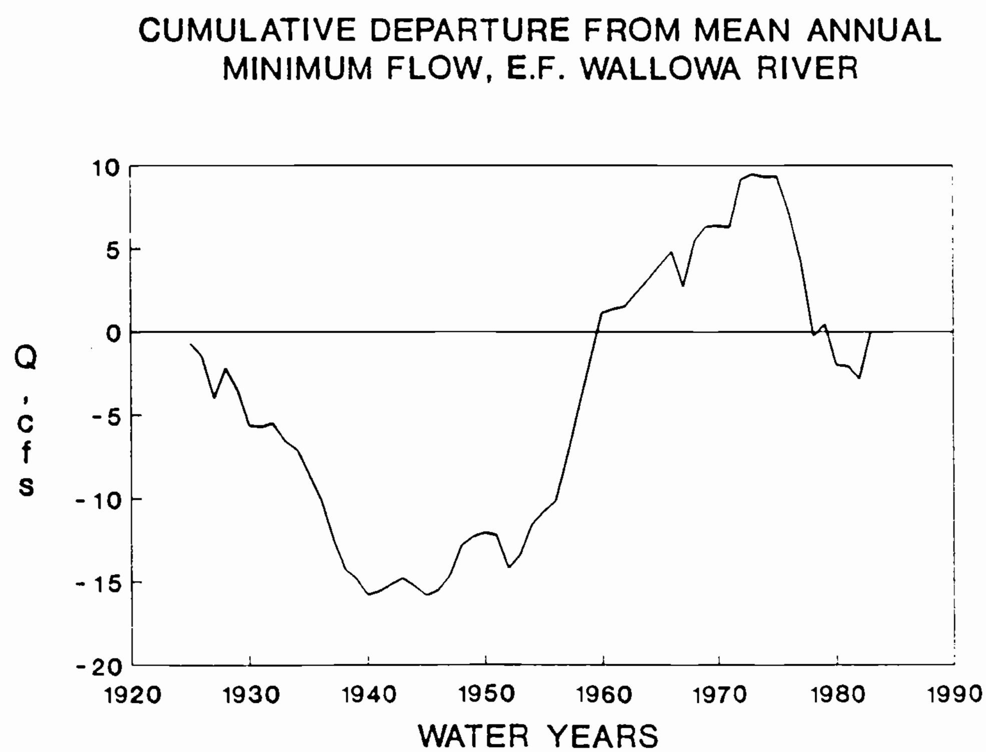

Figure 8. Cumulative departures from the long-term mean annual streamflow for the East Fork Wallowa River, Oregon.

trends (Fig. 8).

TREND SIMILARITIES BETWEEN MINIMUM FLOWS AND PRECIPITATION

5-YEAR MOVING AVERAGES FOR LOW FLOWS AND REGIONAL PRECIPITATION

Three precipitation stations were selected from the northeastern Oregon. These stations are highly similar in long term precipitation trends and patterns. Two precipitation stations in the southeastern Oregon were selected for use in comparing trends in precipitation with trends in low flows. Their long term means are also similar. Low streamflows from three regions were compared with two regions of precipitation. Five-year moving averages and the cumulative departures from long term mean for regional precipitation were calculated. Low streamflow trends for the northeastern Oregon streams (Wallowa and Blue Mountain regions) were compared with the precipitation trends in the northeastern Oregon region. Similarly, low streamflow trends for the southeastern Oregon region were compared with the precipitation trends in the region.

CUMULATIVE DEPARTURES FOR LOW FLOWS AND PRECIPITATION

The cumulative departures from long term mean for each stream for each low flow parameter were plotted against cumulative departures from long term mean for regional annual precipitation. Trend similarities between annual, August, September and October low flows' cumulative departures and regional annual precipitation' cumulative departures were studied separately for each region.

CORRELATION BETWEEN LOW FLOWS AND PRECIPITATION

REGIONAL ANALYSIS:

For the purpose of identifying relationships between minimum flows and precipitation, eastern Oregon was divided into two precipitation regions, the northeastern region (averaged for the La Grande, Union and Wallowa precipitation stations) and the southeastern region (averaged for the Burns and P-ranch precipitation stations). The streams were divided into three regions: Wallowa Mountain region, Blue Mountain region and the southeastern Oregon region. For each region, minimum streamflows were averaged for streams in that region.

For the Blue and Wallowa mountain regions, annual, August, September and October minimum flows were regressed against northeastern Oregon's regional precipitation. Similarly, southeastern region minimum flows were regressed against precipitation of that region.

ANALYSIS BY STREAMS

Annual, August, September and October minimum flows for each stream were calculated. Individual minimum flow parameters for each stream were regressed against regional as well as local precipitation.

REGRESSION ANALYSIS

CORRELATION BETWEEN PRECIPITATION AND MINIMUM FLOWS

Annual, August, September and October minimum flows for each stream were used to calculate the average values for each minimum flow parameter. Similarly, average annual precipitation, regional as well as local, for each of the stations was calculated. Because there are only nine streams in the sample, multiple or stepwise regression analysis could not be performed. Simple regression was used to determine the degree of correlation between annual, August, September and October minimum flows and precipitation.

CORRELATION BETWEEN WATERSHED PARAMETERS AND MINIMUM FLOWS

WATERSHED AND CHANNEL LENGTH:

Channel length is the distance measured along the main channel from the watershed outlet to the basin divide, and is denoted by L.

SHAPE FACTOR: (L_l)

$L_l=(LL_{ca})^{0.3}$, where,

L is the length of the watershed in miles

L_{ca} is the distance measured in miles along the main channel from the basin outlet to the point in the main channel opposite to the center of mass (McCuen, 1989).

CIRCULATORY RATIO (F_c):

$F_c= P/\{(4piA)^{0.5}\}$, where

P= perimeter of the watershed in the feet

A= area of the watershed (ft^2)

pi= 3.1416

Channel slope $S_c= \triangle E/L_c$

Watershed slope $S_{ws}= \triangle E/L_{ws}$

where

L_c= channel length

L_{ws}= watershed length

$\triangle E$= elevation difference

(McCuen, 1989).

Watershed parameters such as area, perimeter, length of the main channel, elevation change, length of the watershed, circulatory ratio, shape factor, channel slope, watershed slope and area under floodplains were calculated for each watershed in the study. Simple regression was used to find the degree of correlation between minimum flows and each watershed parameter.

RESULTS AND DISCUSSION

YEAR-TO-YEAR DEPENDENCE OF MINIMUM FLOWS

Randomness and independence of observations are important for their statistical analysis. However hydrologic time series are non-random observations with variable dependence. Results showed that year-to-year dependence varies from variable to variable (annual, August, September and October minimum flows) and from region to region. Low flows for streams in the Wallowa Mountain region are fairly independent except annual minimum flows. Year-to-year dependence for streams in the Blue Mountain region is highly significant (Table 2) for majority of the minimum flow variables. Low flows for the Silvies River and the Donner Und Blitzen River in the southeastern Oregon region are also highly dependent upon previous years' flows. Low flows for Bridge Creek are independent from previous years' flows except annual minimum flows. Annual and August minimum flows for majority of the streams showed higher dependence on previous years' flows. October minimum flows for the majority of the streams showed the least year-to-year dependence.

REGIONAL COMPARISON

Regional analysis showed highly significant year-to-year dependence of all the minimum flow variables for the Blue Mountain and southeastern Oregon regions (Table 3). Within the three regions, year-to-year dependence of minimum flows decreased from annual to August to September minimum flows. The Blue Mountain region has the highest dependence followed by the southeastern Oregon region (Fig. 9).

Table 2. Regression correlation coefficients (r) and associated probability levels (p) showing year-to-year dependence of annual (ANN), August (AUG), september (SEP) and October OCT) minimum flows for different selected streams in eastern Oregon.

Name of stream		ANN	AUG	SEP	OCT
Wallow Mountain region					
EF Wallowa	r	0.351	0.231	0.087	0.047
River	p	0.007	0.081	0.510	0.730
Hurricane	r	0.060	-0.030	-0.06	-0.01
Creek	p	0.670	0.840	0.660	0.970
Bear Creek	r	0.030	0.210	0.210	0.210
	p	0.830	0.098	0.110	0.830
Blue Mountain region					
SF Walla Walla	r	0.688	0.643	0.692	0.610
River	p	0.000	0.000	0.000	0.000
Mill Creek	r	0.580	0.630	0.620	0.520
	p	0.000	0.000	0.000	0.000
Umatilla River	r	0.489	0.382	0.260	0.074
	p	0.000	0.004	0.060	0.600
Southeastern Oregon region					
Silvies River	r	0.600	0.530	0.490	0.560
	p	0.000	0.000	0.000	0.000
Donner Und	r	0.559	0.404	0.449	0.445
Blitz. River	p	0.000	0.002	0.000	0.001
Bridge Creek	r	0.353	0.198	0.183	0.183
	p	0.044	0.280	0.320	0.310

Statistically significant correlations for year-to-year dependence of minimum flow variables for streams in the Blue Mountain and southeastern Oregon regions indicate carryovers of climatic effects in these watersheds. These watersheds may have higher ground-water storage capacity to sustain supply of water for longer time than the Wallowa Mountain region. Decreased dependence of late summer and October flows may be attributed to the depletion of soil moisture during early summer because of high evapotranspirational demands and less precipitation. Stream catchments in the Wallowa Mountain region are steeper with denser vegetative cover than the rest of the catchments. Less storage capacity of basins or quicker

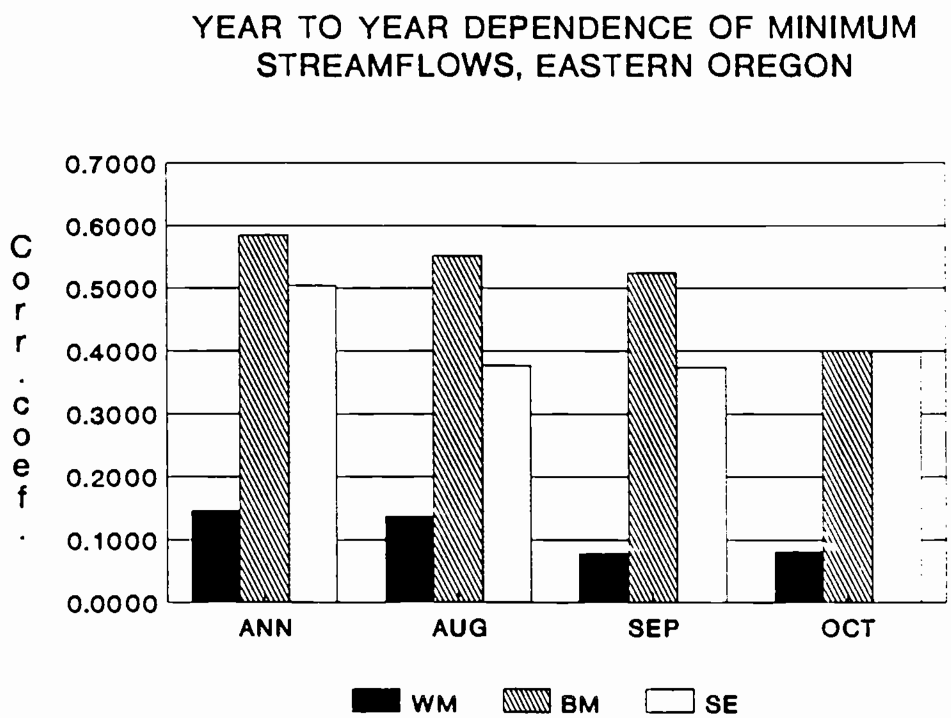

Figure 9. Dependence of regional low flows for the Wallowa Mountain (WM) Blue mountain (BM) and southeastern Oregon (SE) regions.

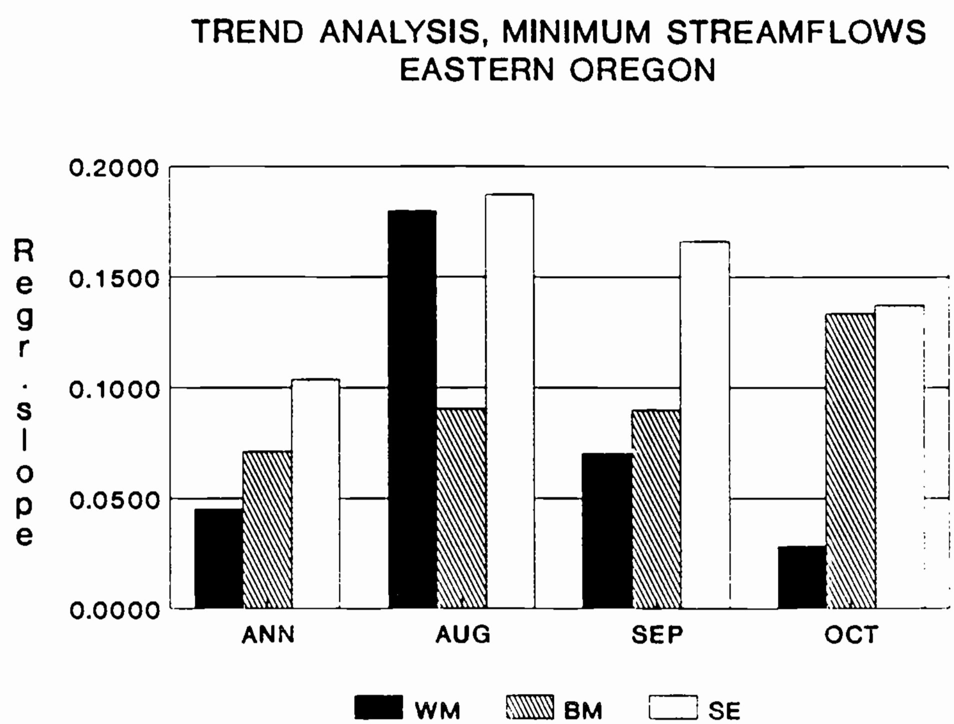

Figure 10. Trend analysis of low flows for the Wallowa Mountain (WM), Blue Mountain (BM) and southeastern Oregon (SE) regions, Oregon.

subsurface flow of infiltrated water to the streams and higher evapotranspirational demand may be plausible reasons for lower year-to-year dependence of minimum flows in the Wallowa Mountain region.

Table 3. Regression correlation coefficients (r) and associated probability levels (p) showing year-to-year dependence of regional annual (ANN), August (AUG), September (SEP) and October (OCT) minimum flows.

Minimum flows		Wallowa Mountains	Blue Mountains	Southeastern Oregon
ANN	r	0.147	0.585	0.504
	p	0.134	0.000	0.000
AUG	r	0.137	0.552	0.377
	p	0.374	0.000	0.000
SEP	r	0.079	0.524	0.374
	p	0.962	0.000	0.000
OCT	r	0.082	0.401	0.400
	p	0.811	0.000	0.000

TIME SERIES TREND ANALYSIS

Time series trend analysis of minimum flows showed variable results. Trends are positive for all the streams except Mill Creek and Bridge Creek (Table 4). The South Fork Walla Walla River showed the maximum increase in low streamflows over the period of record followed by the Silvies River and the Donner Und Blitzen River. Bridge Creek and Mill Creek showed decrease in low flows over the period of record, however, their trends are not statistically significant at 95% confidence level. Bear Creek has small increase in low streamflows with time but statistically it is highly significant at 95% confidence level (p=0.000), except for October minimum flows. Maximum increase in low flows occurred for August and September minimum flow variables and minimum for October minimum flows for the majority of streams.

Table 4. Regression slopes (b) and p-values (p) showing trends for annual (ANN), August (AUG), September (SEP) and October (OCT) minimum flows for different selected streams in eastern Oregon.

Name of stream		ANN	AUG	SEP	OCT
Wallowa Mountain region					
EF Wallowa	b	0.015	0.110	0.061	0.025
River	p	0.220	0.000	0.006	0.220
Hurricane Creek	b	0.050	0.310	0.070	0.050
	p	0.270	0.002	0.280	0.998
Bear Creek	b	0.070	0.120	0.080	-0.010
	p	0.000	0.000	0.000	0.730
Blue Mountain region					
SF Walla Walla	b	0.251	0.353	0.290	0.345
River	p	0.017	0.002	0.008	0.005
Mill Creek	b	-0.150	-0.180	-0.190	-0.080
	p	0.040	0.190	0.130	0.270
Umatilla River	b	0.112	0.099	0.170	0.136
	p	0.005	0.009	0.000	0.042
Southeastern Oregon region					
Silvies River	b	0.200	0.230	0.260	0.250
	p	0.000	0.000	0.000	0.000
Donner Und Blit.	b	0.142	0.373	0.285	0.221
River	p	0.097	0.005	0.011	0.035
Bridge Creek	b	-0.031	-0.041	-0.046	-0.058
	p	0.371	0.211	0.202	0.109

REGIONAL COMPARISON

Trend analysis for the regional minimum flows showed highly significant increase in low flows for the southeastern Oregon region (Table 5). In general, regression slopes increased from the Wallowa Mountain region to the Blue Mountain region to the southeastern Oregon region for all the parameters except for August minimum flows. Within the parameters, slopes are smallest for annual minimum flows and largest for August minimum flows except for the Blue Mountains (Fig. 10).

Trend analysis gave some sense of the low flow regimes for different streams over the recorded period. When the behavior of all streams in a region is similar, it may be attributed to some regional factors. However, when

Table 5. Regression slopes (b) and p-values (p) showing regional trends for annual (ANN), August (AUG), September (SEP) and October (OCT) minimum flows.

Minimum flows		Wallowa Mountains	Blue Mountains	Southeastern Oregon
ANN	b	0.045	0.071	0.104
	p	0.032	0.310	0.000
AUG	b	0.180	0.090	0.187
	p	0.287	0.563	0.001
SEP	b	0.070	0.090	0.166
	p	0.278	0.443	0.005
OCT	b	0.028	0.134	0.137
	p	0.643	0.880	0.000

streams in the same region show different trends with the time, it becomes more important to look into local factors. Mill Creek and the South Fork Walla Walla River showed highly significant year-to-year dependence of low flows. Although they are adjacent to one another, their trends are opposite.

FLOW DURATION CURVES

Flow duration curves provide a way to study runoff patterns. These curves are useful for detecting changes in the hydrology after timber harvest or other changes (Fowler et al., 1979). The slope of the flow duration curve reflects the hydrologic storage capacity of a watershed. In snow zone watersheds, the storage capacity is influenced by the amount and timing of the snow melt. A steep slope indicates a variable flow regime often associated with minimal storage capacity, large snow melt volumes, or synchronized snow melt.

The shape of a flow-duration curve is significant in evaluating the stream and basin characteristics in its upper and lower regions. Sustained moderate flows throughout the year due to natural streamflow regulation or to a large groundwater capacity which provides a nearly steady base to the stream result into a very flat curve in the low flow region (Peter Klingeman, OSU CE543 classnotes, 1991).

Generally, flow duration curves for most of these streams can be divided into three portions on the basis of slope. The extreme high flows are represented by the steepest portion of the curve, which usually extends over less than 5% of the total period of record for these streams. It is followed by a more normal high flow period which has a decreased slope and a variable length. Low flows are represented by the flatter and longer portion of the curve.

WALLOWA MOUNTAIN REGION

For the most part, the middle portion of the flow duration curve for the East Fork Wallowa River is relatively flat (Fig. 11). For 60% of the time, the flow remained lower than 20 cfs. Flow exceeded 30 cfs only 20 % of the time, during rapidly changing flow levels. At the lower end of the curve, flows less than 15 cfs showed higher variability. The flatter portion of the curve indicates snowmelt or groundwater contribution to the flow. However, the high elevation and steepness of this watershed suggest that late season snowmelt is the major source of sustained low flow, and is supplemented by sub-surface contributions.

Hurricane Creek's flow duration curve has a gradually

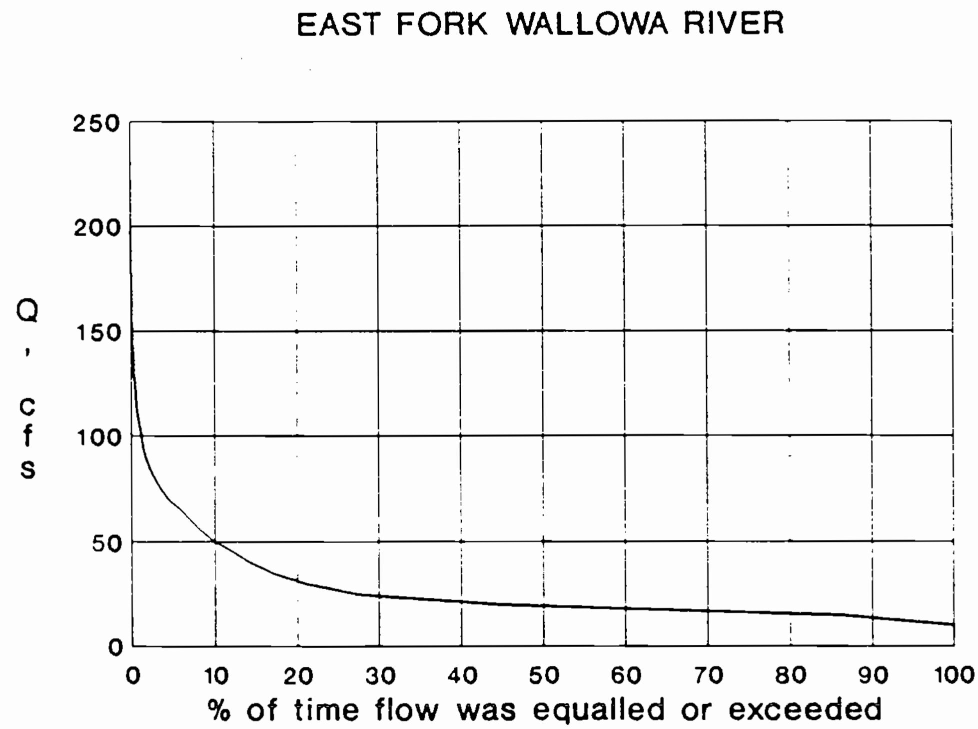

Figure 11. Flow duration curve for the East Fork Wallowa River.

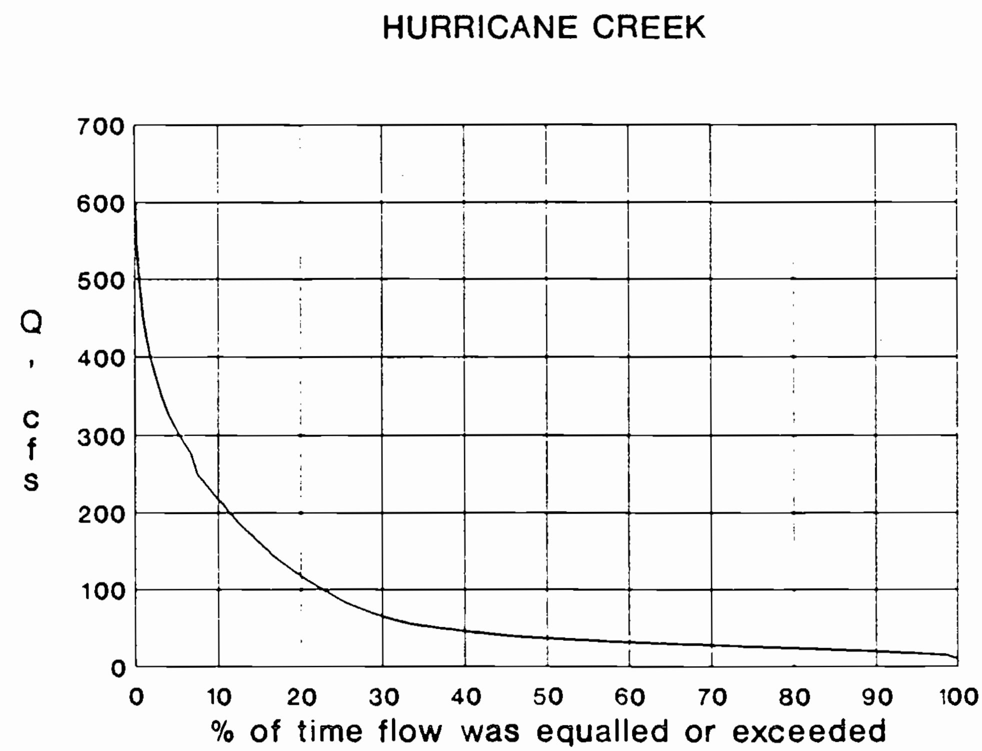

Figure 12. Flow duration curve for Hurricane Creek.

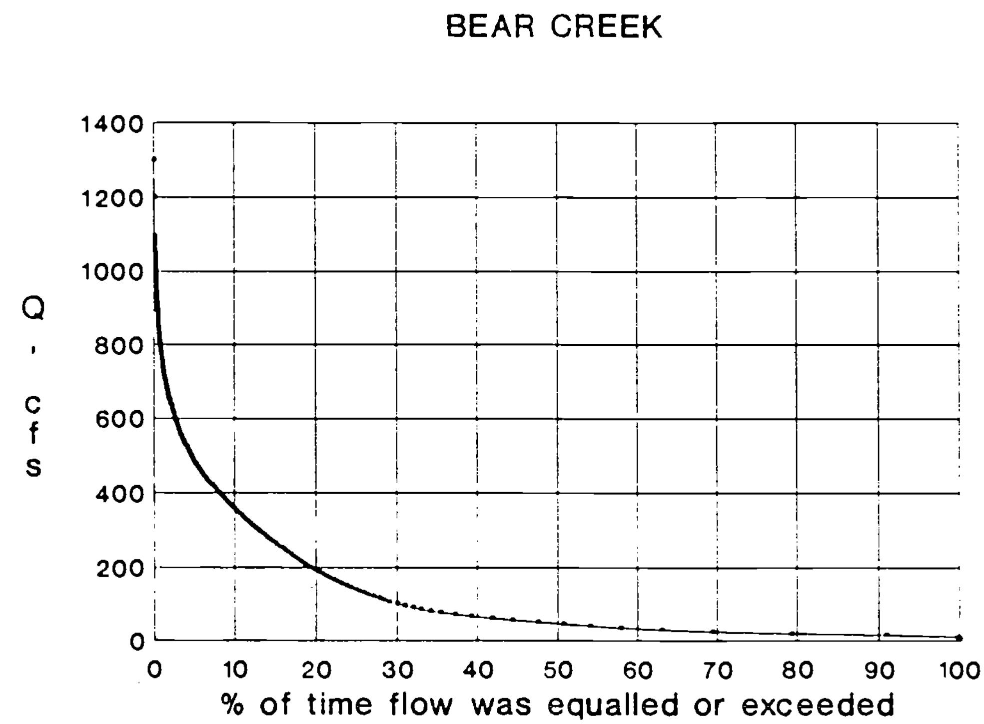

Figure 13. Flow duration curve for Bear Creek.

changing slope (Fig. 12) which differs from the nearby East Fork Wallowa River. Over 35 % of the time the flow is above 50 cfs. Flow for any class is not sustained for an extended period of time. Only 10% of the time the flow is less than 20 cfs.

The flow duration curve for Bear Creek (Fig. 13) is quite similar to that of Hurricane Creek. About 50 % of the time the flow is less than 50 cfs.

For all three streams in the Wallowa mountain region, most of the peak flows are caused by snowmelt during late winter to mid summer (March to June).

BLUE MOUNTAIN REGION

Discharge in the low flow portion of the flow duration curve for the South Fork Walla Walla River (Fig. 14) is higher than that of the other two streams in the Blue mountains region . The curve can be divided into two slope categories, with the lower part being quite flat and long. More than 90 % of the time the flow exceeds 90 cfs. However, snowmelt is the major contributor to the higher, prolonged and gentler upper portion of the curve.

The flow duration curve for Mill Creek (Fig. 15) is similar to that of the South Fork Walla Walla River . Low flows change more gradually over time. Lowest flows are above 20 cfs. Flow is gradually dominated by snowmelt recession and sub-surface contribution in the low flow portion. For 50 % of the time, the flow is below 65 cfs.

The flow duration curve for the Umatilla River (Fig. 16) is similar to that of Mill Creek. However, the variability of flow is greater compared to other two streams. The flow is greater than or equal to 100 cfs 55 % of the time. The low flow portion of the curve is short and flat compared to Mill Creek but steeper than the South

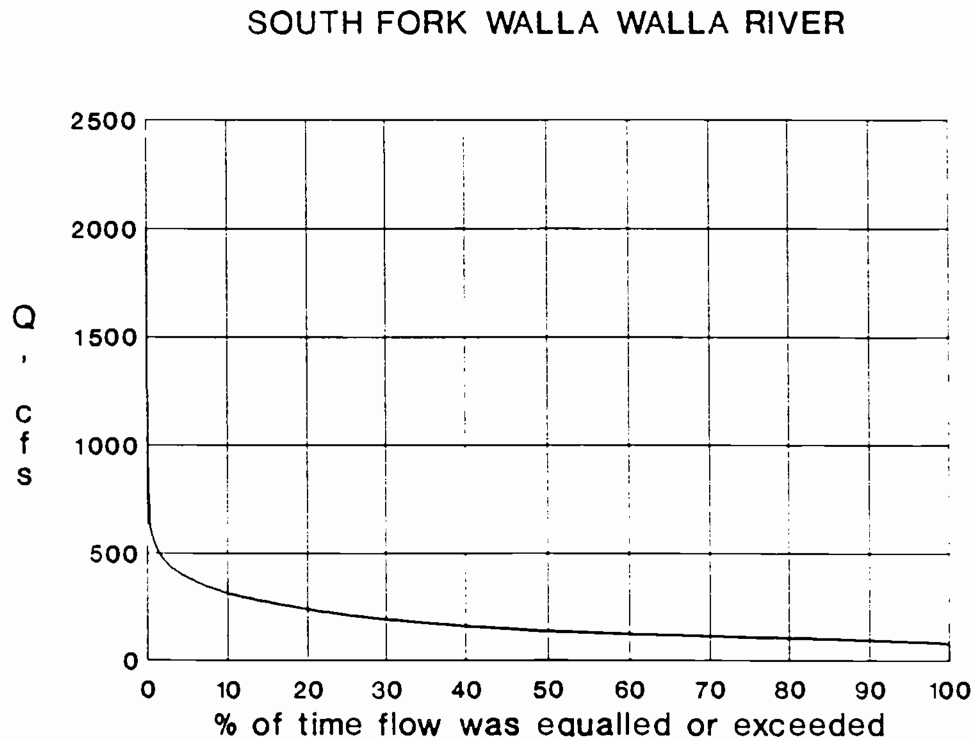

Figure 14. Flow duration curve for the South Fork Walla Walla River.

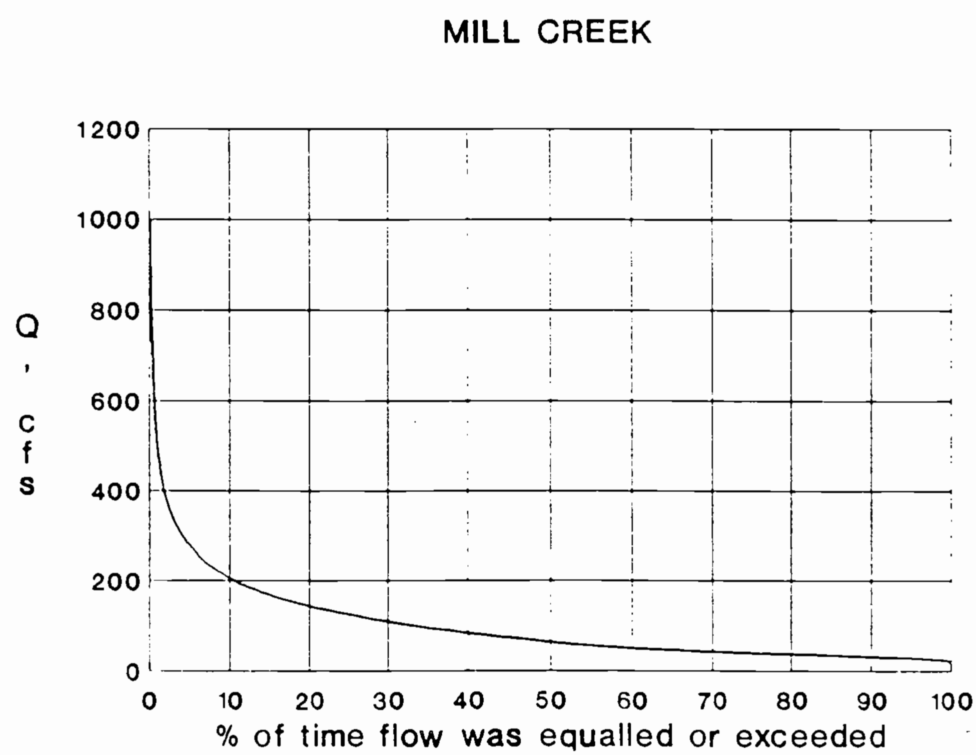

Figure 15. Flow duration curve for Mill Creek.

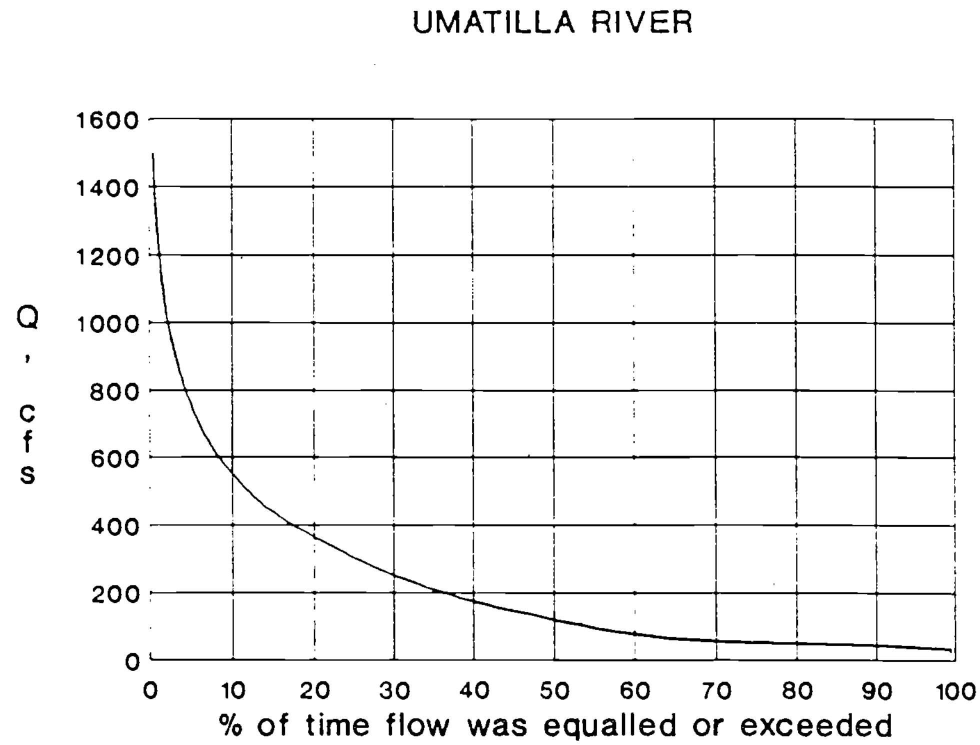

Figure 16. Flow duration curve for the Umatilla River.

Fork Walla Walla River. This curve is more representative of extended period of snowmelt caused flows. The lowest flow is above 30 cfs. Low flows are much lower than the South Fork Walla Walla River, despite having a larger catchment area.

SOUTHEASTERN OREGON REGION

The flow regime for the Silvies River (Fig. 17) is quite similar to that of Bear Creek in the Wallowa region. There is no stable sustained low flow portion in the curve. The variation in discharge in the low flow portion of the curve is greater than that of the other two streams in the region. The lowest flow is approximately 10 cfs. The flow is less than 50 cfs more than 50 % of the time. Groundwater contribution to low flows decreases with time.

The Donner Und Blitzen River (Fig. 18) has a flow duration curve similar to that of the Silvies River. However, the extremes are different. It has an extreme low flow just greater than 20 cfs. More than 50 % of the time the flow is less than 65 cfs.

The flow duration curve for Bridge Creek (Fig. 19) is similar in shape to that of the East Fork Wallowa River. It can be divided into three parts. Extreme high flows are approximately 80 cfs and extreme low flows are below 10 cfs. Both extremes are steeper, representing the rare peak flows in wet years and rare low flows during extreme drought periods, respectively. For approximately 80 % of the time, flow is between 10 and 20 cfs. The flow duration curve has minor effects of snowmelt and rain on the increased flows. However, most of the time a sustained low flow is maintained. This suggests that groundwater is a major contributor to streamflow.

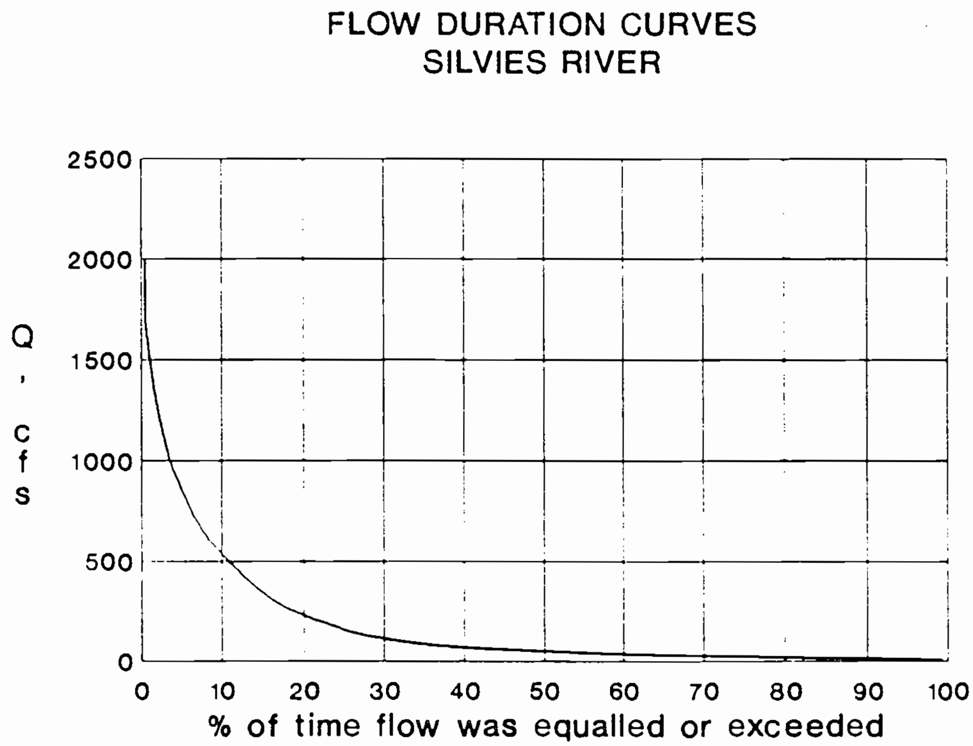

Figure 17. Flow duration curve for the Silvies River.

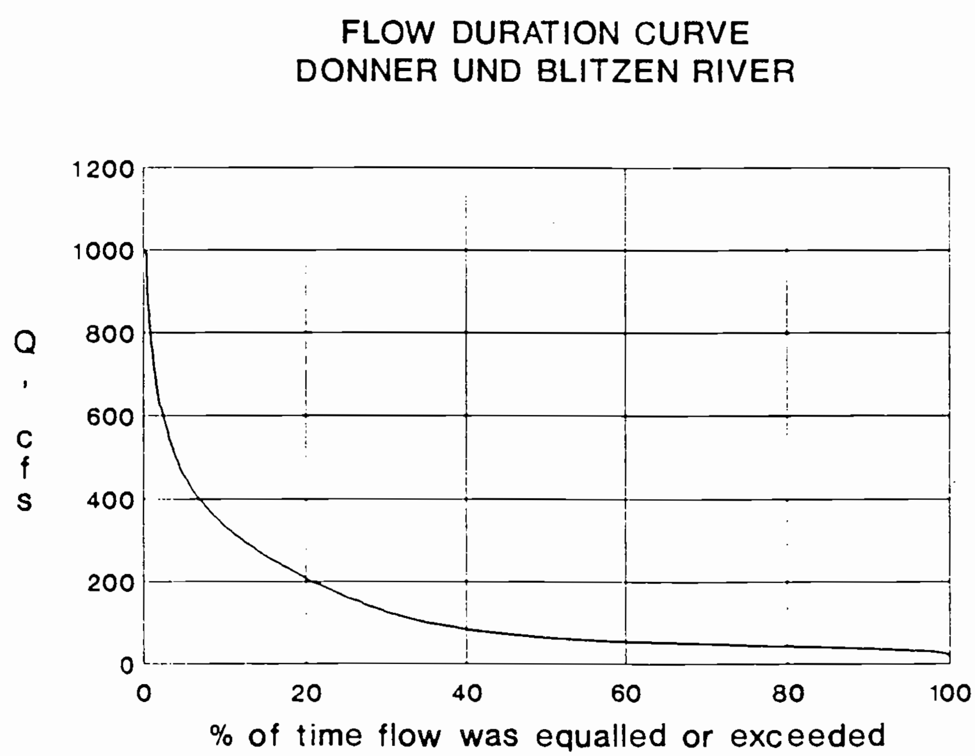

Figure 18. Flow duration curve for the Donner Und Blitzen River.

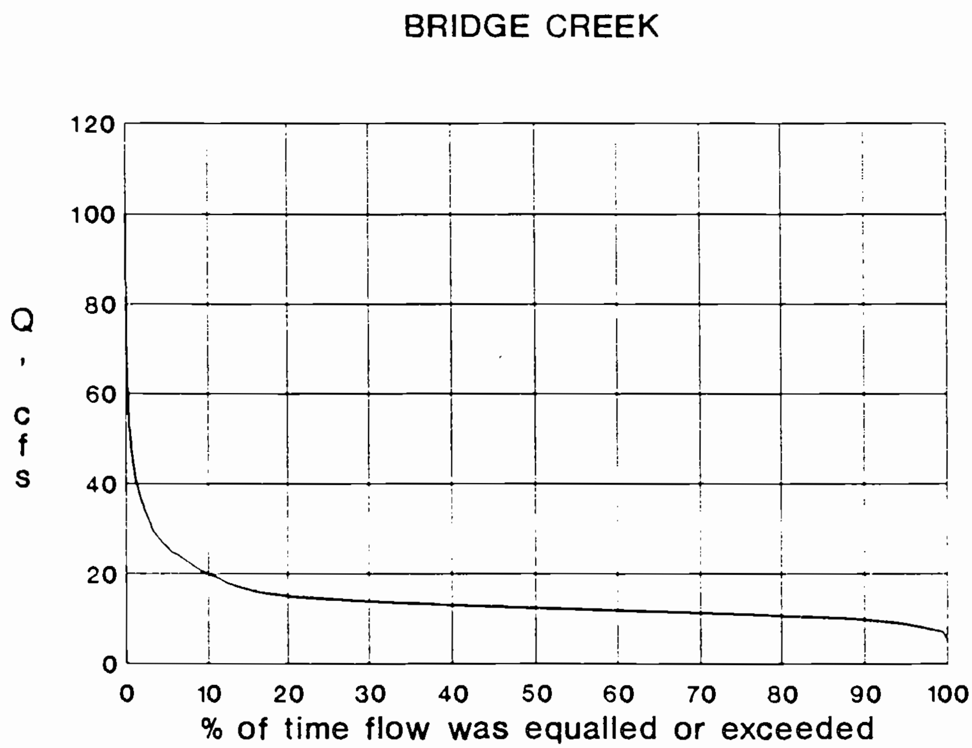

Figure 19. Flow duration curve for Bridge Creek.

FLOW DATE CURVES

The flow duration curve gives a clearer picture of the daily streamflows. The flow date curves for the three regions are developed separately for each of the streams and then combined for each region.

WALLOWA MOUNTAIN REGION

The flow date curves for Bear Creek and Hurricane Creek are very similar. The flow date curve for Bear Creek shows the strongest "S"-shaped in the region, having low flow during late summer and fall (Fig. 20). High flows start during March or April and attain their peaks during early summer. Bear Creek has the steepest slope for the central portion of the curve. More than 70% of the total flow occurs during the last week of March through the end of June. However, only 40% of the total flow for the East Fork Wallowa River and 44% of the total flow for Hurricane Creek occurs during the same period. The flow date curves for the East Fork Wallowa River and Hurricane Creek show extreme low flows during winter. The central portion of the flow date curve for the East Fork Wallowa River has a lower slope compared to the other two streams. Less than 3% of the total flow for Bear Creek occurred during the last two months of the water year. This can be seen in the shape of the right end of the flow date curve. Peak flows start at a later date in the East Fork Wallowa River and Hurricane Creek (last week of May), compared to Bear Creek (last week of April).

BLUE MOUNTAIN REGION

The flow date curves (Fig. 21) for the streams in the Blue mountain region differ from those of the Wallowa

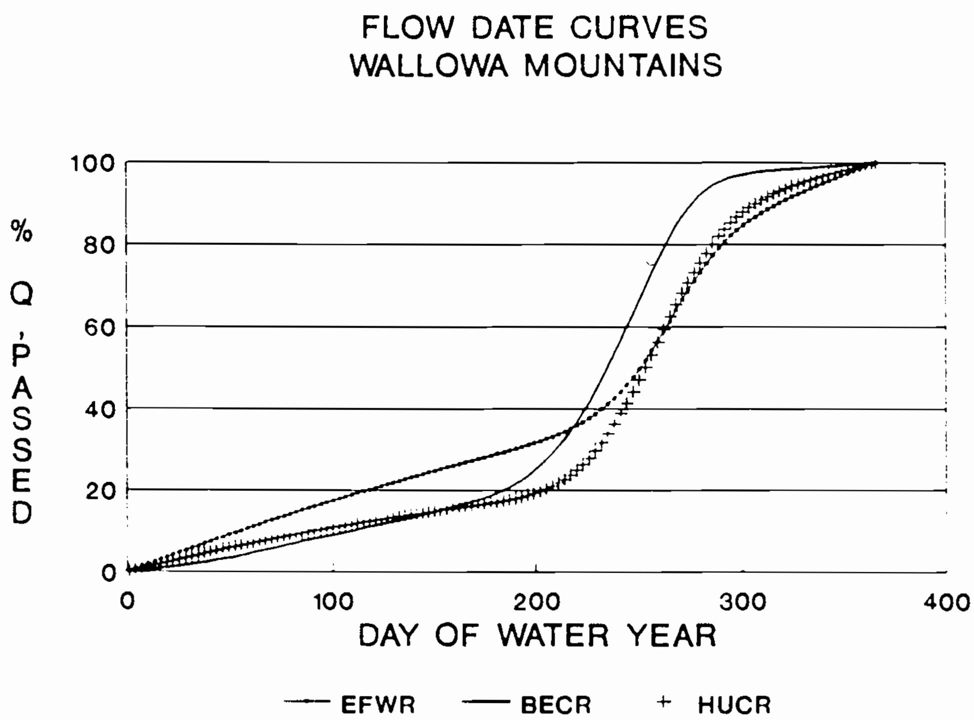

Figure 20. Flow date curves for streams in the Wallowa Mountain region.

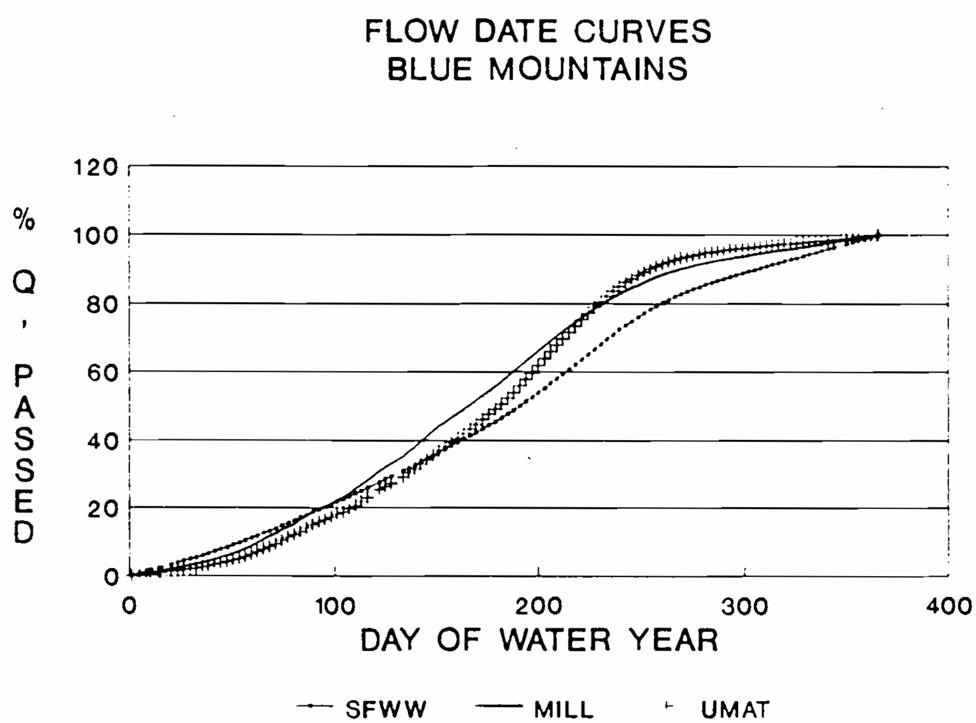

Figure 21. Flow date curves for streams in the Blue Mountain region.

Mountain region. The flow date curves have a steeper rise at the beginning of the water year. The South Fork Walla Walla River has a less "S"-shaped flow date curve, compared to the other two streams in the region. It gradually increases with a constant increment until the last Week of April, when it has a comparatively steeper rise. For the later portion of the flow date curve, from the second week of June to the end of the water year, the stream has a comparatively low flow period. The flow date curve for Mill Creek is similar to that of the Umatilla River for both the end portions (during late summer and early fall low flows). The Umatilla River has flatter and longer end portions of the curve than the other two streams in the region, showing more sustained low flows during late summer and early fall. It has a steeper central portion, which shows the highly variable flow during mid January through mid May. The South Fork Walla Walla River has less curvature in the flow date curve until July, showing steady flow during winter and spring. During summer, flow date curve is comparatively less steep, which shows the low flow period. Intra-regional flow date curve similarities for the streams in the Blue mountain region are greater, compared to the other two regions. For Mill Creek, the South Fork Walla Walla River and the Umatilla River, 37%, 40% and 47% of the total flows occur during April through June, respectively.

SOUTHEASTERN OREGON REGION

The Silvies River (Fig. 22) has the strongest "S"-shaped flow date curve of all the nine streams analyzed, making three distinct portions. It is similar to the flow date curve for Bear Creek in the Wallowa Mountain region. The flow date curve for the Silvies River has a prolonged

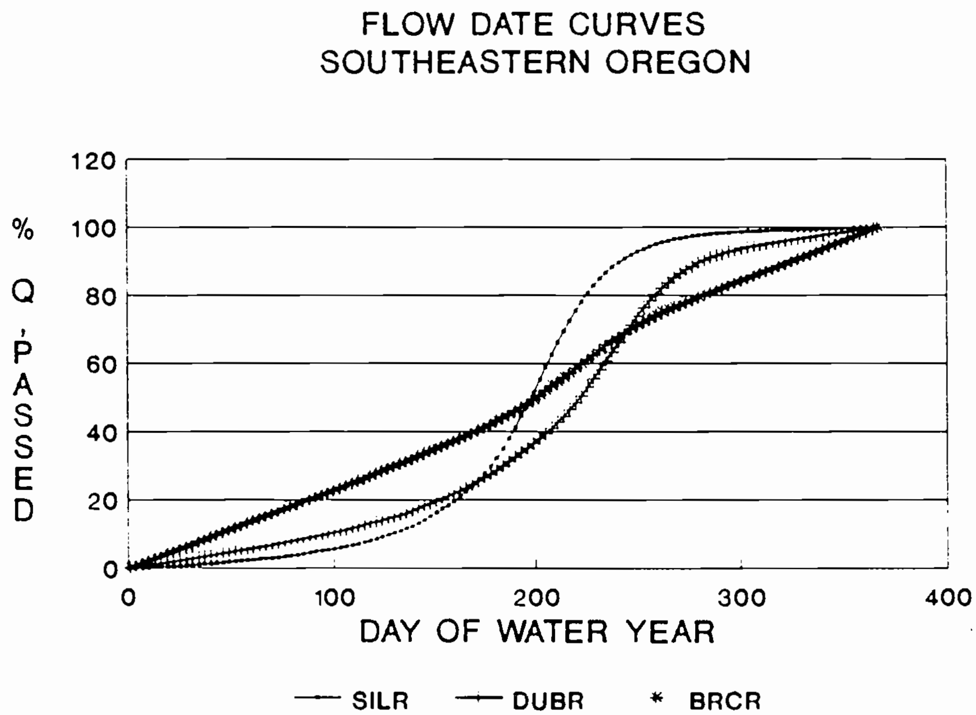

Figure 22. Flow date curves for streams in the southeastern Oregon region.

period of low flows from late summer to the early winter. It has a steeper central portion of the curve (during the late winter and early summer), compared to the other streams in the study. During late winter and early summer it has high peak flows because of precipitation and snowmelt. Bridge Creek has the least "S"-shaped flow date curve of all the streams under study, almost a straight line. It has a slightly steeper portion of the curve during the early summer. For rest of the year, it has a stable source of water for streamflow, and is relatively unaffected by the climatic changes during the year. Bridge Creek has the minimum year-to-year, as well as seasonal, variability in the streamflow. The flow date curve for the Donner Und Blitzen River is similar to that of the Silvies River, with slightly more variability in the streamflow during low flow periods. The high flow portion of the flow date curve during late winter and early summer is less steep than that of the Silvies River.

Intra-regional flow date curve similarities for the streams in the southeastern Oregon region are minimum, compared to the other two regions. More than 75% of the total flow for the Silvies River occurs during March through mid June. However, only 54% of the total flow for the Donner Und Blitzen River and 35% of the total flow for Bridge Creek occur during the same period.

Overall, streams in the Blue mountain region have their low flow periods during late summer and the first few weeks of fall, and have the weakest "S"-shaped flow date curves. Streams in the Wallowa mountain region have stronger "S"-shaped flow date curves. The low flow period extends from late summer to early winter. The southeastern Oregon region has high variability in the flow date curves. The Silvies River has the strongest "S" shaped flow date curve with most variable streamflow during a water year. The flow date curve for Bridge Creek is close to a straight line, has a permanent water supply through subsurface and ground water storage.

LOW FLOW FREQUENCY CURVES

Low flow levels, once attained in natural conditions remain stable over a long period of the time. Range of flows between monthly low flows or 7-and 30-day average minimum flows is much smaller than the range of flow between different return intervals. In the region where minimum flows occur during the winter season, flow frequency curves for 7-and 30-day average low flow or absolute minimum flows give little information regarding summer low and base flows. When 7-and 30-day average low flow frequency curves are similar for a stream, it means that low flows are consistent and sustained throughout their range. Flow frequency curves are constructed from 7-day and 30 day average minimum flows. Another set of frequency curves is constructed from annual, August, September and October absolute minimum flows for each stream. July low flows for streams in the Wallowa and Blue Mountain regions are always higher than the August and September low flows (Widner, 1991). When the curve is flatter it means that year-to-year variability is low and vice versa. Seasonal curves also provide information about recession of low flows by spacing between successive months' curves.

ANNUAL AND SEASONAL LOW FLOW FREQUENCIES:

WALLOWA MOUNTAIN REGION:

7-AND 30-DAY LOW FLOW FREQUENCIES:

Seven-and 30-day average minimum flow frequency curves are quite similar for the East Fork Wallow River (Fig. 23) and have minimum variation for different return intervals. Bear Creek (Fig. 25) and Hurricane Creek (Fig. 27) have slightly steeper 7-and 30-day average minimum flow frequency curves, compared to those of the East Fork Wallowa River, showing more year-to-year variability in minimum flows. Annual and 7-and 30-day average low flow frequency curves for each stream in the region are similar.

ANNUAL, AUGUST, SEPTEMBER AND OCTOBER LOW FLOW FREQUENCIES:

August minimum flow frequency curves have the highest values. Low flows keep decreasing from August to September to October. Lowest minimum flows occur in winter rather than summer, and annual low flow frequency curves are lower than summer monthly minimum flow frequency curves. The low flows are lower because 1) extreme cold periods, ice formation during winter and 2) aquifer yield, if any, is finally depleted. Low flow frequency curves are higher and more variable for Hurricane Creek (Fig. 26), compared to those of the East Fork Wallowa River (Fig. 24) and Bear Creek (Fig. 28). However, variability in low flows for all the streams is very low for higher return intervals (20 years and above).

BLUE MOUNTAIN REGION:

7-AND 30-DAY LOW FLOW FREQUENCIES:

Seven-and 30-day average low flow frequency curves

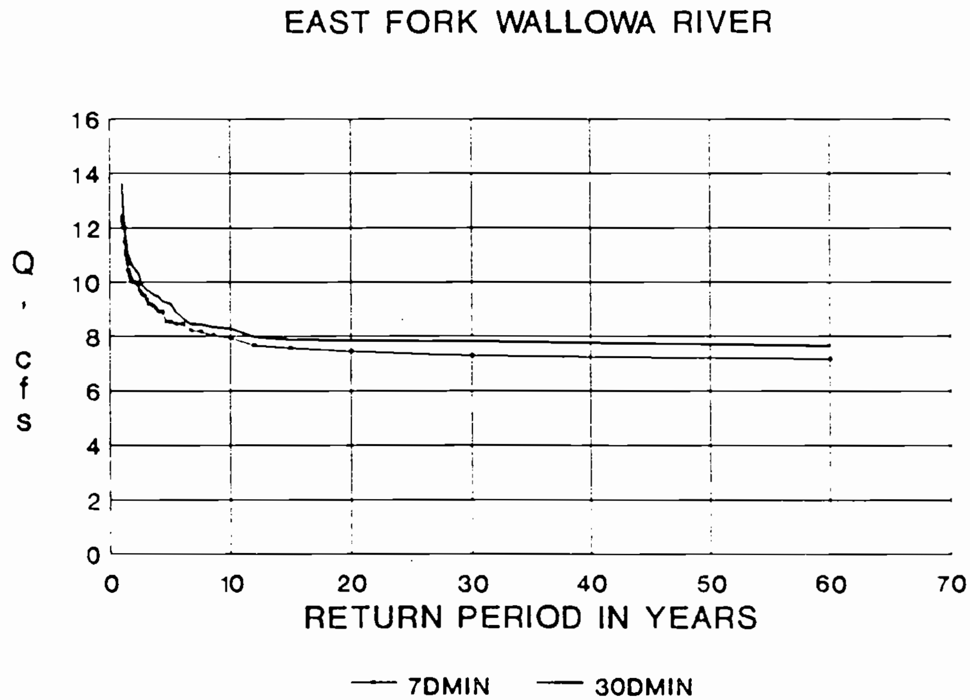

Figure 23. Seven- and 30-day low flow frequencies for the East Fork Wallowa River.

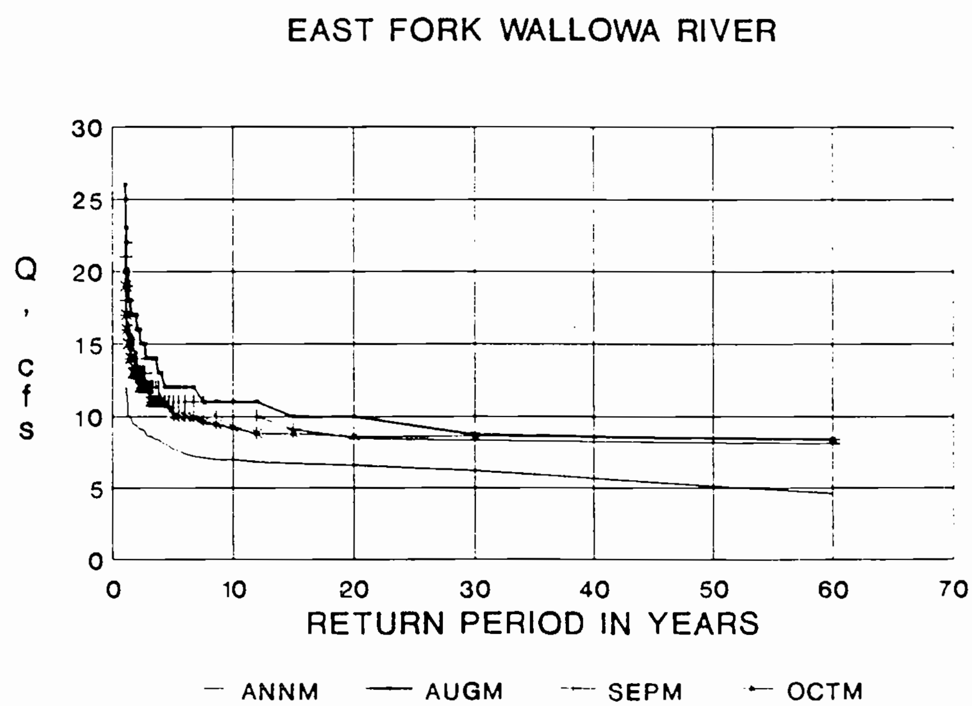

Figure 24. Annual and monthly low flow frequencies for the East Fork Wallowa River.

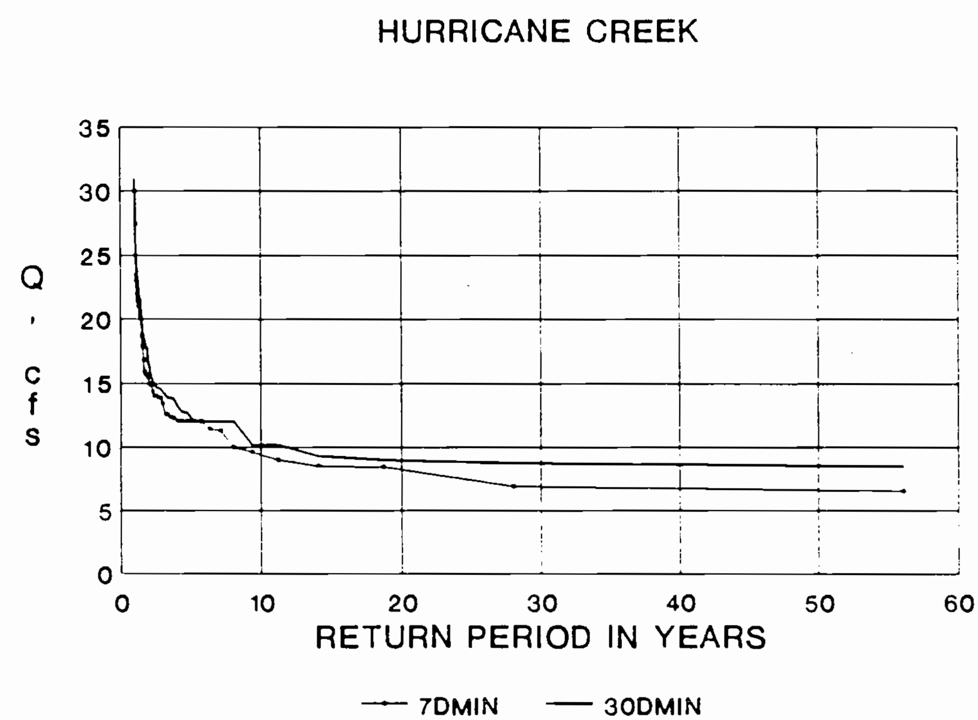

Figure 25. Seven- and 30-day low flow frequencies for Hurricane Creek.

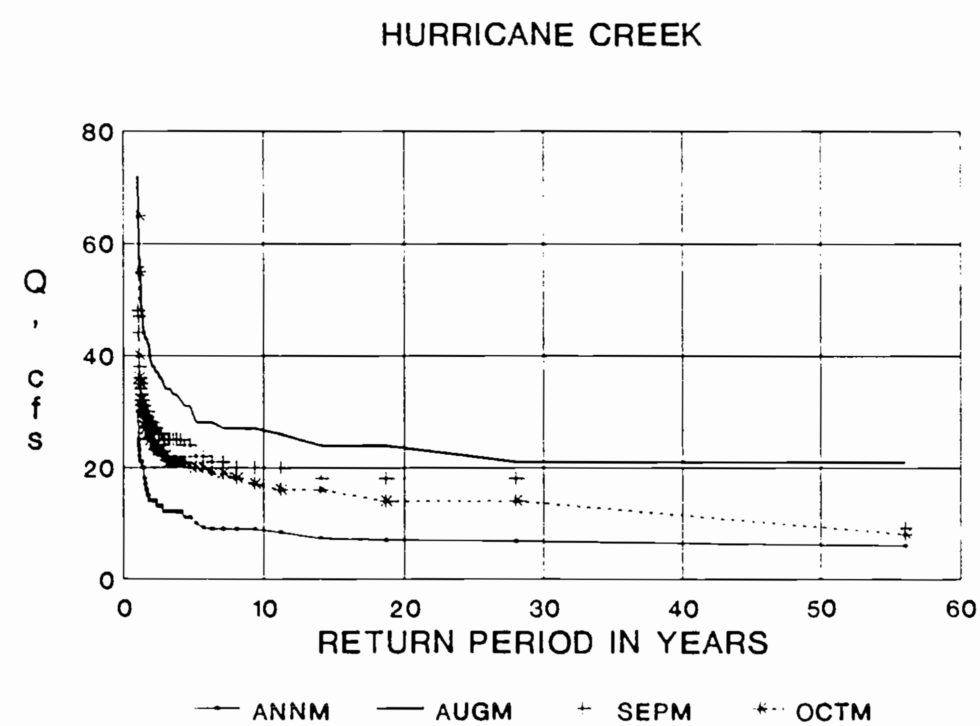

Figure 26. Annual and monthly low flow frequencies for Hurricane Creek.

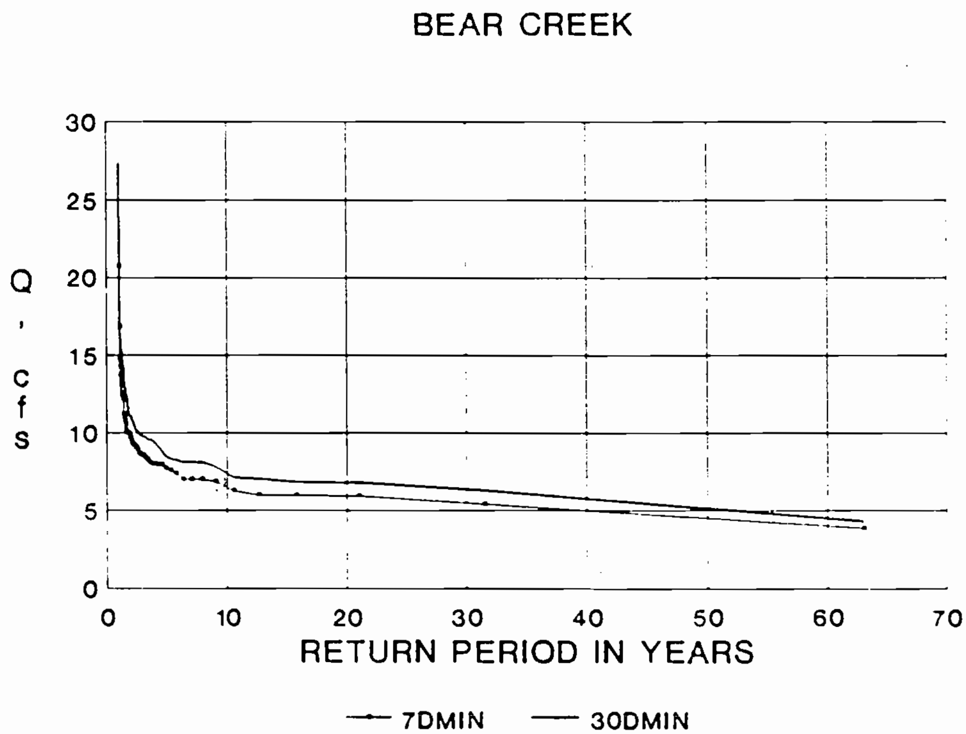

Figure 27. Seven- and 30-day low flow frequencies for Bear Creek.

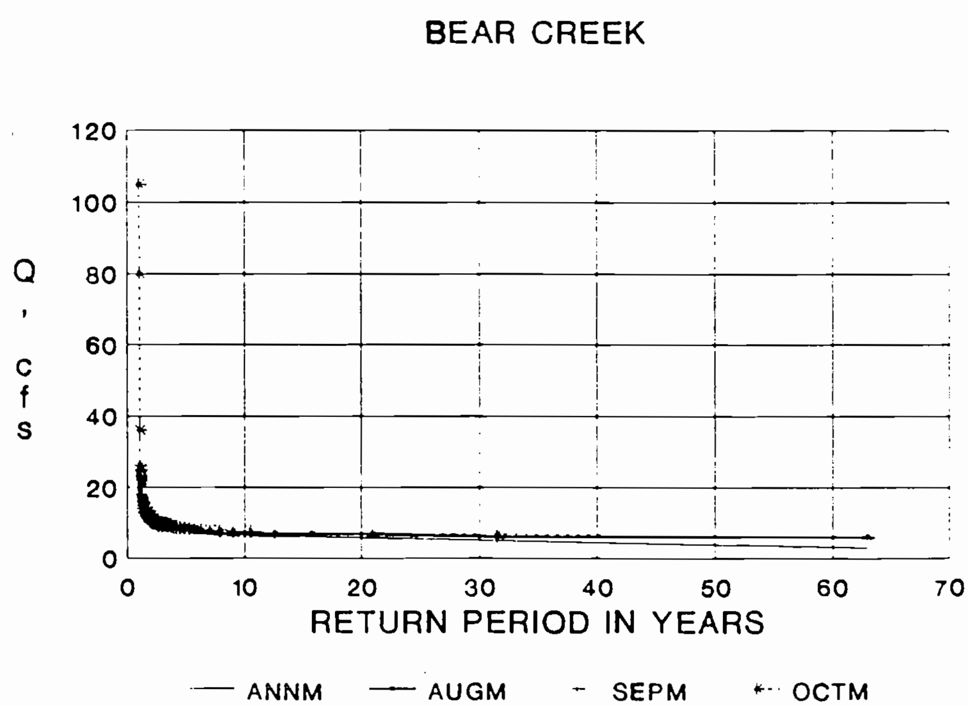

Figure 28. Annual and monthly low flow frequencies for Bear Creek.

for the South Fork Walla Walla River are quite similar, with minor variability in flow (Fig. 29). Flatness of the low flow frequency curve increases with the length of return interval. Seven and 30 day low flow frequency curves for Mill Creek are different. This difference increases with increase in return interval. Variability in 7 day low flow frequency curve for different return intervals is high. Variability in flows for 30 day low flow frequency curve decreases with increase in return intervals. For larger return intervals (> 22 years), the flow remains the same. The 7-day low flow frequency curve is quite similar to those of annual and August minimum flow frequency curves. The flow frequency curve for Mill Creek (Fig. 31) shows unsustained low flows with high variability for different return intervals.

Variations in 7-and 30-day minimum flow frequencies curves for the Umatilla River (Fig. 33) are less than Mill Creek and more than the South Fork Walla Walla. Low flows vary over shorter periods of time. The low flow frequency curves become gentler with the increase in return period.

ANNUAL, AUGUST, SEPTEMBER AND OCTOBER LOW- FLOW FREQUENCIES:

The annual, August, September and October minimum flow frequency curves are almost superimposed on each other for the South Fork Walla Walla River (Fig. 30) and the Umatilla River (Fig. 34). The August minimum flow frequency curve (the South Fork Walla Walla River) and the October minimum flow frequency curve (the Umatilla River) are at the top of the frequency curves band. For Mill Creek (Fig. 32), values of low flows for different low flow frequency parameters are close to each other for smaller than 12 years return intervals. Inter-low flow

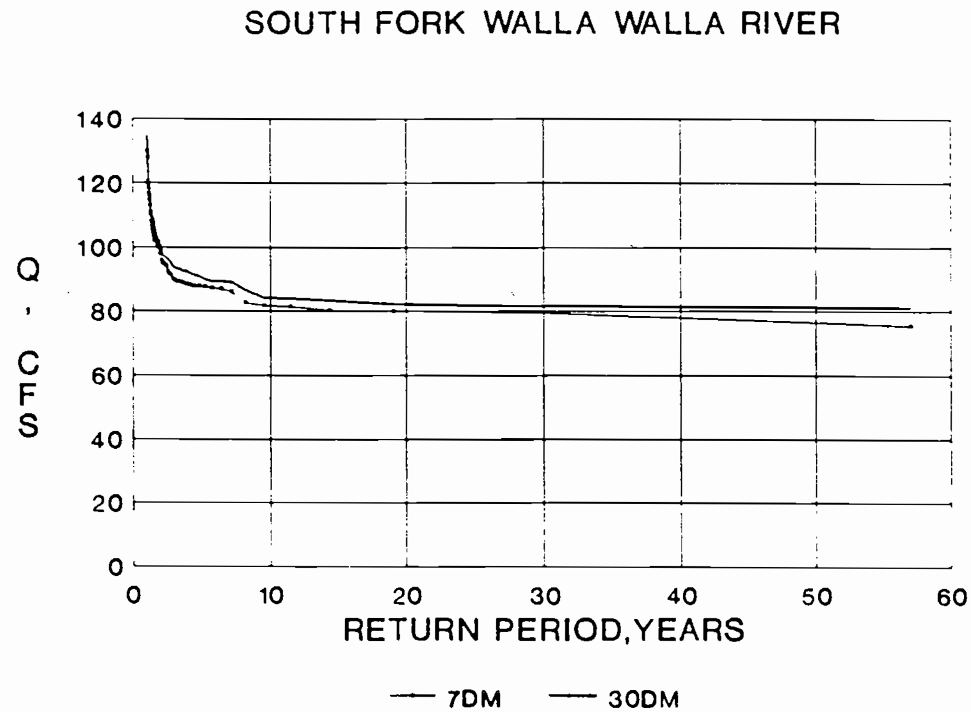

Figure 29. Seven-and 30-day low flow frequencies for the South Fork Walla Walla River.

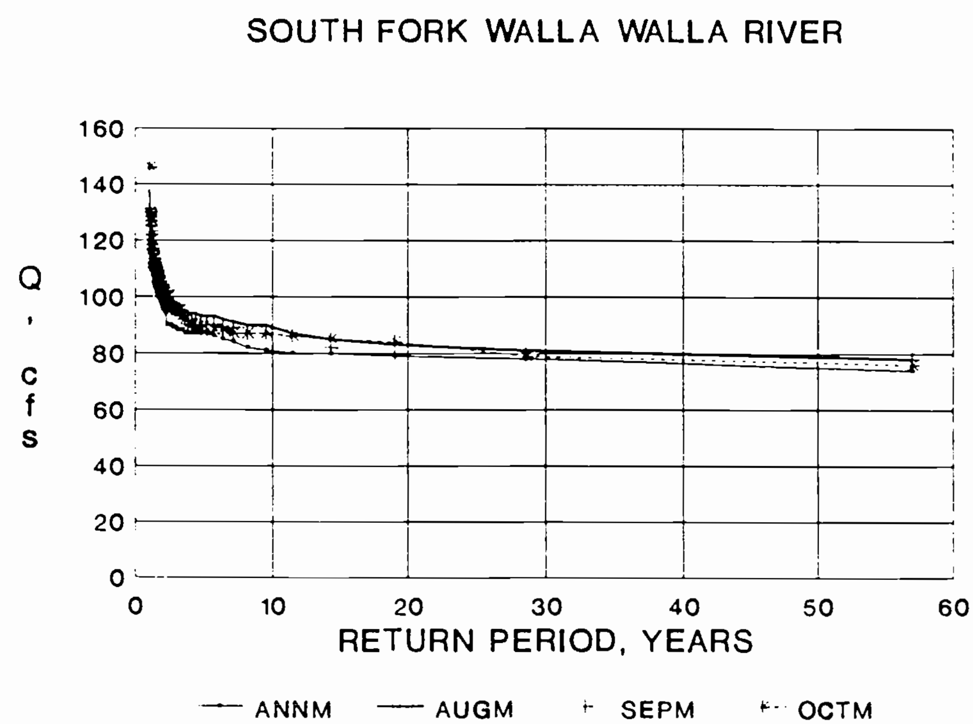

Figure 30. Annual and monthly low flow frequencies for the South Fork Walla Walla River.

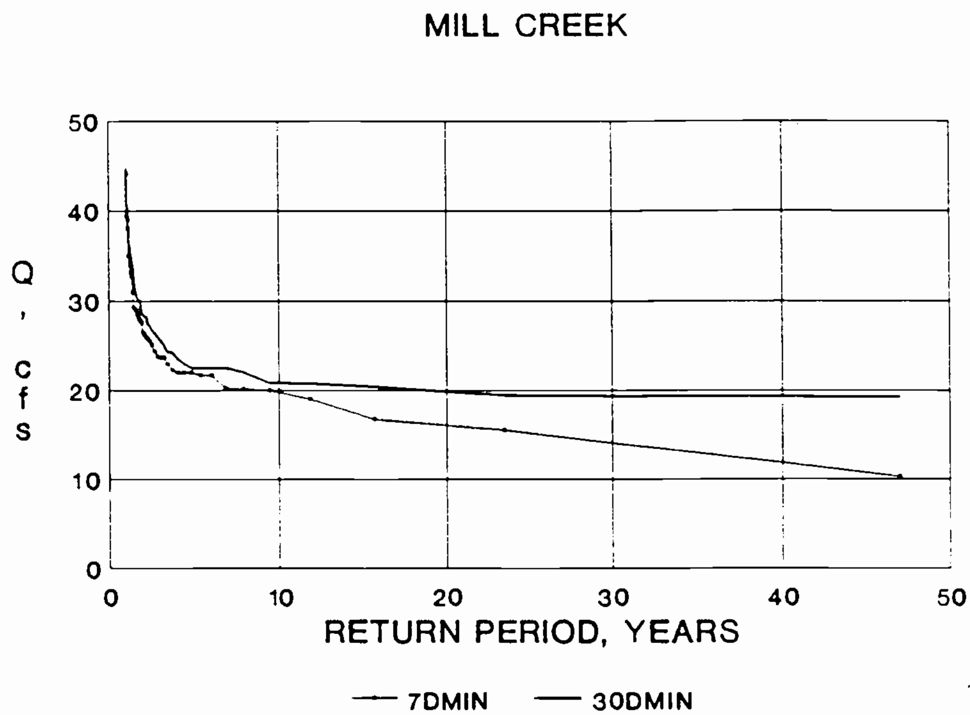

Figure 31. Seven-and 30-day low flow frequencies for Mill Creek.

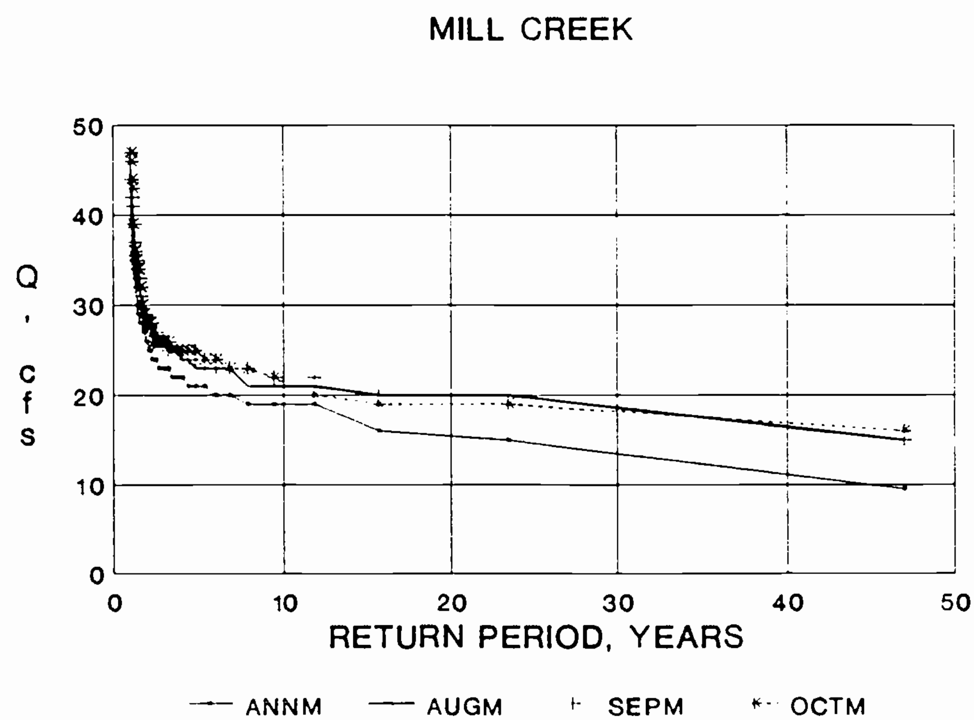

Figure 32. Annual and monthly low flow frequencies for Mill Creek.

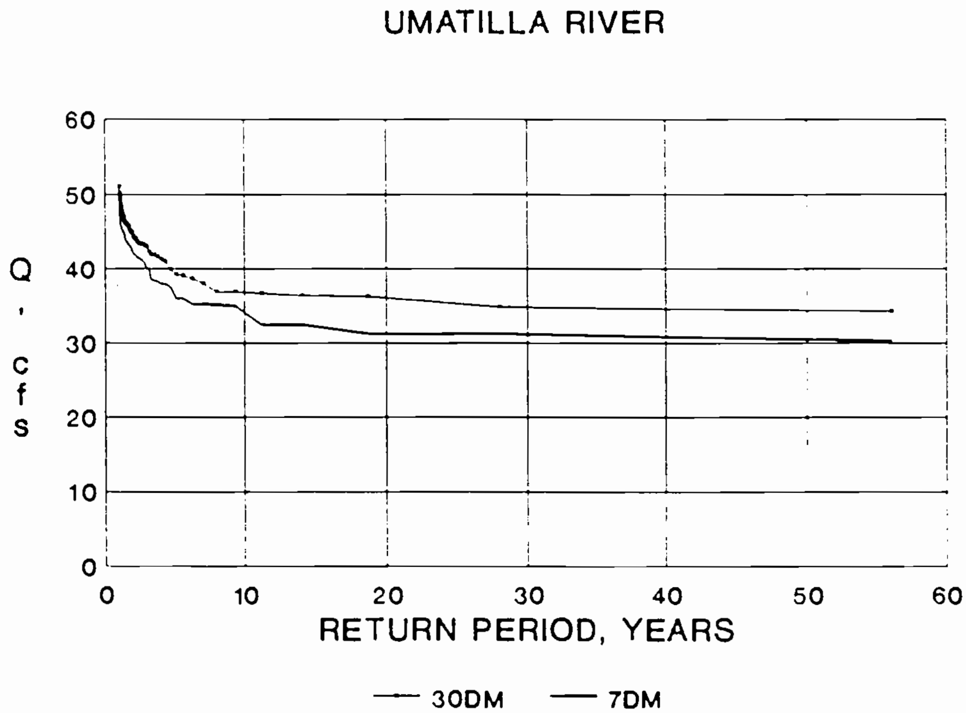

Figure 33. Seven-and 30-day low flow frequencies for the Umatilla River.

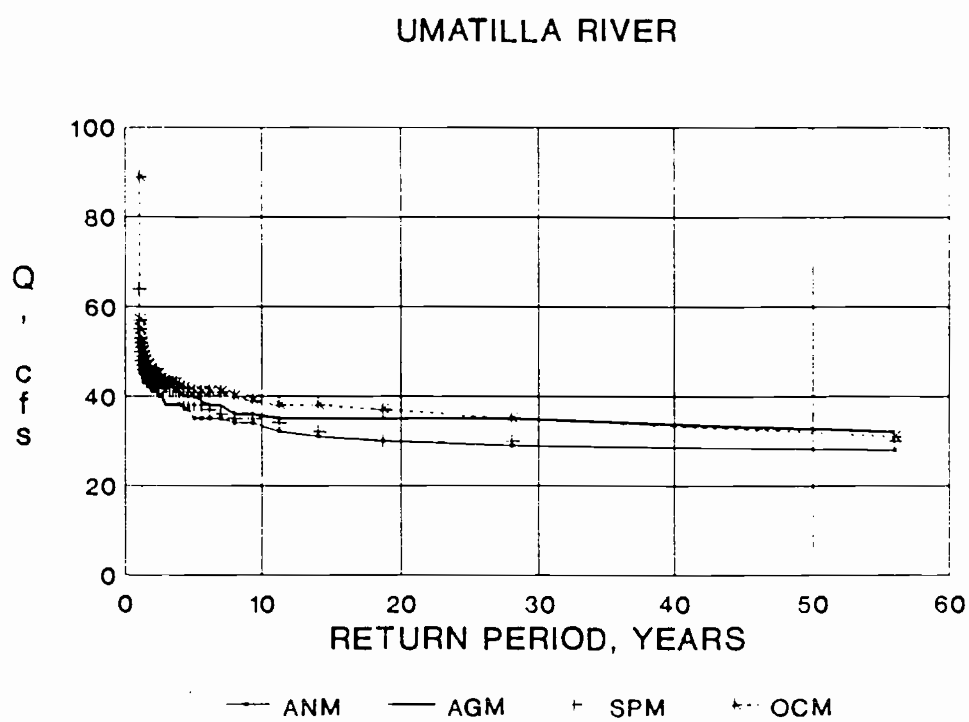

Figure 34. Annual and monthly low flow frequencies for the Umatilla River.

frequency curves spacing increased for longer periods (for more than 13 years return period), with October frequency curve at the top. Variability in low flows is greater, compared to those of the other two streams in the region.

SOUTH EASTERN OREGON REGION:

7-AND 30-DAY LOW FLOW FREQUENCIES:

Seven-and 30-day average minimum flow frequency curves for Bridge Creek (Fig. 39) are almost superimposed. For the Silvies River (Fig. 35) and the Donner Und Blitzen River (Fig. 37), 7-day average minimum flow frequency curves are slightly lower than 30-day average minimum flow frequency curves. Their difference increases gradually with the increase in return period for the Donner Und Blitzen River, with high variability in the 7-day minimum flow frequency curve. Variability in the 7-and 30-day minimum flows frequency curves for different return intervals is highest for Bridge Creek and lowest for the Silvies River.

ANNUAL, AUGUST, SEPTEMBER & OCTOBER LOW FLOW FREQUENCIES:

The October minimum flow frequency curve for the Silvies River is gentler and higher in magnitude, compared to annual, August and September minimum flow frequency curves (Fig. 36). Extreme low flows for the Silvies River occur during late August. Annual and August low flow frequency curves are similar. Minimum flow frequency curves for August and September are similar in magnitude, as well as in variability, for different return intervals for the Donner Und Blitzen River (Fig. 38). The October minimum flow frequency curve is higher than the August and September minimum flow frequency curves. Streamflow increases from late summer to fall. Bridge Creek has

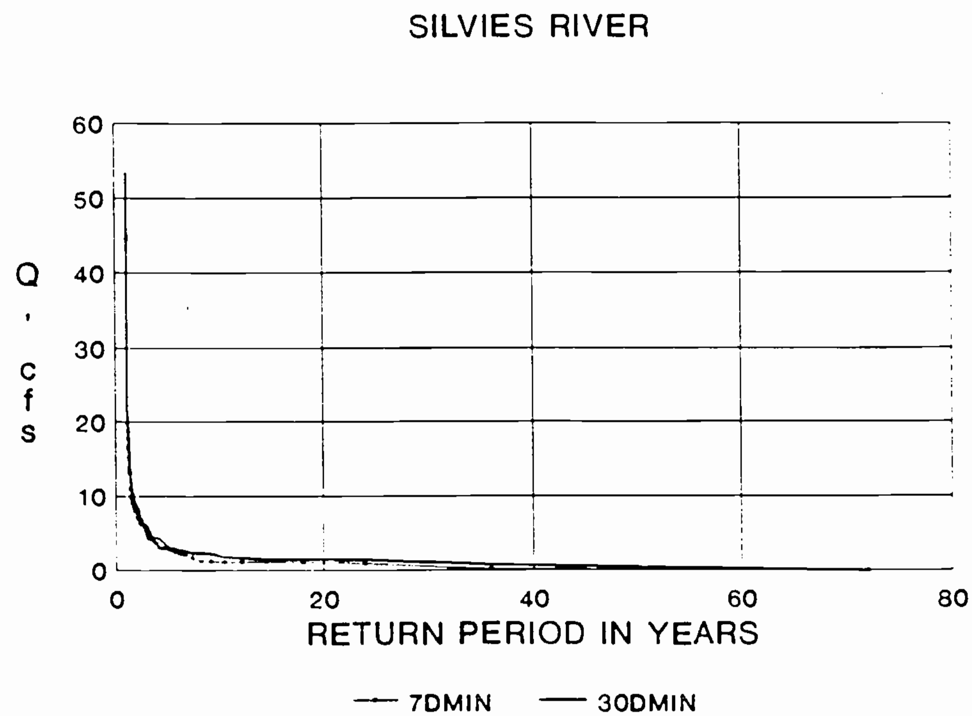

Figure 35. Seven-and 30-day low flow frequencies for the Silvies River.

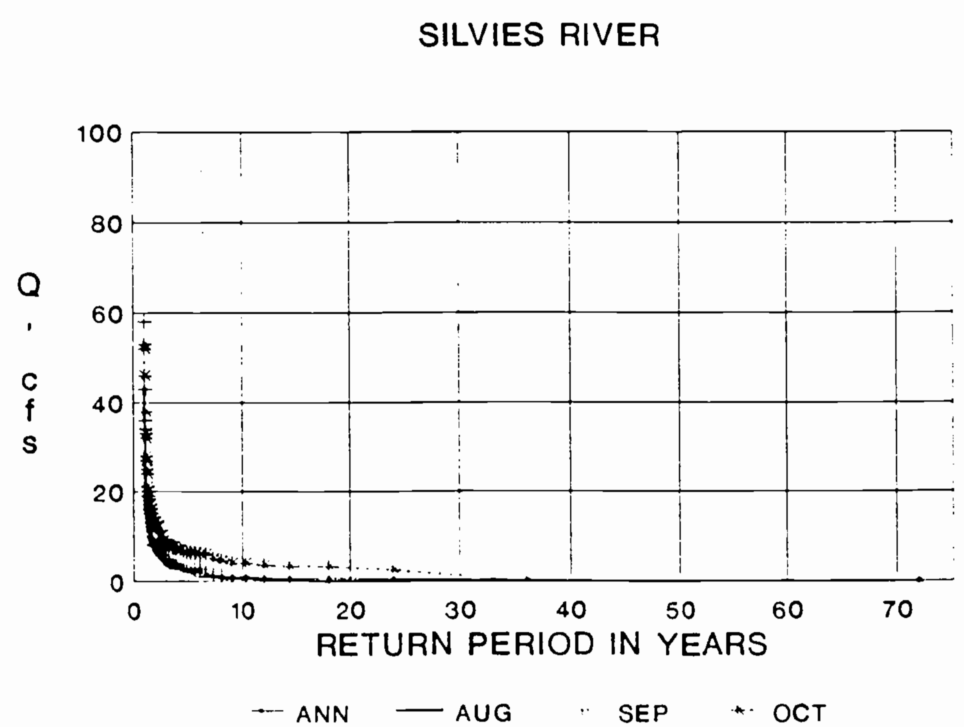

Figure 36. Annual and monthly low flow frequencies for the Silvies River.

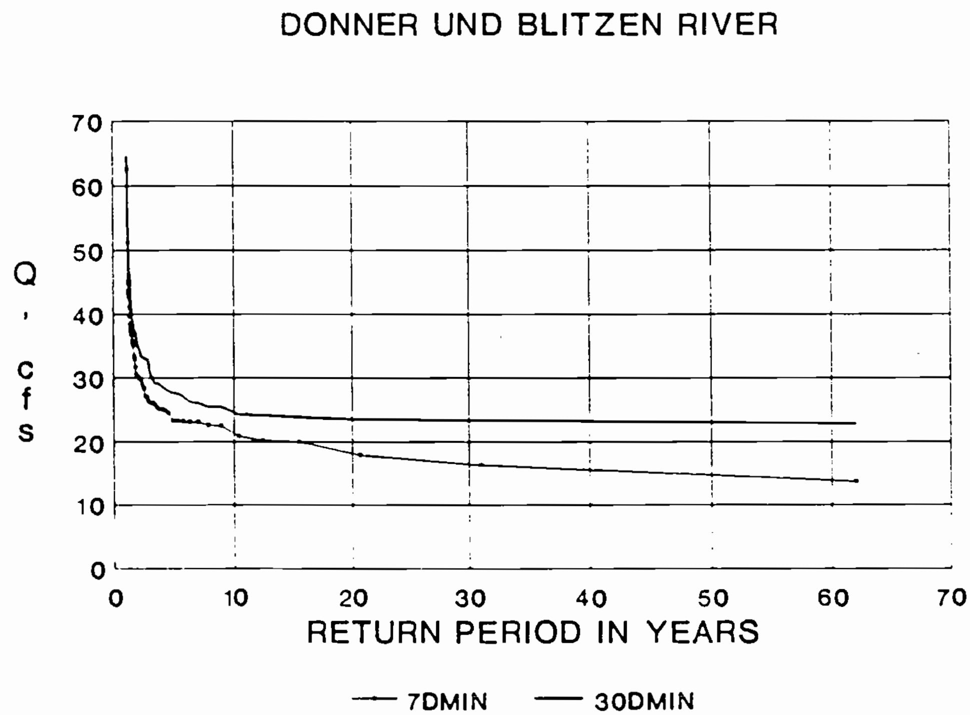

Figure 37. Seven-and 30-day low flow frequencies for the Donner Und Blitzen River.

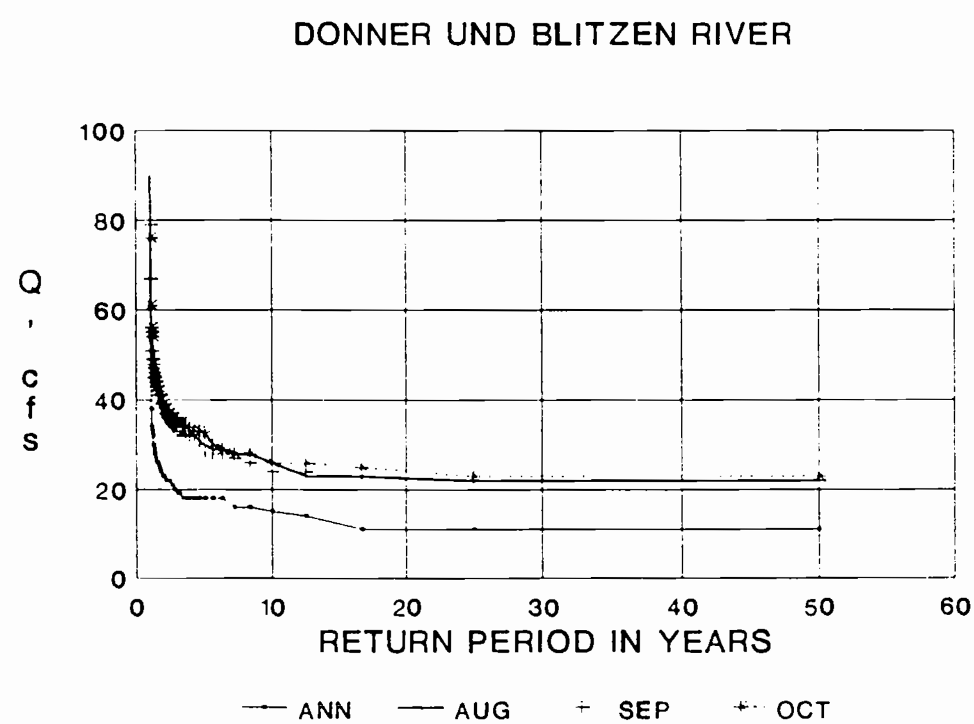

Figure 38. Annual and monthly low flow frequencies for the Donner Und Blitzen River.

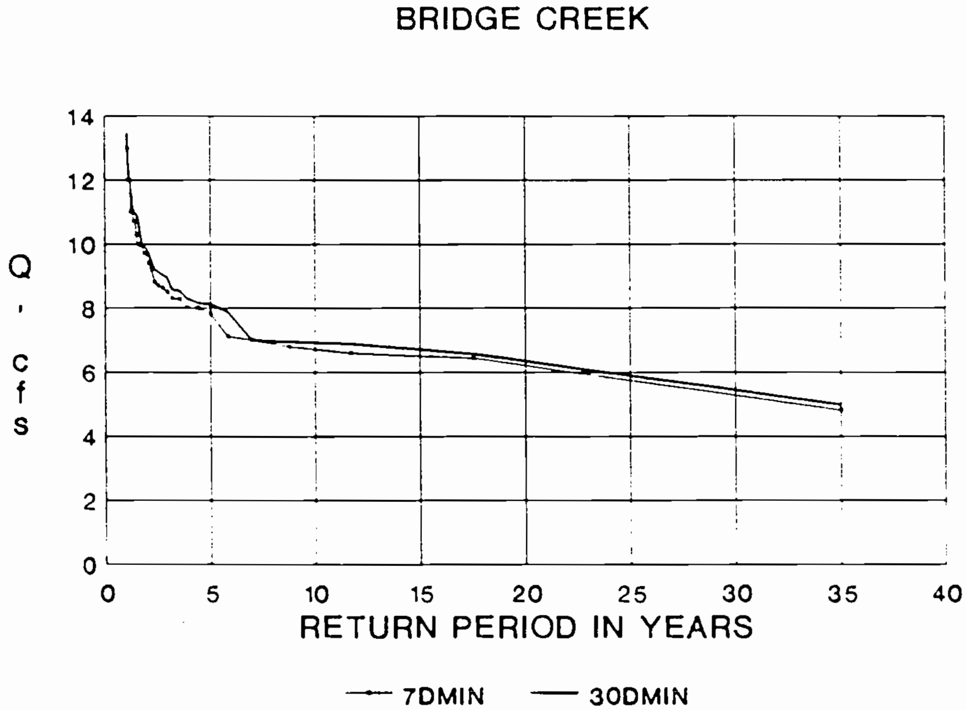

Figure 39. Seven- and 30-day low flow frequencies for Bridge Creek.

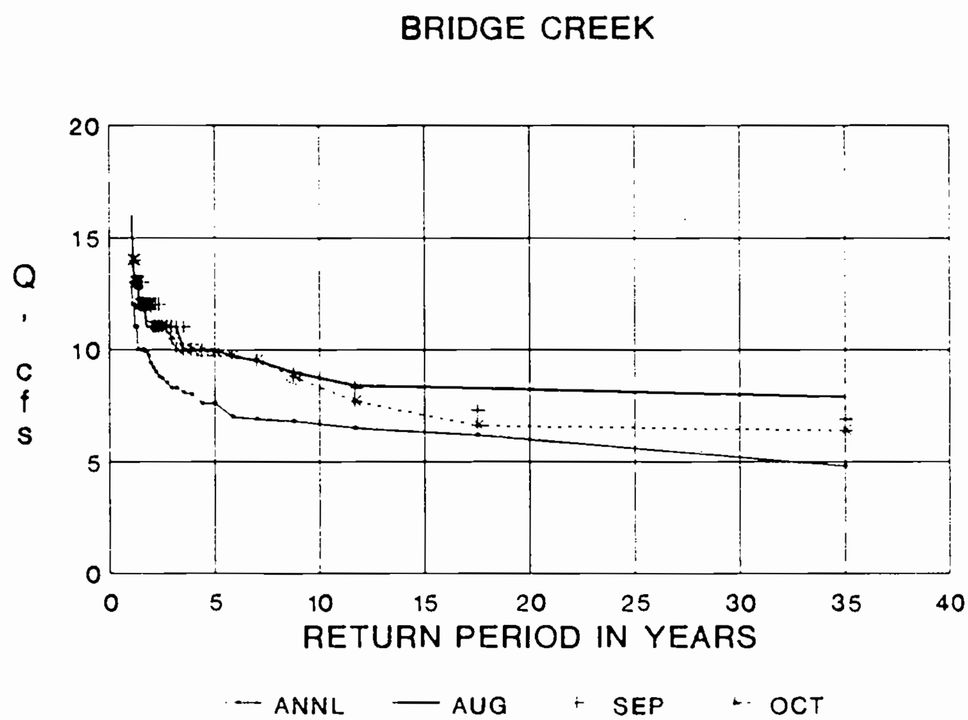

Figure 40. Annual and monthly low flow frequencies for Bridge Creek.

lower magnitudes for low flow frequency curves (Fig. 40), compared to the low flow frequency curves for the other two streams in the region. Variability in low flows for different return intervals is also lower. Low flows decrease in magnitude from August to September to October to annual minimum flows for Bear Creek.

The annual low flow frequency curves for Bridge Creek and the Donner Und Blitzen River are lower in magnitude than the summer months'low flow frequency curves. This indicates that extreme minimum flows for these two streams occur in winter.

Overall, annual low flows in the Blue mountain region occur during summer, while in the Wallowa mountain region they occur during winter. In the southeastern Oregon region, the Silvies River has annual low flows concurrent with summer low flows. However, in the Donner Und Blitzen River and Bridge Creek, annual low flows occur during winter. Snow accumulation and lower temperature at the higher elevations causes the surface, as well as some part of the subsurface, water supply to the streamflow to cease in winter. Therefore, streams in the Wallowa Mountains and the Steens Mountains have extreme low flows during winter. In the Blue Mountain region and the Silvies River, snowmelt occurs until mid-summer. During late summer, the only source of streamflow is subsurface storage and groundwater. Precipitation during the months of July and August is also minimal. Therefore, extreme minimum flows for these streams occur during late summer. Low flow frequency curves provide the information regarding the magnitudes of extreme low flows for larger return intervals. Using this information, one can plan the uses of streamflows during low flow periods with some degree of confidence. For irrigation and fish habitat, the July, August low flows may be the most important.

AVERAGE ANNUAL HYDROGRAPH

An average annual hydrograph per unit area was made for each stream. Discharge per square mile (csm) for each day was plotted against water year.

WALLOWA MOUNTAIN REGION

For The Wallowa Mountain region, all three streams have similar average annual hydrographs per unit area (Fig. 41). Bear Creek has the lowest flow during the low flow periods. The rising and falling limbs of all three streams have similar slopes, with the East Fork Wallowa River attaining its peak slightly later (during the last week of June) than the Hurricane Creek and Bear Creek (during the second week of June).

BLUE MOUNTAIN REGION

In the Blue Mountain region, the peak of the average annual hydrograph per unit area is earlier than for the Wallowa region (Fig. 42). The Umatilla River attains its peak around the last week of April, while, the South Fork Walla Walla River attains its peak around the middle of May. Mill Creek has more variability in its hydrograph for average annual discharge as well as average annual discharge per unit area. The largest peak is attained on the 135th day of the water year. Low flows in Mill Creek and the Umatilla River are similar, yet smaller than the South Fork Walla Walla River. The rising limbs of the average annual hydrographs for streams in the Blue Mountain region have considerable variations, may be due to rain-on-snow events.

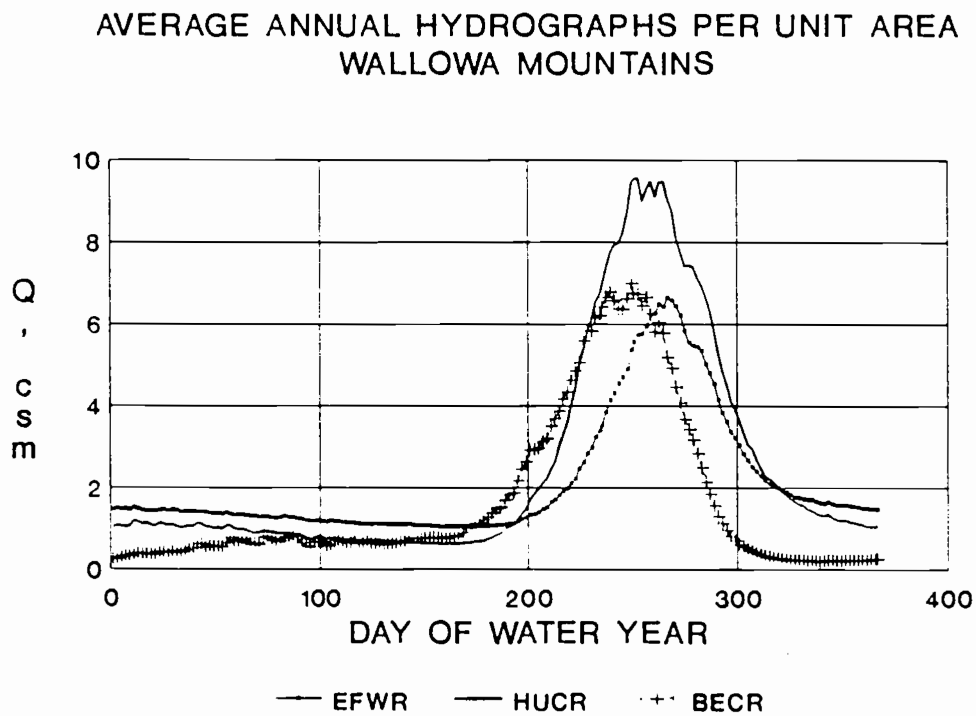

Figure 41. Average annual hydrographs per unit area for streams in the Wallowa Mountain region.

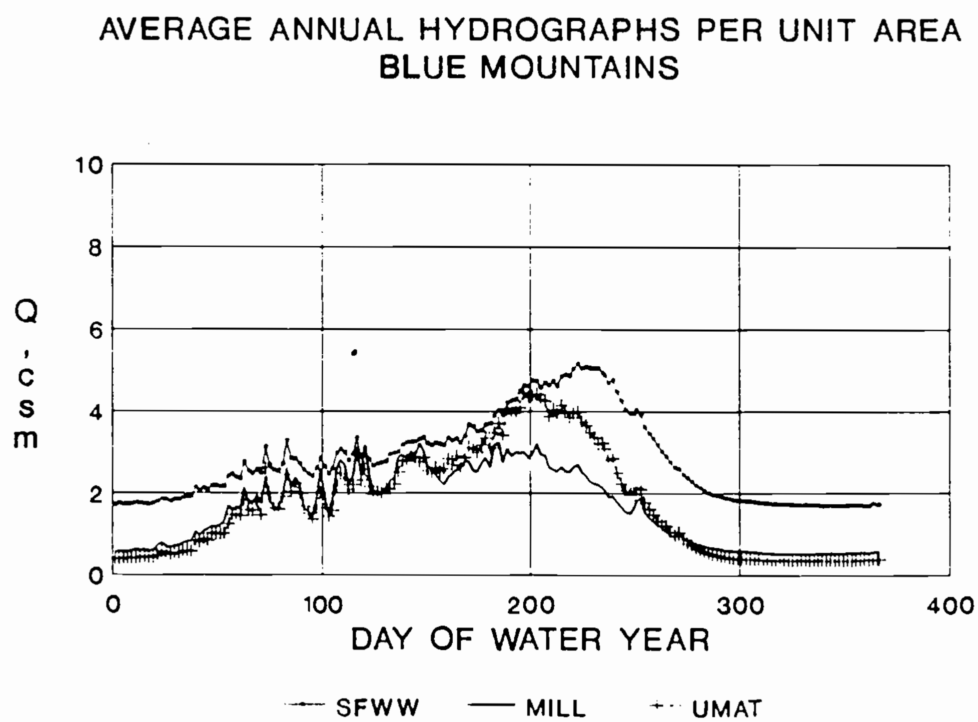

Figure 42. Average annual hydrographs per unit area for stream in the Blue Mountain region.

SOUTHEASTERN OREGON REGION

Average flows per unit area for southeastern Oregon streams are the lowest of all three regions (Fig. 43). The peak of the hydrograph for the Silvies River occurs earlier (during the last week of April), compared to the Donner Und Blitzen River and Bridge Creek (where it occurs during second half of May). The flow for the Silvies River is lower for the majority of the year, compared to the other two streams in the region. Bridge Creek has very gentle rising and falling limbs, with a less conspicuous peak. Bridge Creek has a larger flow during low flow periods than do the Silvies River and the Donner Und Blitzen River.

RECESSION FORECAST MODELS

Graphical comparisons between the forecast flows for recession volume, average August, average September and average last 7 days of water year, and respective observed flows for each stream over the years are shown in Fig. 44 to Fig. 79. Starting days for forecast model for each stream are given in Table 6, along with model equations. Average and forecast errors and percent improvement by forecast models over prediction by average flows are shown in Tables 7 and 8, respectively. Average error for recession volume and August, September and last 7 day average flows are abbreviated as AER, AEAG, AESP & AE7D, respectively. Similarly, forecast errors are shown as FER, FEAG, FESP & FE7D, respectively. Percent improvements in errors are represented as %IMPR, %IMPAG, %IMPSP & %IMPR7D in the same order.

The accuracy of each model for different parameters

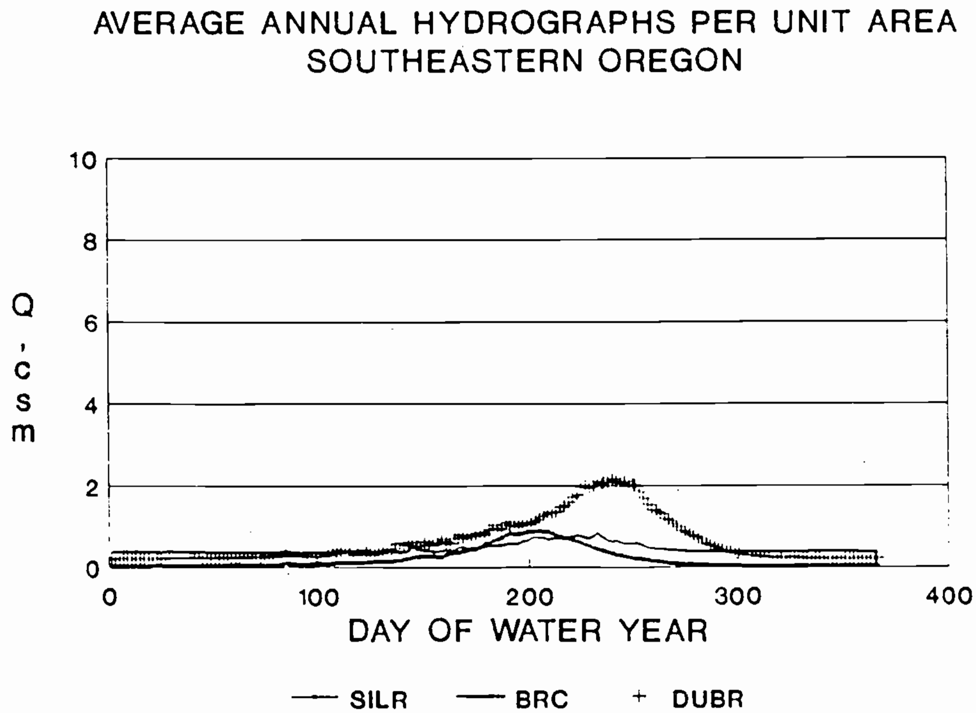

Figure 43. Average annual hydrographs per unit area for streams in the southeastern Oregon region.

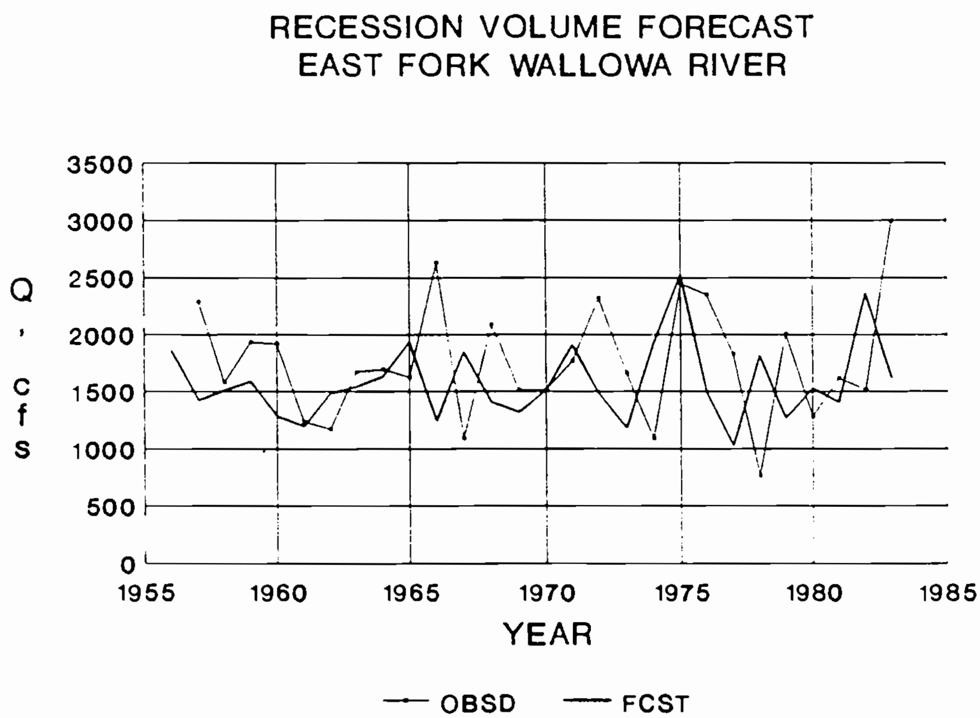

Figure 44. Observed and forecasted recession volumes for the East Fork Wallowa River.

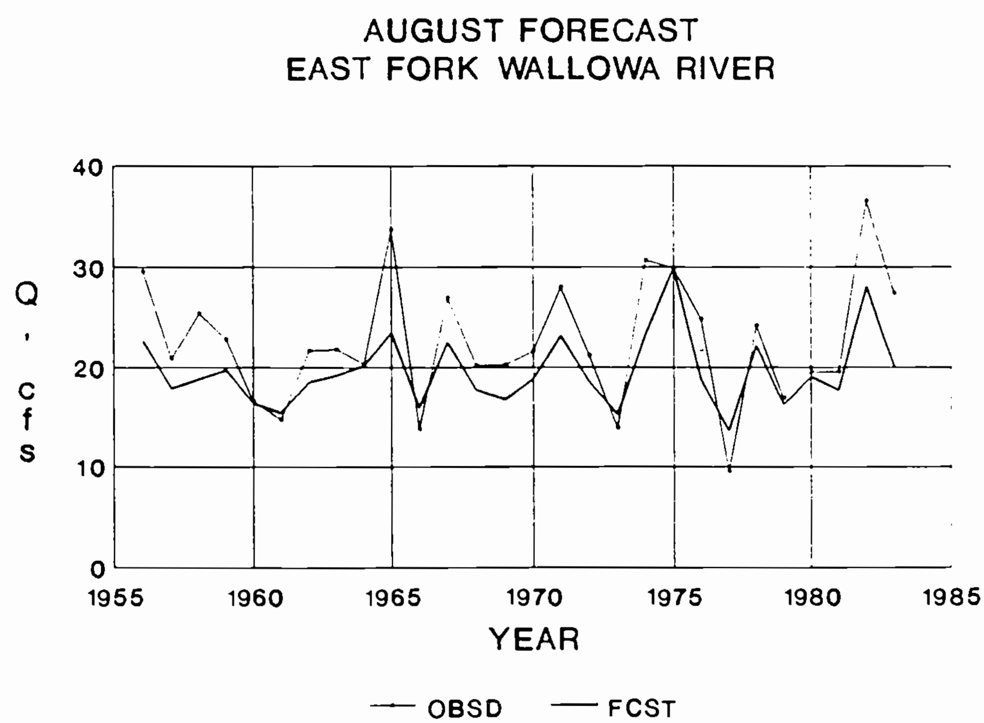

Figure 45. Observed and forecasted August average flows for the East Fork Wallowa River.

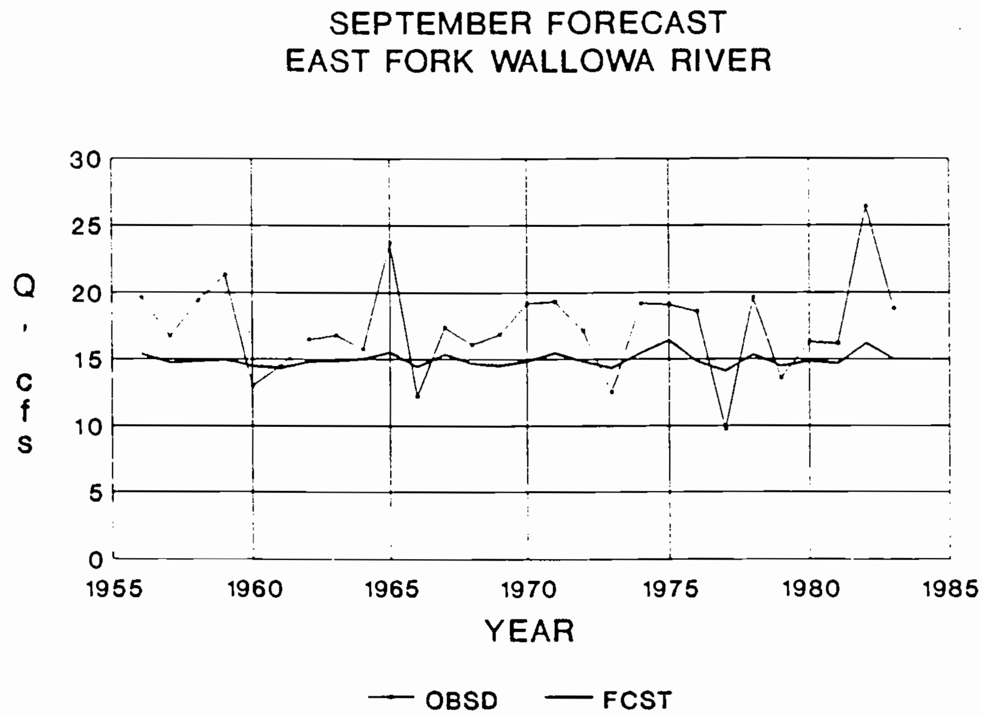

Figure 46. Observed and forecasted September average flows for the East Fork Wallowa River.

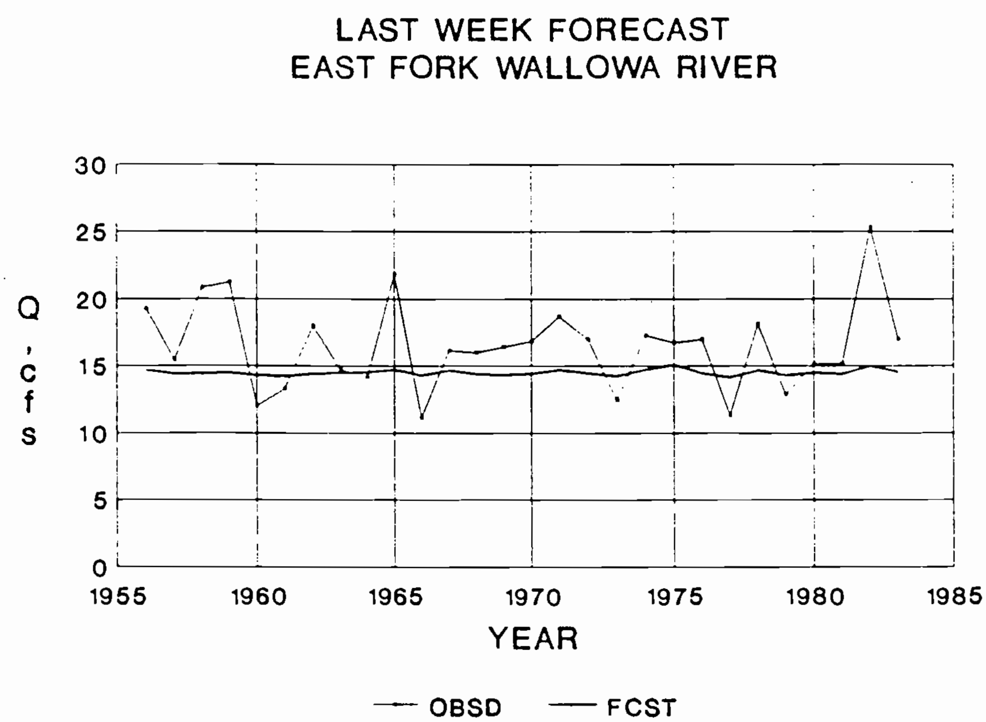

Figure 47. Observed and forecasted last week average flows for the East Fork Wallowa River.

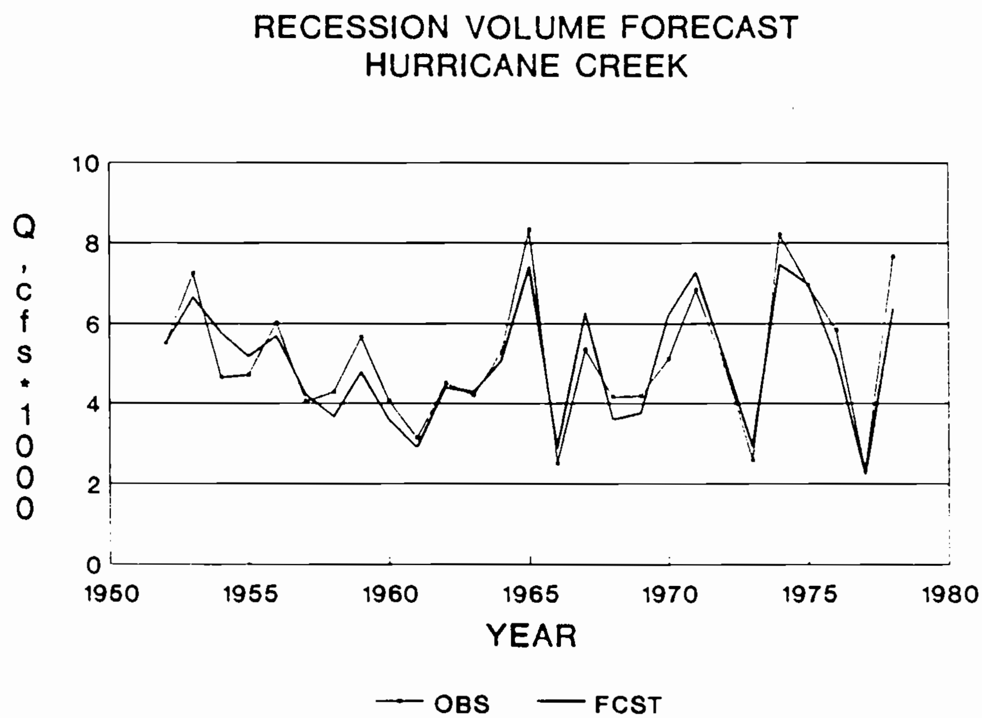

Figure 48. Observed and forecasted recession volumes for Hurricane Creek.

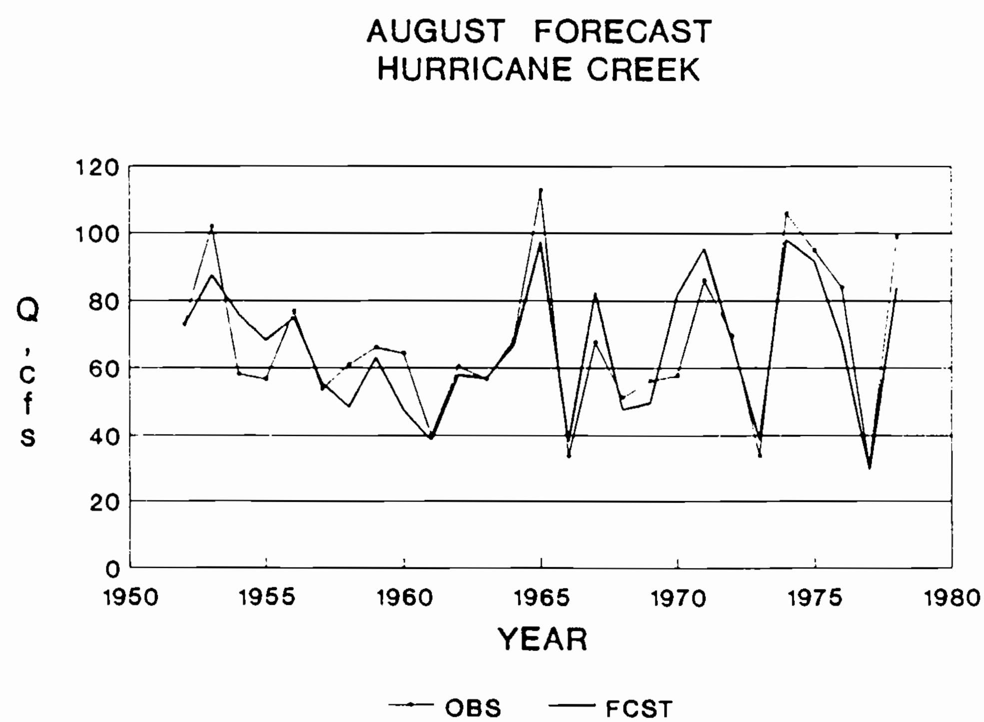

Figure 49. Observed and forecasted August average flows for Hurricane Creek.

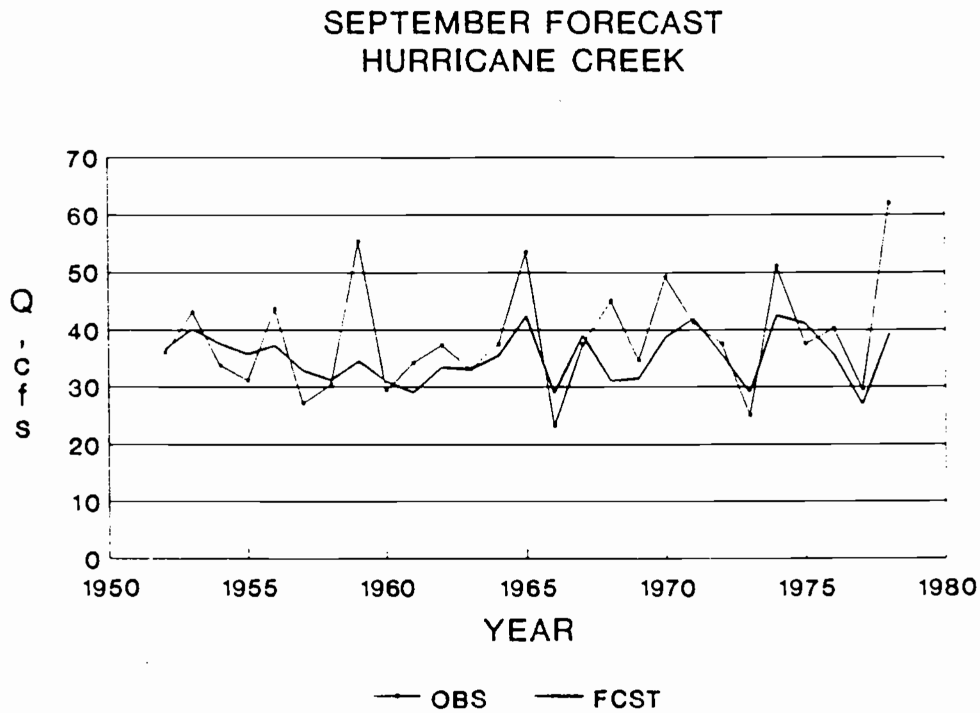

Figure 50. Observed and forecasted September average flows for Hurricane Creek.

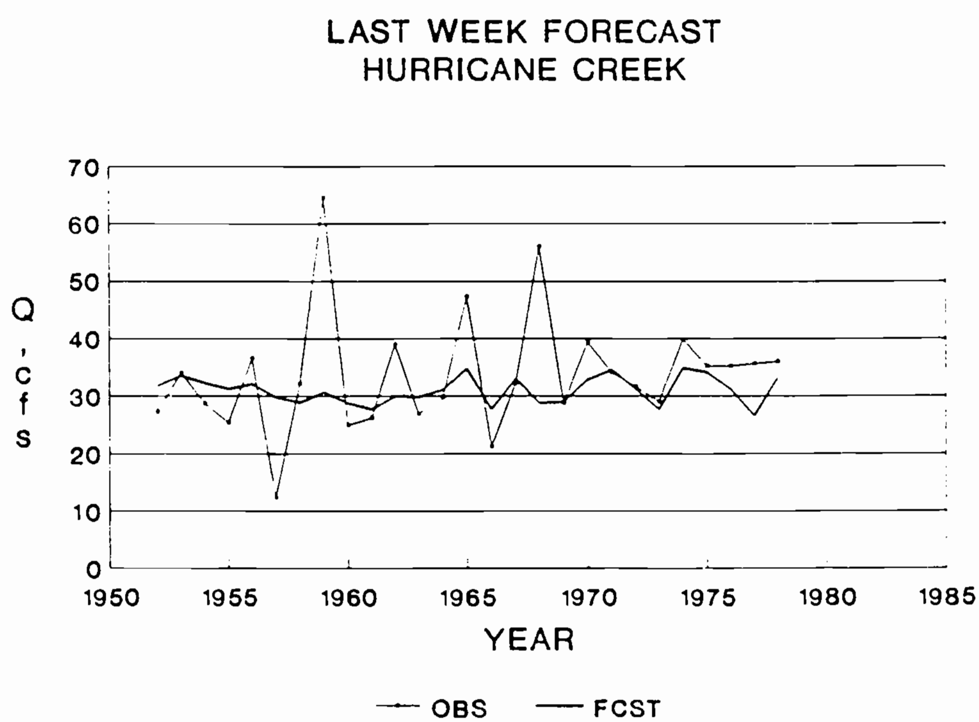

Figure 51. Observed and forecasted last week average flows for Hurricane Creek.

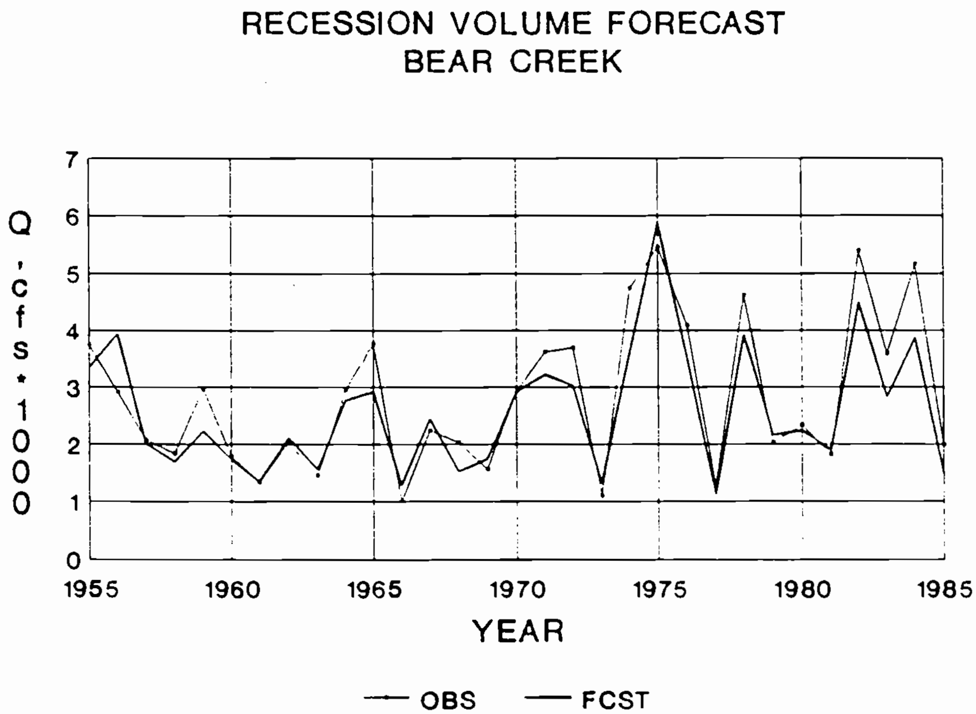

Figure 52. Observed and forecasted recession volumes for Bear Creek.

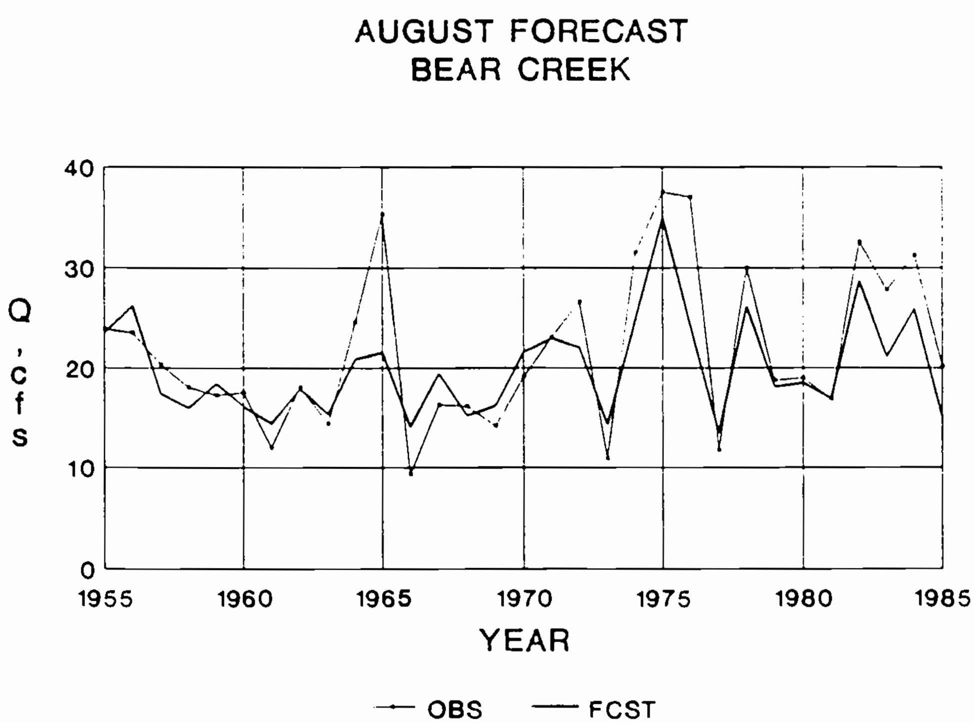

Figure 53. Observed and forecasted August average flows for Bear Creek.

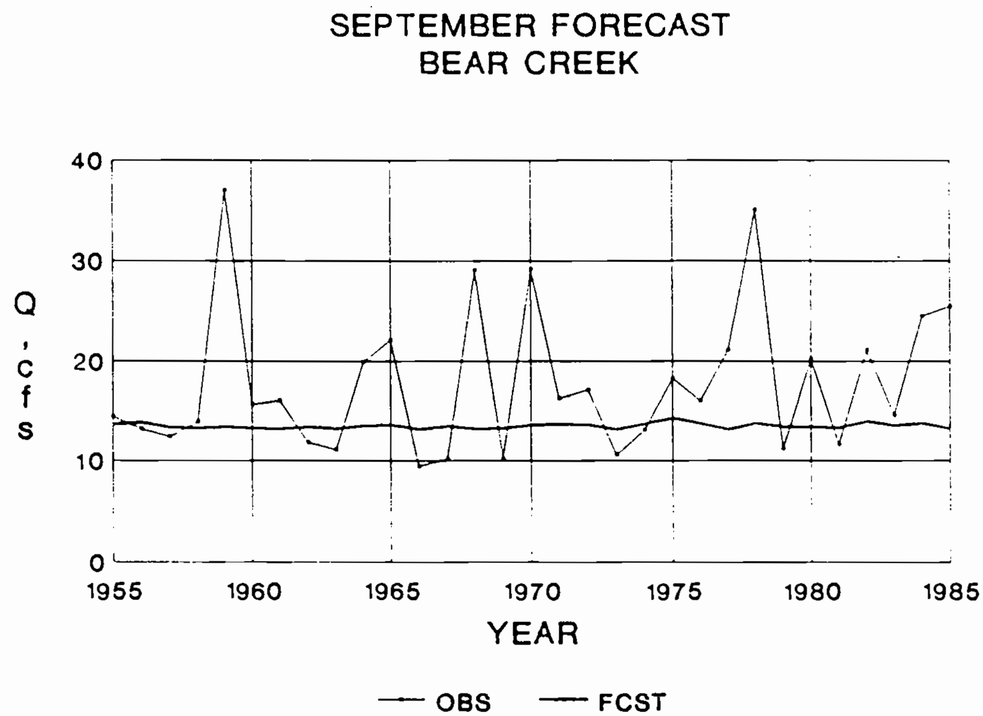

Figure 54. Observed and forecasted September average flows for Bear Creek.

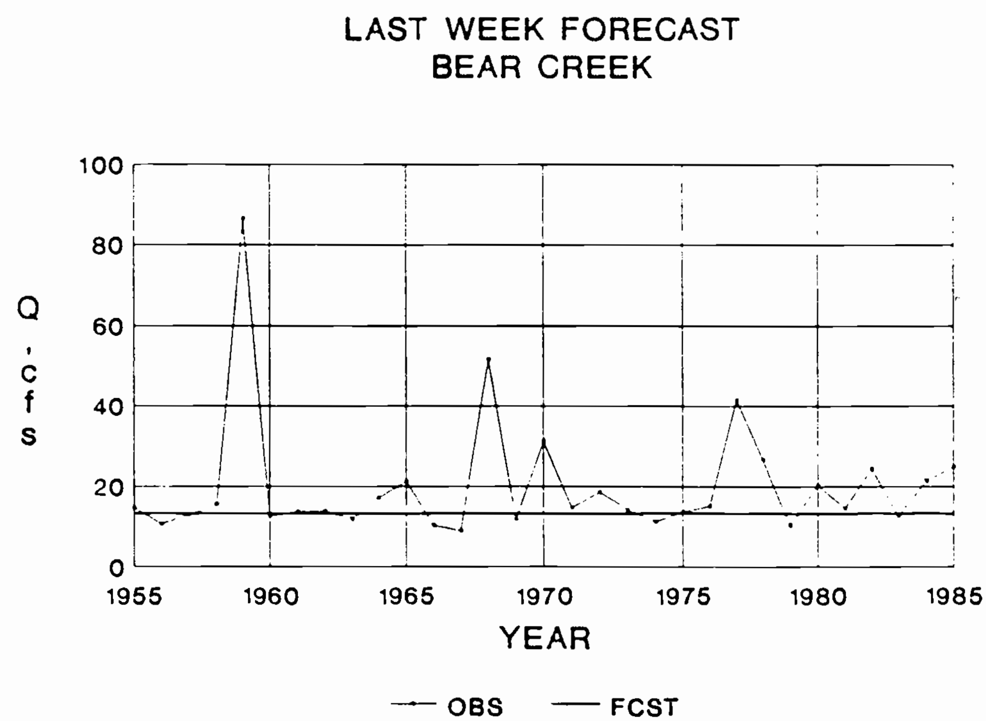

Figure 55. Observed and forecasted last week average flows for Bear Creek.

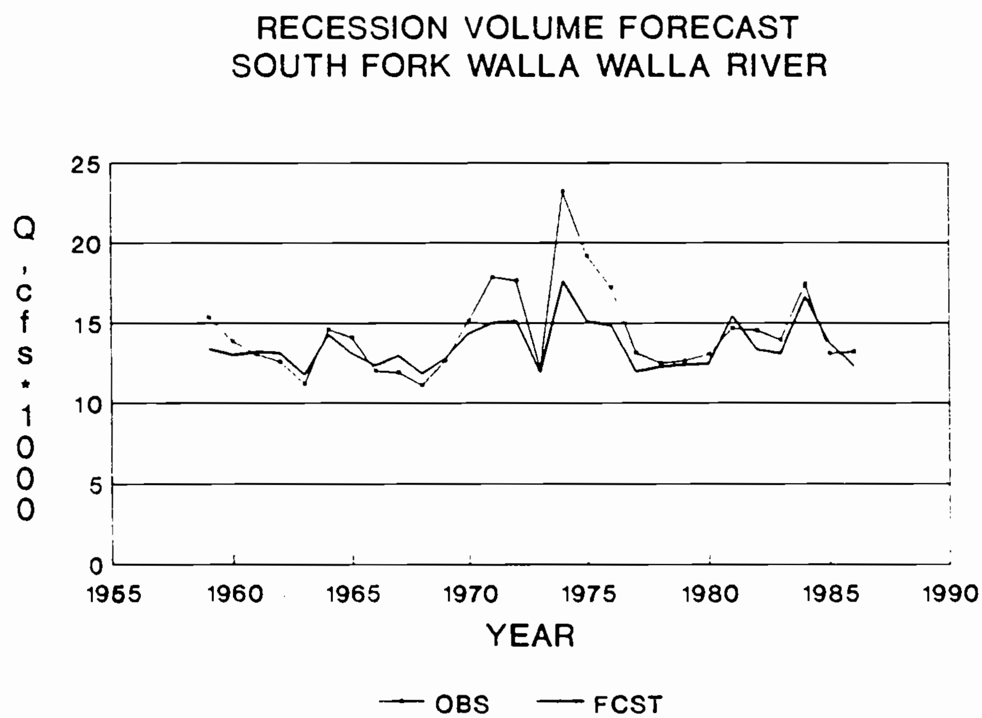

Figure 56. Observed and forecasted recession volumes for the South Fork Walla walla River.

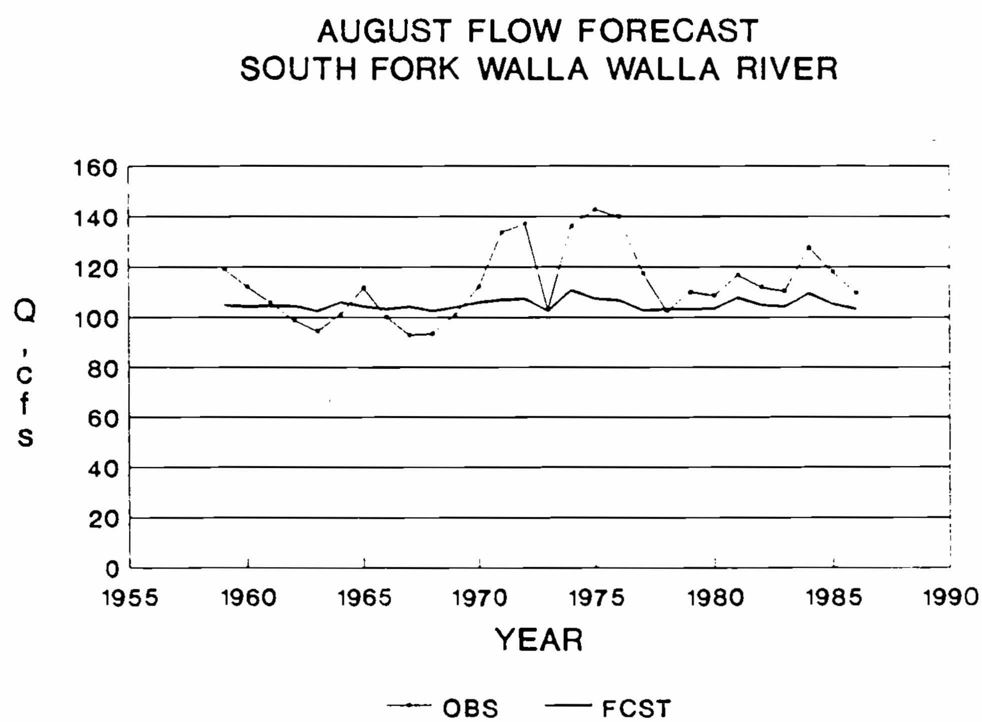

Figure 57. Observed and forecasted August average flows for the South Fork Walla Walla River.

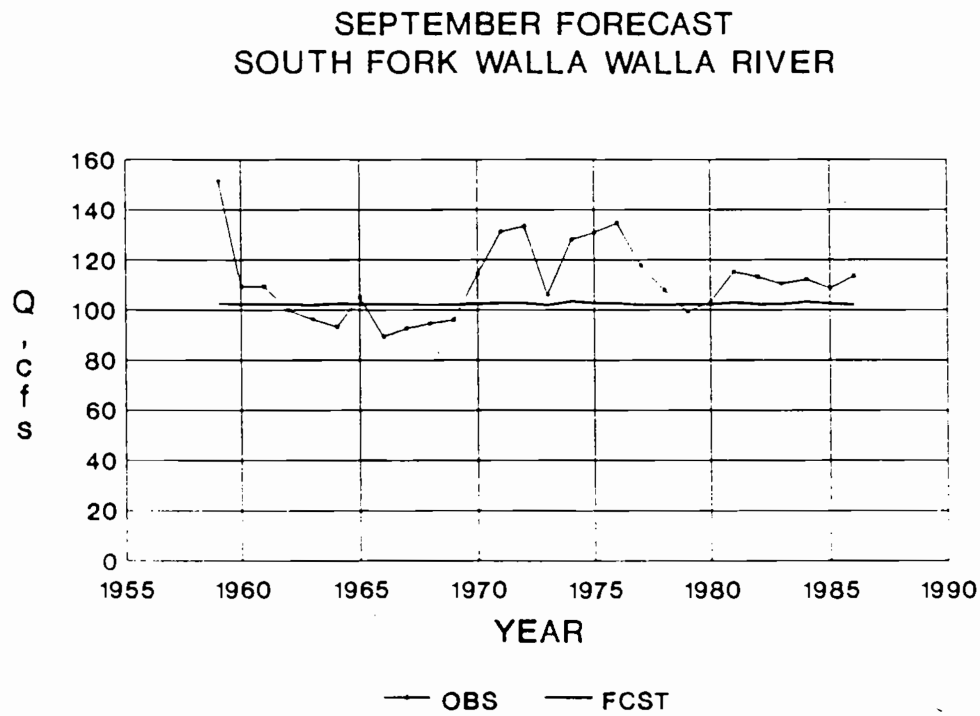

Figure 58. Observed and forecasted September average flows for the South Fork Walla Walla River.

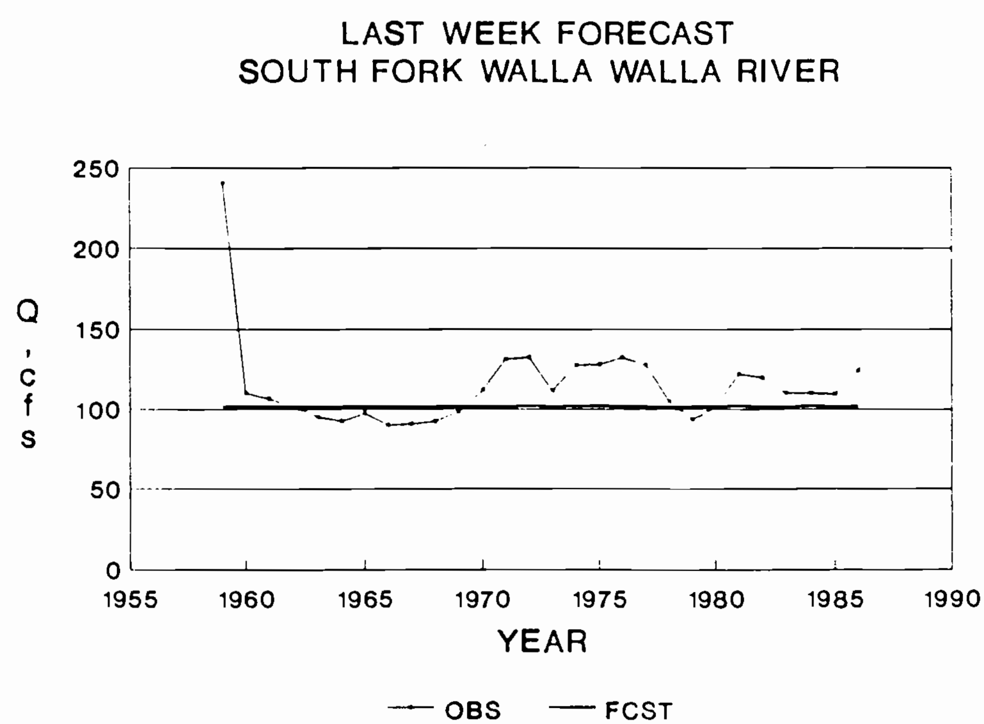

Figure 59. Observed and forecasted last week average flows for the South Fork Walla Walla River.

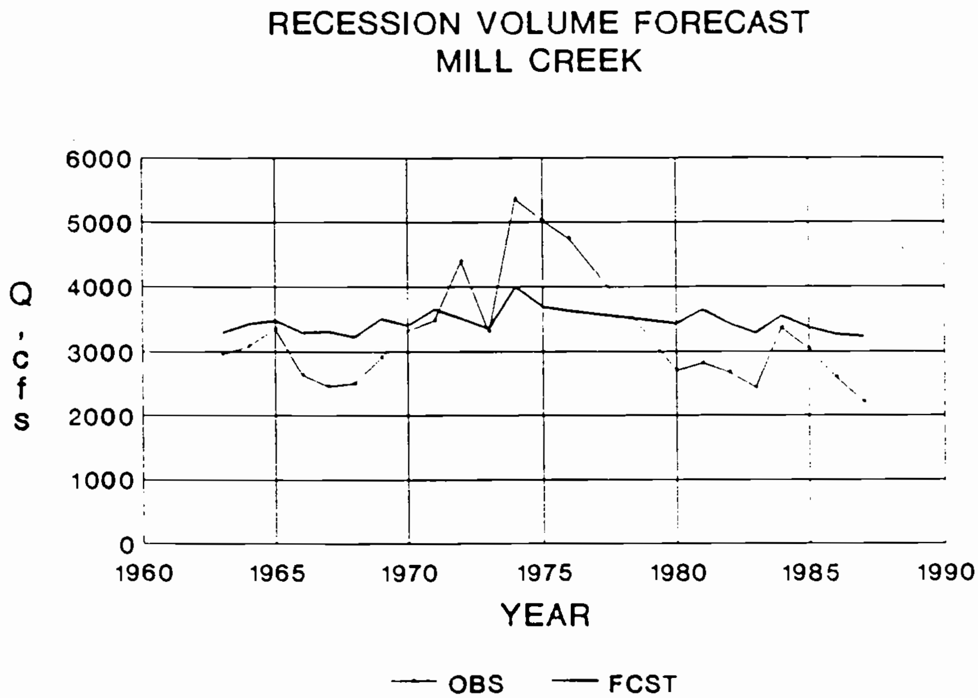

Figure 60. Observed and forecasted recession volumes for Mill Creek.

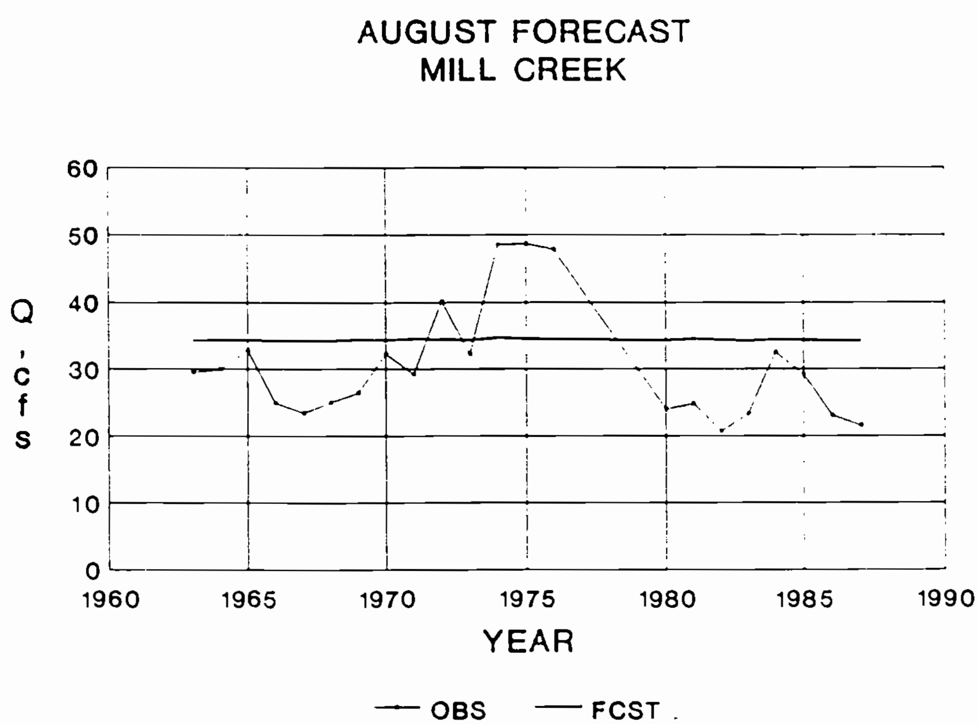

Figure 61. Observed and forecasted August average flows for Mill creek River.

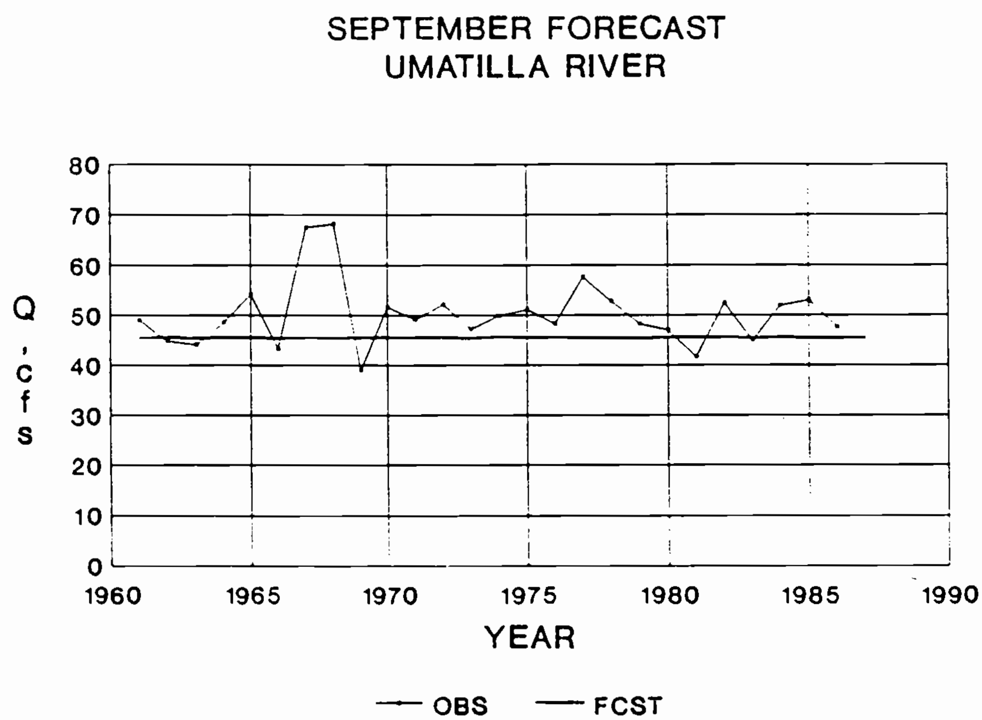

Figure 66. Observed and forecasted September average flows for the Umatilla River.

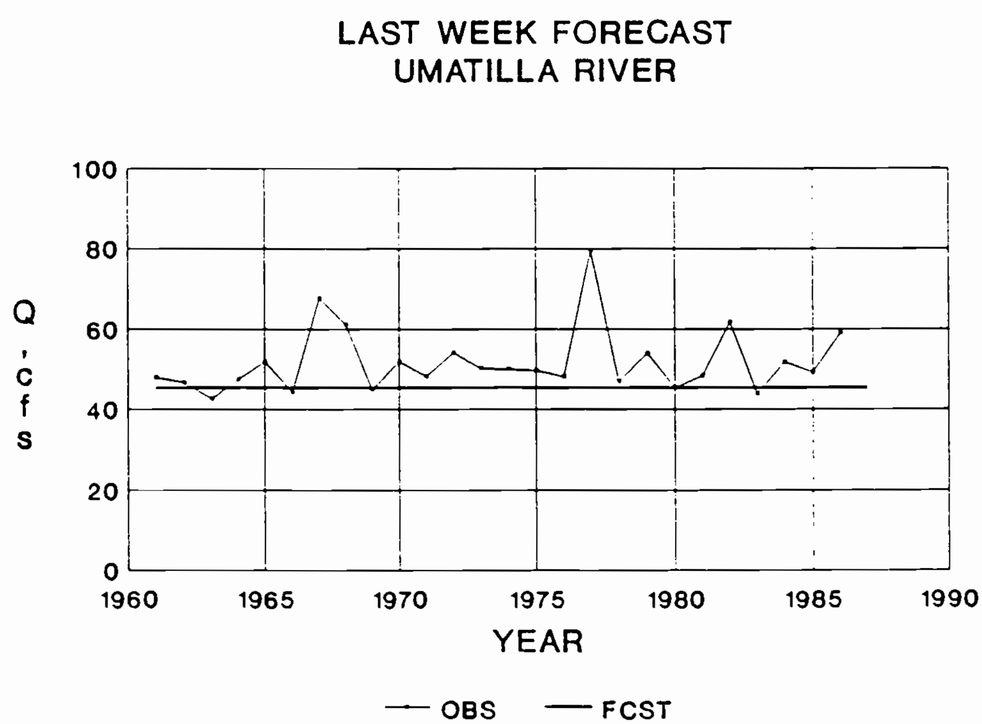

Figure 67. Observed and forecasted last week average flows for the Umatilla River.

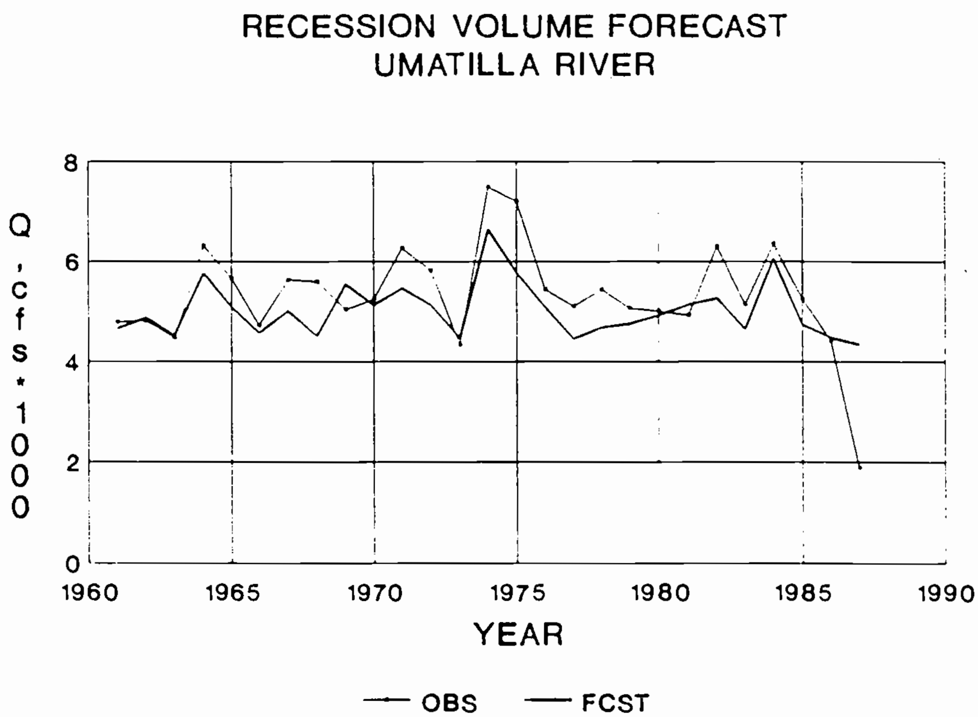

Figure 64. Observed and forecasted recession volumes for the Umatilla River.

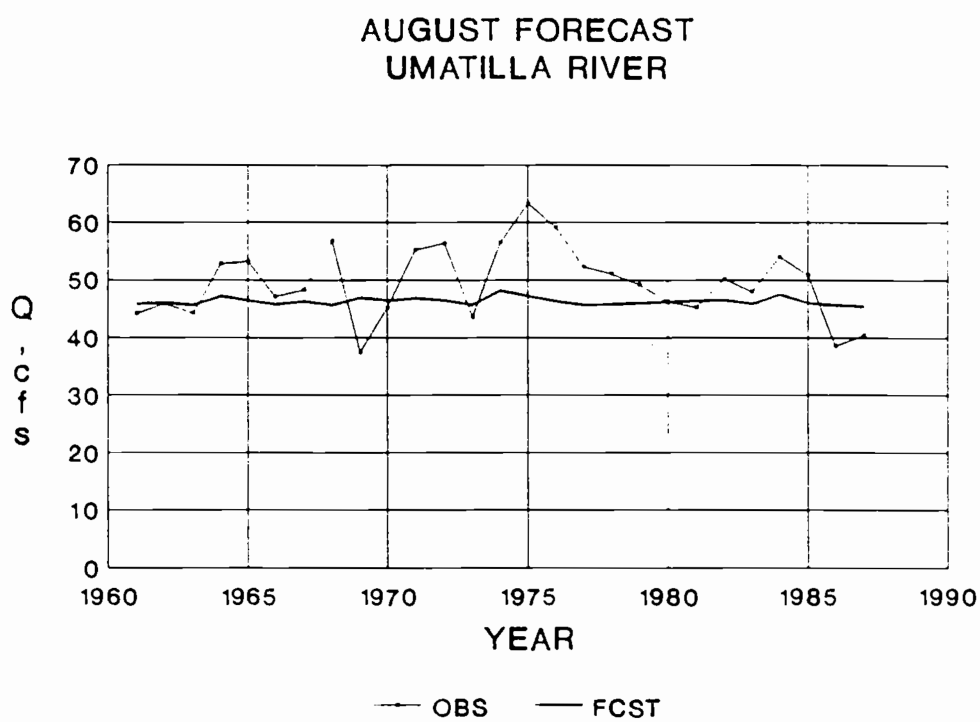

Figure 65. Observed and forecasted August average flows for the Umatilla River.

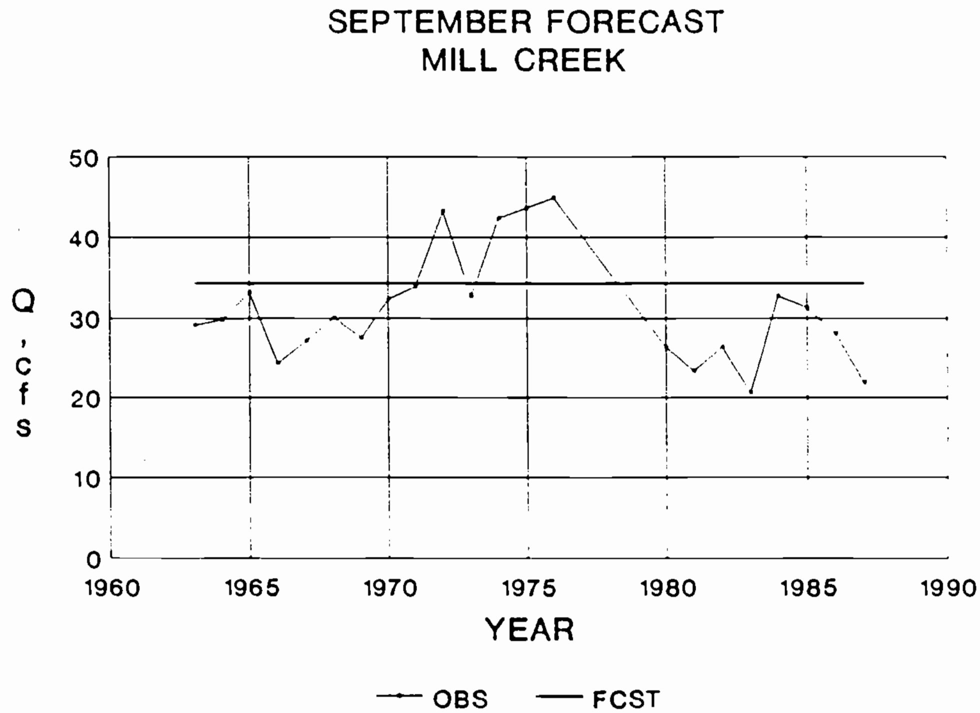

Figure 62. Observed and forecasted September average flows for Mill Creek.

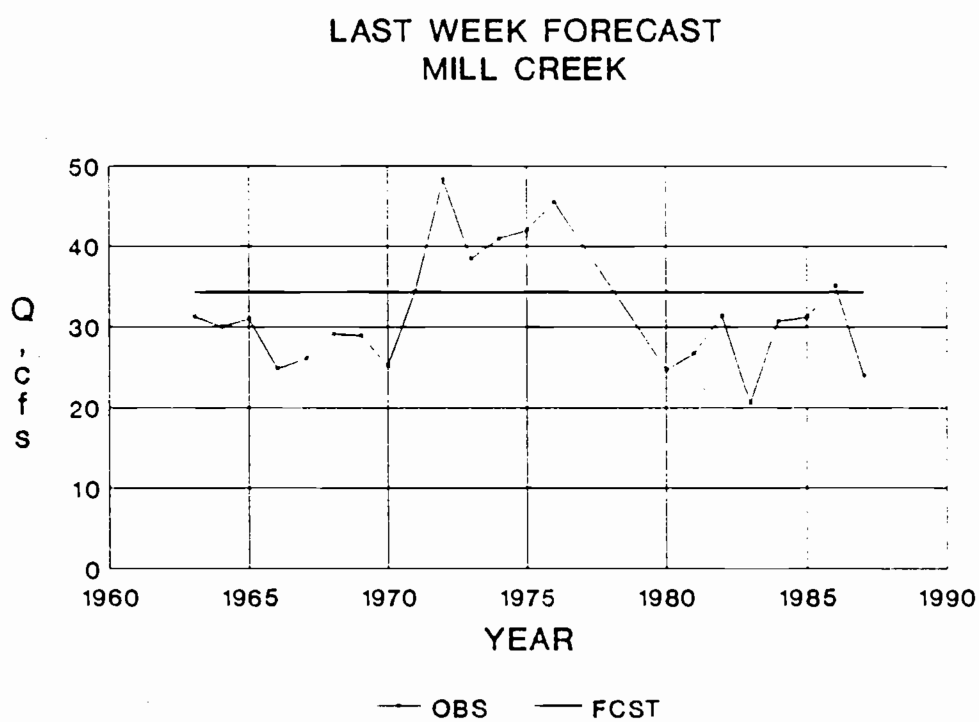

Figure 63. Observed and forecasted last week average flows for Mill Creek.

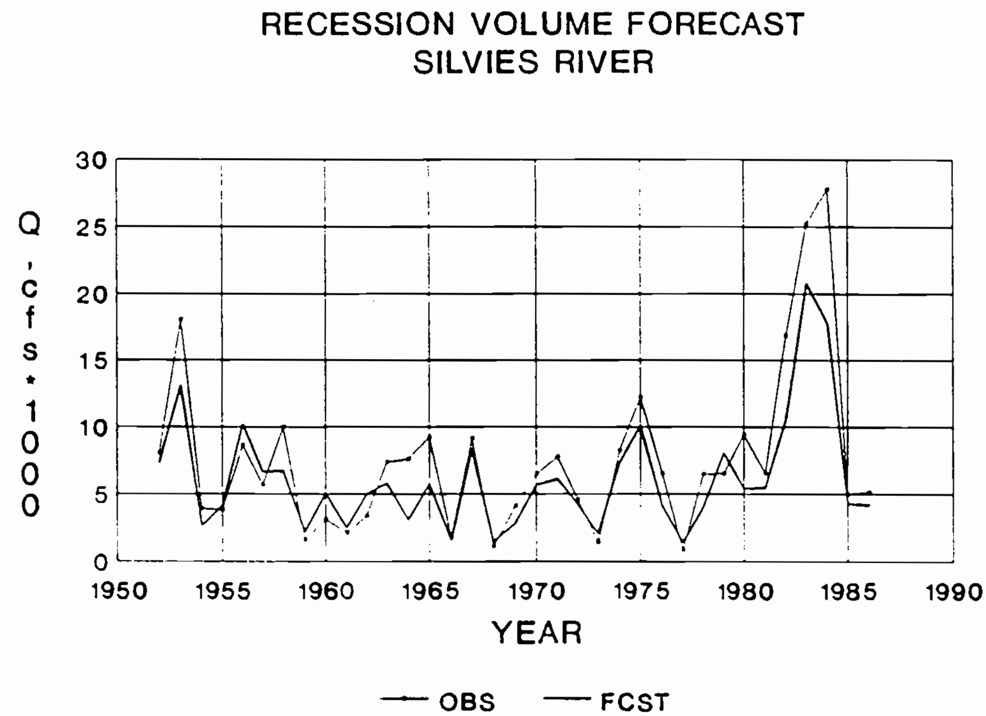

Figure 68. Observed and forecasted recession volumes for the Silvies River.

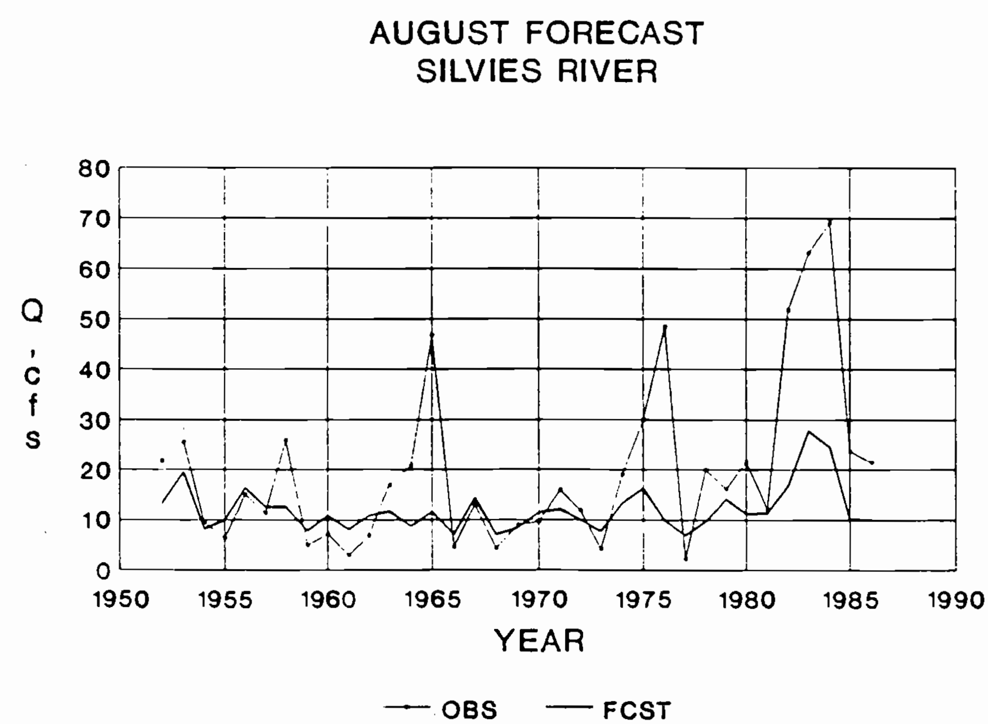

Figure 69. Observed and forecasted August average flows for the Silvies River.

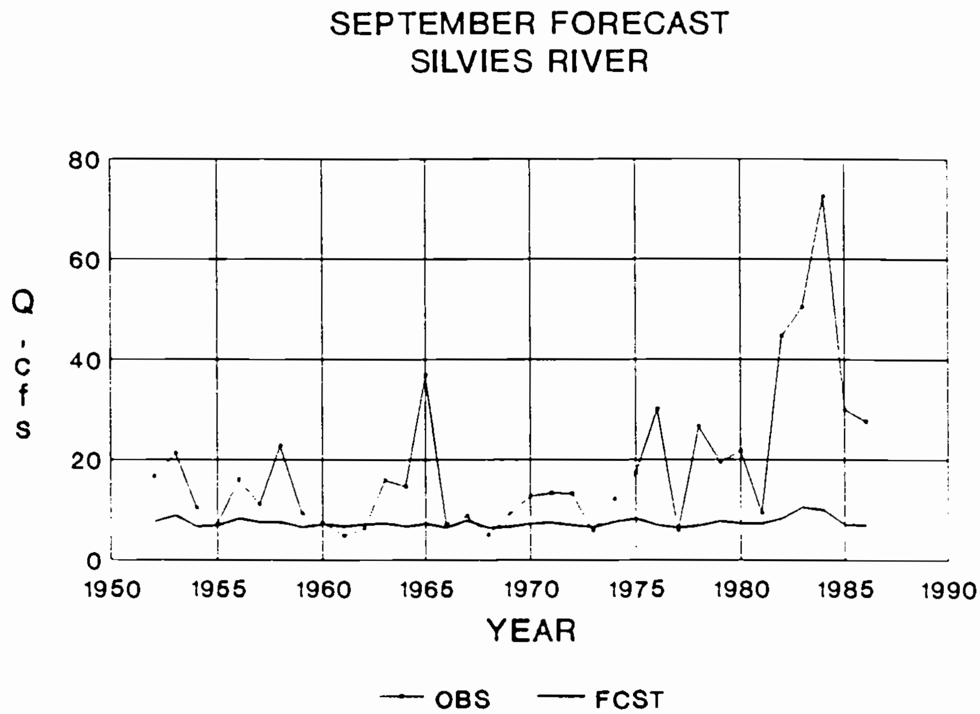

Figure 70. Observed and forecasted September average flows for the Silvies River.

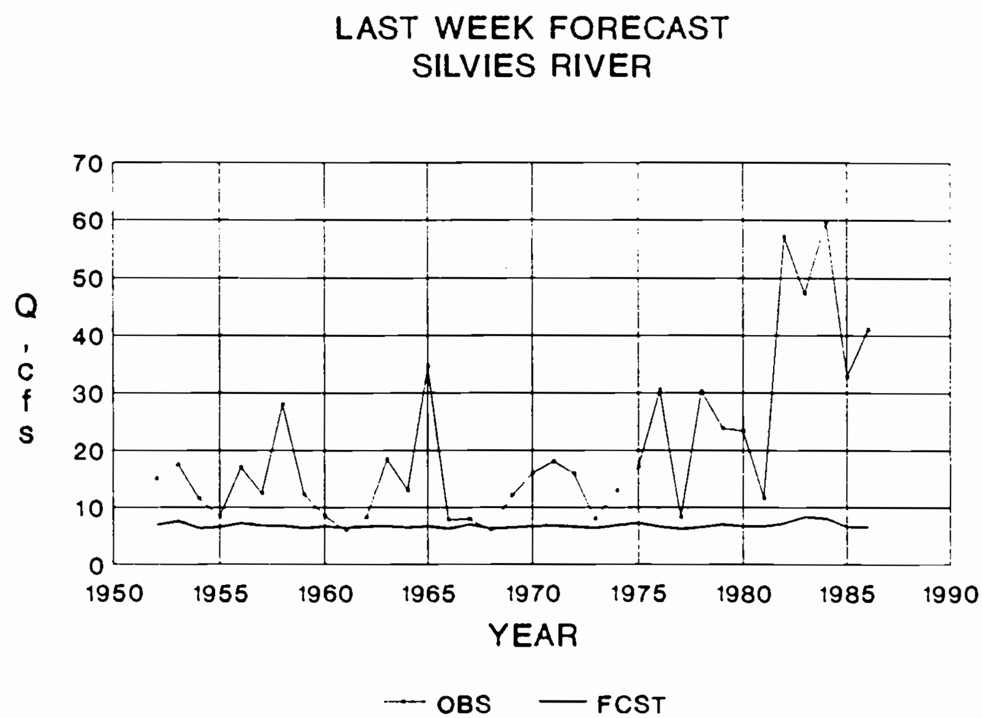

Figure 71. Observed and forecasted last week average flows for the Silvies River.

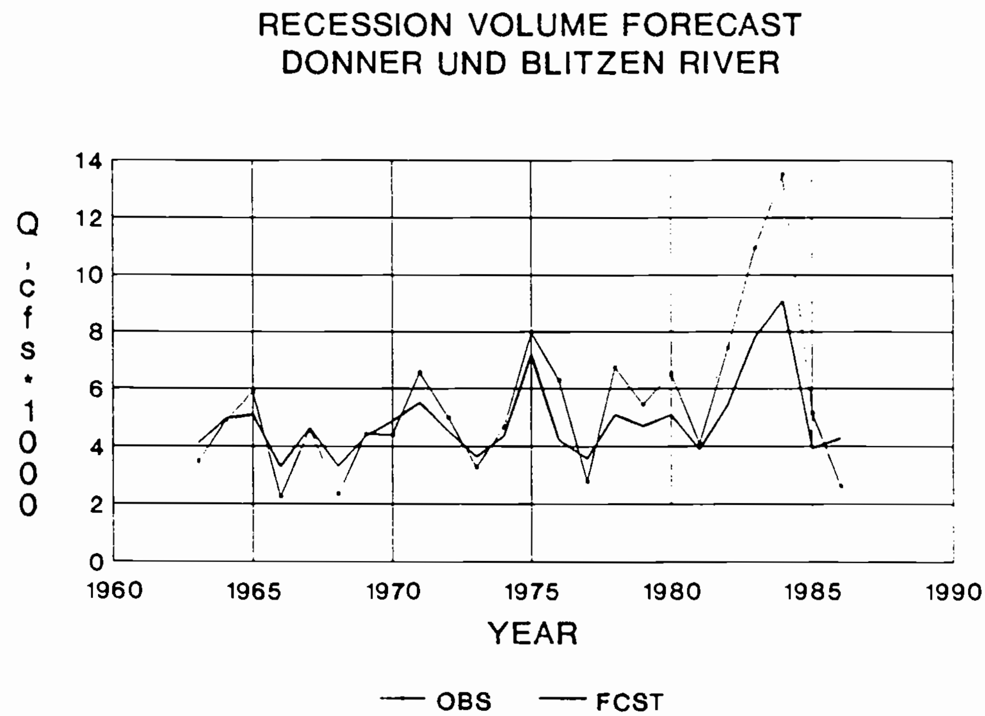

Figure 72. Observed and forecasted recession volumes for the Donner Und Blitzen River.

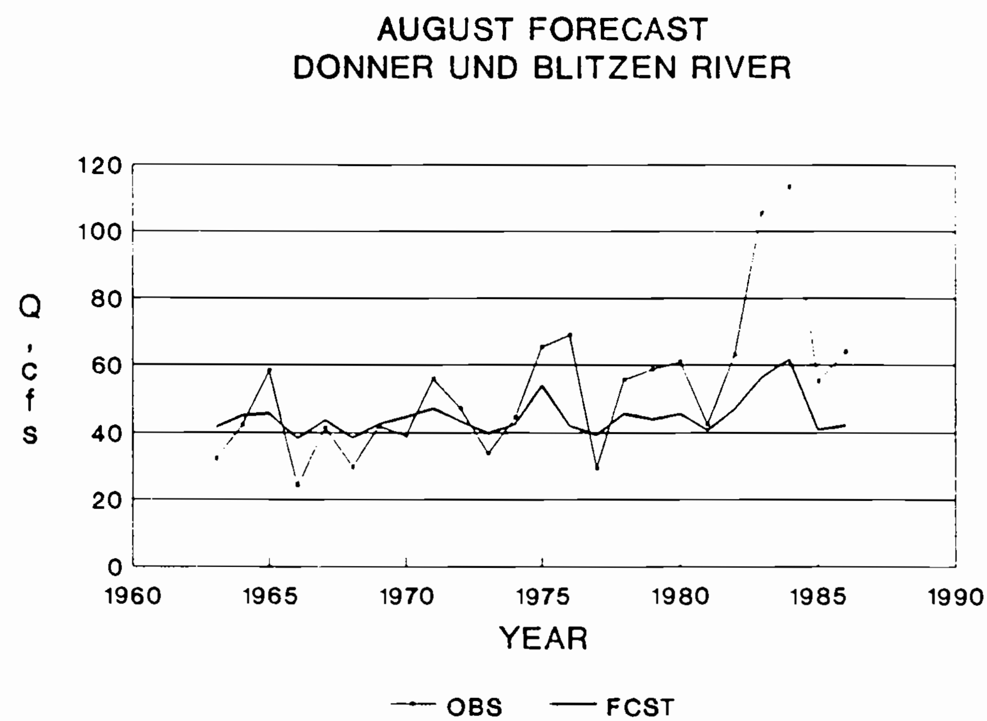

Figure 73. Observed and forecasted August average flows for the Donner Und Blitzen River.

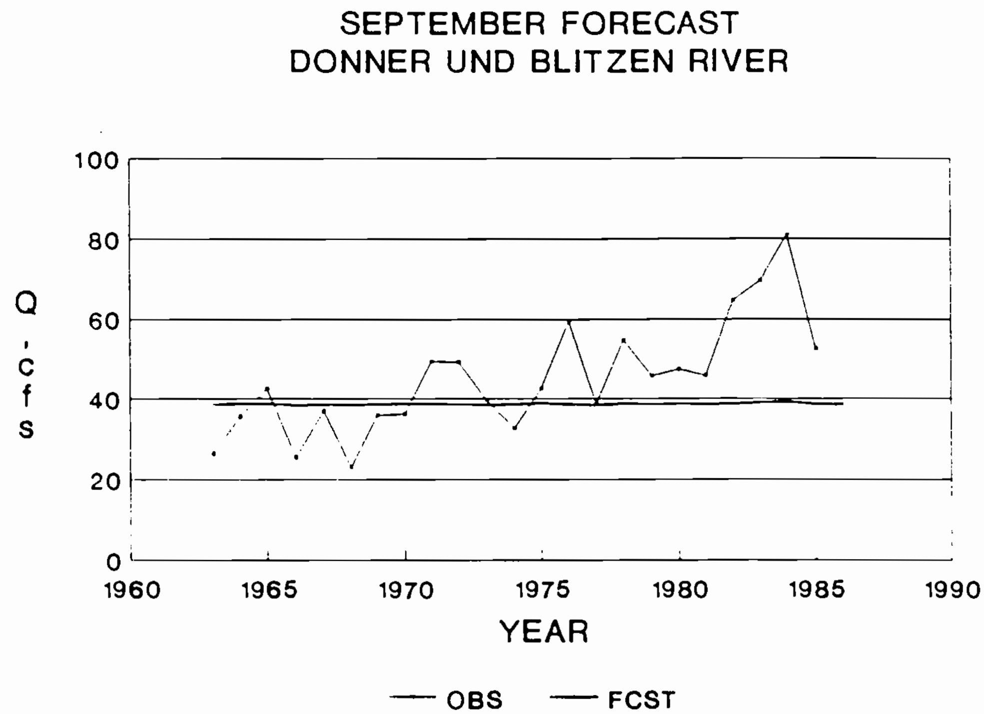

Figure 74. Observed and forecasted September average flows for the Donner Und Blitzen River.

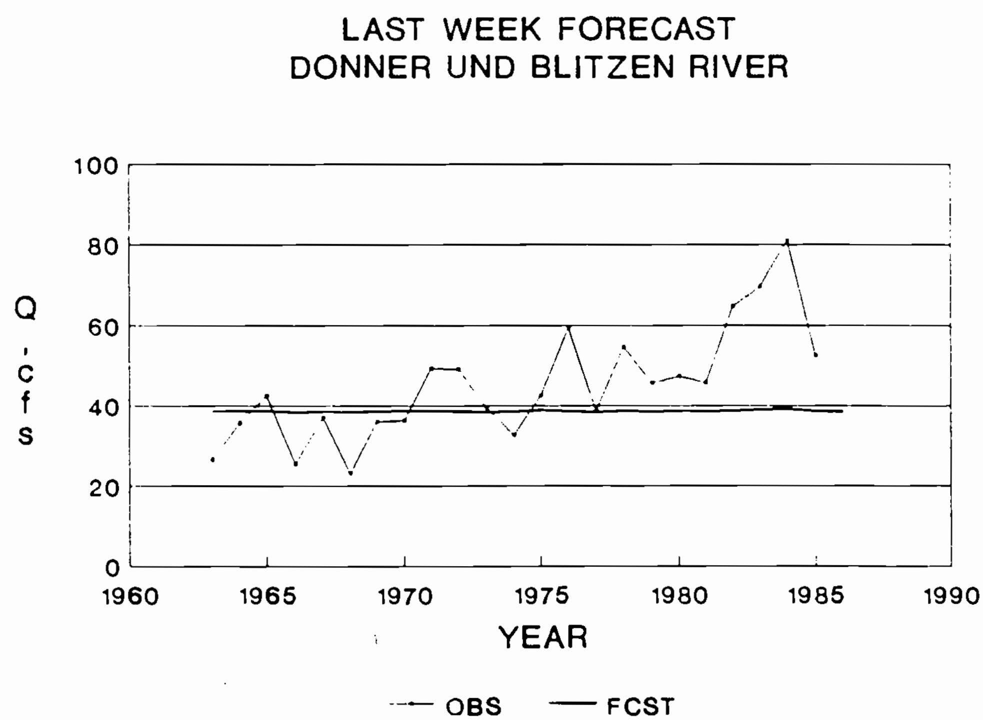

Figure 75. Observed and forecasted last week average flows for the Donner Und Blitzen River.

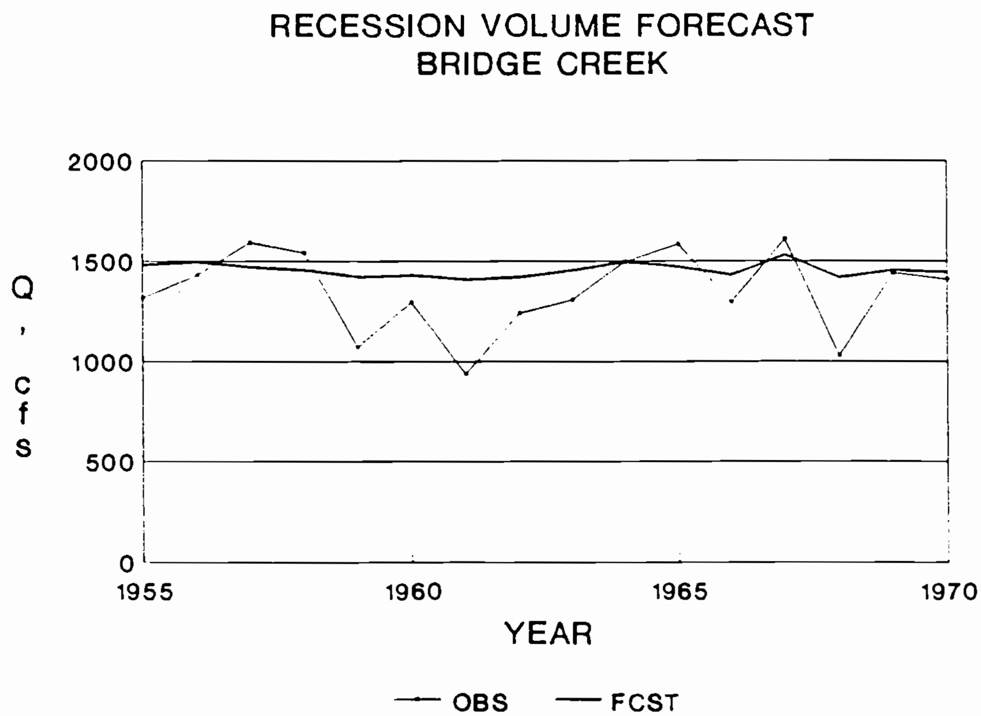

Figure 76. Observed and forecasted recession volumes for Bridge Creek.

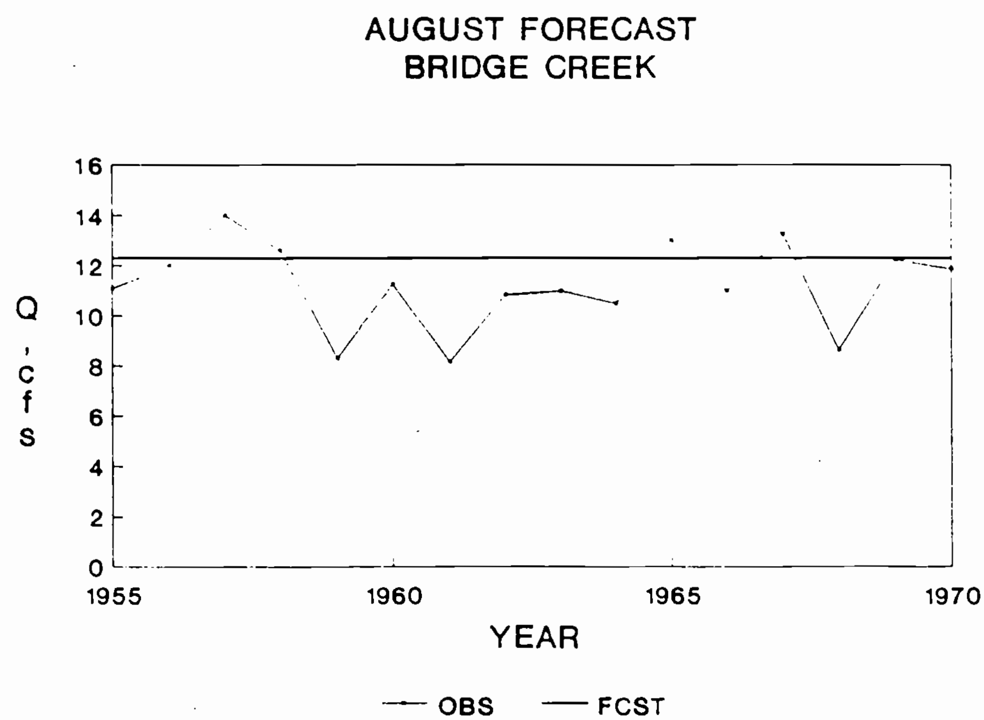

Figure 77. Observed and forecasted August average flows for Bridge Creek.

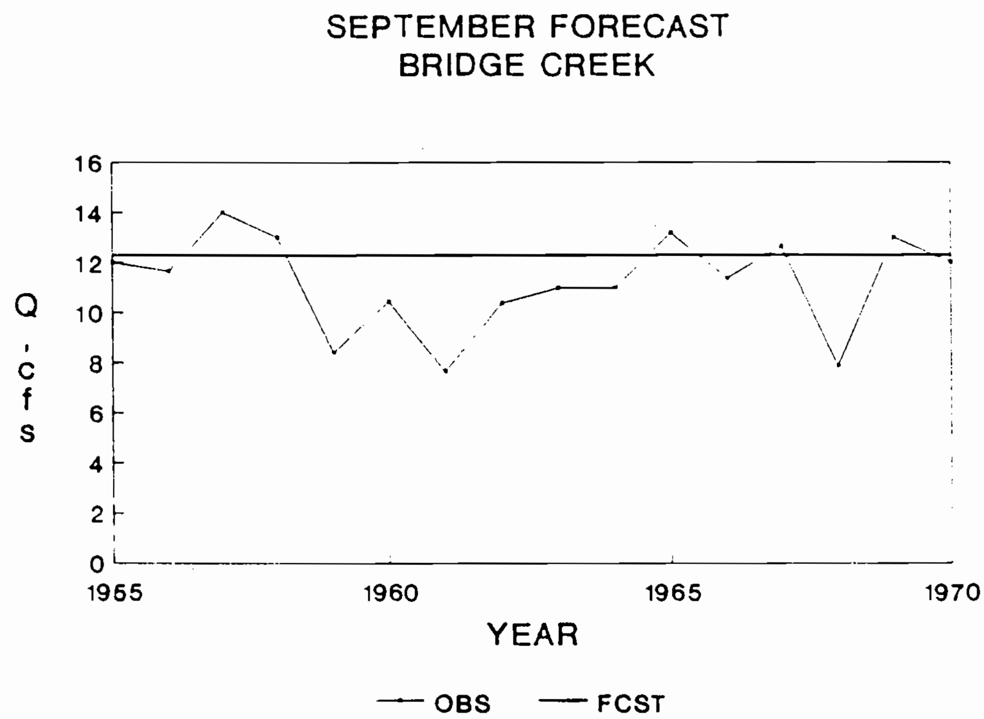

Figure 78. Observed and forecasted September average flows for Bridge Creek.

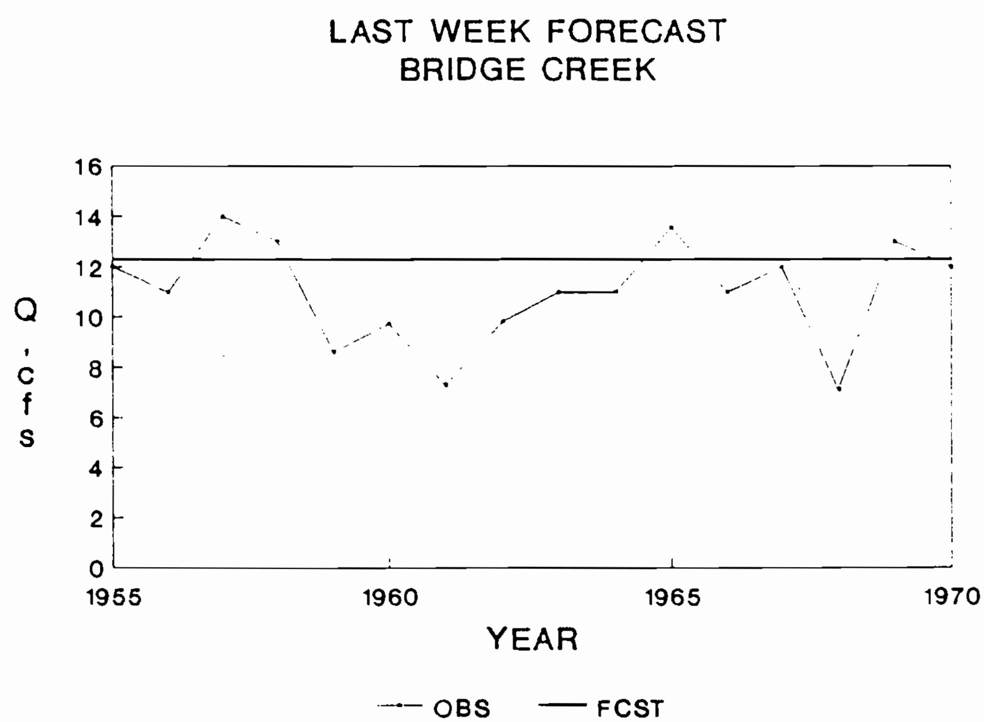

Figure 79. Observed and forecasted last week average flows for Bridge Creek.

(selected periods) was judged on the basis of the extent

Table 6. Starting day for forecast for each stream along with model equations.

Name of Stream	Starting day of forecast model (day of water year)	Forecast model equation
Wallowa Mountain region		
E.F. Wallowa R.	291(17-JUL)	$Q^n = Q_o(0.9387)^n + \sum_{i=1}^{n-1} 0.8686(0.9387)^i$
Hurricane Creek	292(18-JUL)	$Q^n = Q_o(0.9528)^n + \sum_{i=1}^{n-1} 1.2398(0.9528)^i$
Bear Creek	286(12-JUL)	$Q^n = Q_o(0.9089)^n + \sum_{i=1}^{n-1} 1.1986(0.9089)^i$
Blue Mountain region		
S.F. Walla Walla River	255(11-JUN)	$Q^n = Q_o(0.9444)^n + \sum_{i=1}^{n-1} 5.6681(0.9444)^i$
Mill Creek	271(27-JUN)	$Q^n = Q_o(0.8945)^n + \sum_{i=1}^{n-1} 3.6178(0.8945)^i$
Umatilla River	271(27-JUN)	$Q^n = Q_o(0.9117)^n + \sum_{i=1}^{n-1} 4.0178(0.9117)^i$
Southeastern Oregon region		
Silvies River	245(01-JUN)	$Q^n = Q_o(0.9492)^n + \sum_{i=1}^{n-1} 0.3153(0.9492)^i$
Donner und Blitz. River	280(06-JUL)	$Q^n = Q_o(0.9265)^n + \sum_{i=1}^{n-1} 2.8310(0.9265)^i$
Bridge Creek	250(06-JUN)	$Q^n = Q_o(0.8939)^n + \sum_{i=1}^{n-1} 1.3061(0.8939)^i$

Q^n=forecasted flow (cfs) for nth day, Q_o=observed flow (cfs) on the starting day of the forecast model.

of similarities between observed and forecasted flows over the whole period of forecast. Forecasts are good for the early days of the recession period for all streams, compared to the later part of the water year. Forecasts are very good for recession volume, compared to August average flow forecasts. August average flow forecasts, in turn, are better than September and last week of water year flow forecasts. Of the nine streams, recession volume forecasts are best for Hurricane Creek followed by Bear Creek and the Silvies River, the East Fork Wallowa River, the South Fork Walla Walla River, the Umatilla River and the Donner Und Blitzen River, respectively.

Table 7. Average and forecast errors for recession volume, August average flow, September average flow, September average flow and last week of water year' average flow for each stream.

	AVERAGE ERRORS				FORECAST ERRORS			
Name of stream	AER cfs	AEAG cfs	AESP cfs	AE7D cfs	FER cfs	FEAG cfs	FESP cfs	FE7D cfs
E.F. Wallowa R.	-270	-4	-2.4	-2.4	-188	-2.9	-2.4	-2
Hurrican Creek	-1117	-16	-6	-4	-111	-1.3	-3.2	-2.7
Bear Creek	-671	-4.4	-4.4	-6.3	-236	-1.7	-4.3	-7
S.F. Walla Walla R.	-498	-8.2	-8.1	-12	-836	-8.1	-8.9	-13
Mill Creek	361.6	3.1	3.1	3.8	212	4	3.1	2.5
Umatilla River	140.9	-3.4	-2.7	-0.9	-294	-3.2	-4.6	-6.3
Silvies River	-2998	-11	-9.3	-8.8	-1421	-7.7	-11	-13.2
Bridge Creek	160.4	0.9	1.3	1.5	105	1.1	1.1	1.3
Donner und Blitzen R	-917	-9.9	-7	-6	-589	-8.3	-6.5	-6.3

AER= Average error for recession volume, AEAG= Average error for August average flows, AESP= Average error for September average flows, AE7D= Average error for average flow for the last week of the water year, FER= Forecast error for recession volume, FEAG= Forecast error for August average flows, FESP= Forecast error for September average flow and FE7D= Forecast error for average flow for the last week of the water year.

Forecast for Mill Creek and Bridge Creek are poorest.

August average flow forecasts fit best with the observed flows for Hurricane Creek, Bear Creek and the East Fork Wallowa River, respectively. Forecasts for the Silvies River and the Donner Und Blitzen River are fit fairly well with their observed flows. Forecasts for August flows for the Umatilla River and the South Fork Walla Walla River are poorly matched with observed flows, while Mill Creek and Bridge Creek have the poorest forecasts.

Table 8. Percent improvements of forecast models over simple prediction made from average flows for recession volume (%IMPR), August average flow (%IMPAG), September average flow (%IMPSP) and last week of water year's average flow (%IMP7D) for each stream.

Name of stream	%IMPR	%IMPAG	%IMPSP	%IMP7D
E.F. Wallowa R.	43.7	36.6	2.98	19
Hurricane Creek	901	1084	89.4	49.9
Bear Creek	183.8	157.9	1.3	-9.96
S.F.Walla Walla R.	-40.5	0.5	-8.7	-4.9
Mill Creek	70.3	-21	-0.23	55.7
Umatilla River	-147.95	7.9	-42.3	-84.96
Silvies River	111	39.7	-15.6	-33
Bridge Creek	52.4	-16.2	17.95	12.72
Donner und blitzen R.	55.6	18.8	5	-3.6

The September and last week of water year forecasts for Hurricane Creek are the best of the nine streams forecasts, followed by the East Fork Wallowa River. For the rest of the streams, September and the last week of water year forecasts are consistently poor. This increasing degree of error with later periods of forecast is attributed to the error accumulation. This error is minimum for the first day of forecast period and accumulates as the forecast length increases. Errors are maximum for the last week of water year forecasts for each stream. Accuracy of forecast depends upon the smoothness of average annual hydrographs' falling limb. Average annual hydrographs for Mill Creek and Bridge Creek are "noisy".

Similarly, average and forecast errors are plotted for comparison over the years. It is a simple way to see, graphically, how much improvement is made by the forecast model over the average predictions. Forecast errors are closer to zero than average errors for recession volume and August average flows. This is true for all streams, except Mill Creek and Bridge Creek. For September average flows, average error and forecast errors are quite similar, except for Hurricane Creek and the Silvies River. For Hurricane Creek, forecast errors are closer to zero than average errors. For the Silvies River, average errors are closer to zero than the forecast errors, showing that average prediction was better than forecast model here. For the last week of the water year, forecast errors are close to zero for Hurricane Creek and Mill Creek. For the East Fork Wallowa River, the Umatilla River and the Silvies River average errors are closer to zero than forecast errors. Bear Creek, Bridge Creek and the Donner Und Blitzen River have almost the same values for average and forecast errors (Fig. 80 to 115).

To overcome the error accumulation problem, forecasts for some of the streams are made for shorter periods, using the same forecast model developed for the whole period. August and September forecasts are made for the Donner Und Blitzen River (Fig. 116 to 119). Mill Creek was chosen for the last week of water year forecasts (Fig.

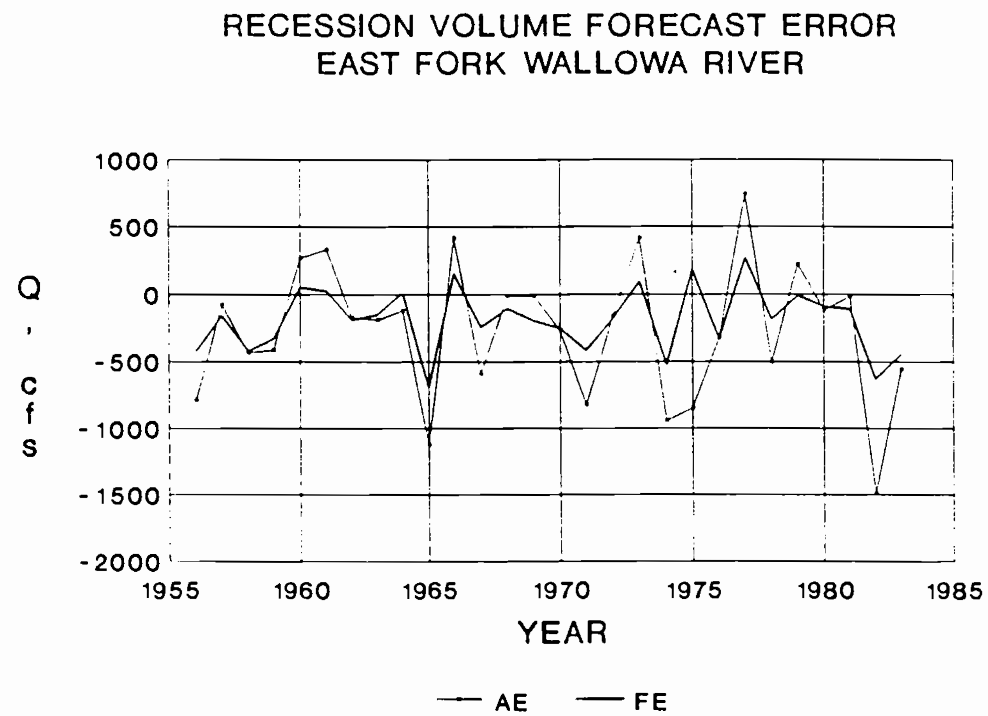

Figure 80. Average and forecast errors for recession volume for the East Fork Wallowa River.

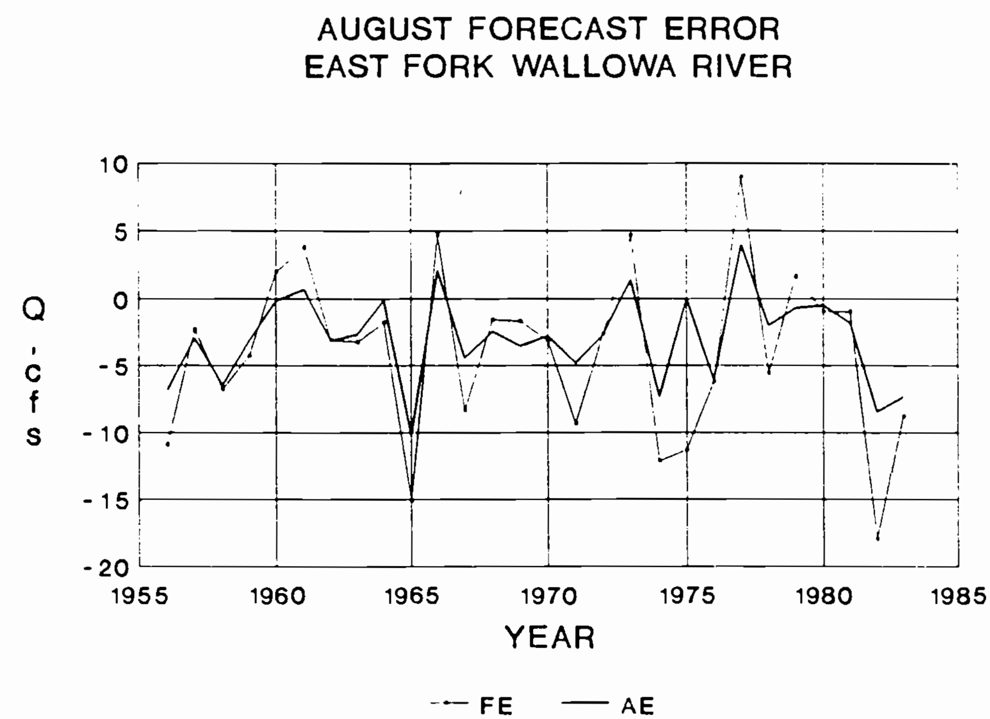

Figure 81. Average and forecast errors for August flow for the East Fork Wallowa River.

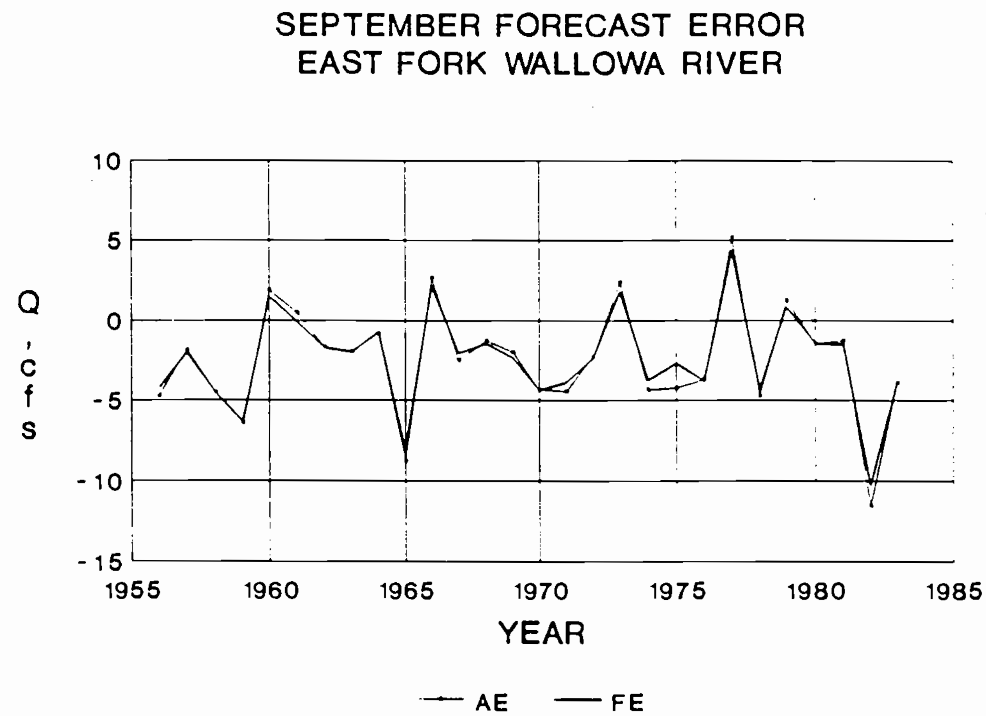

Figure 82. Average and forecast errors for September flow for the East Fork Wallowa River.

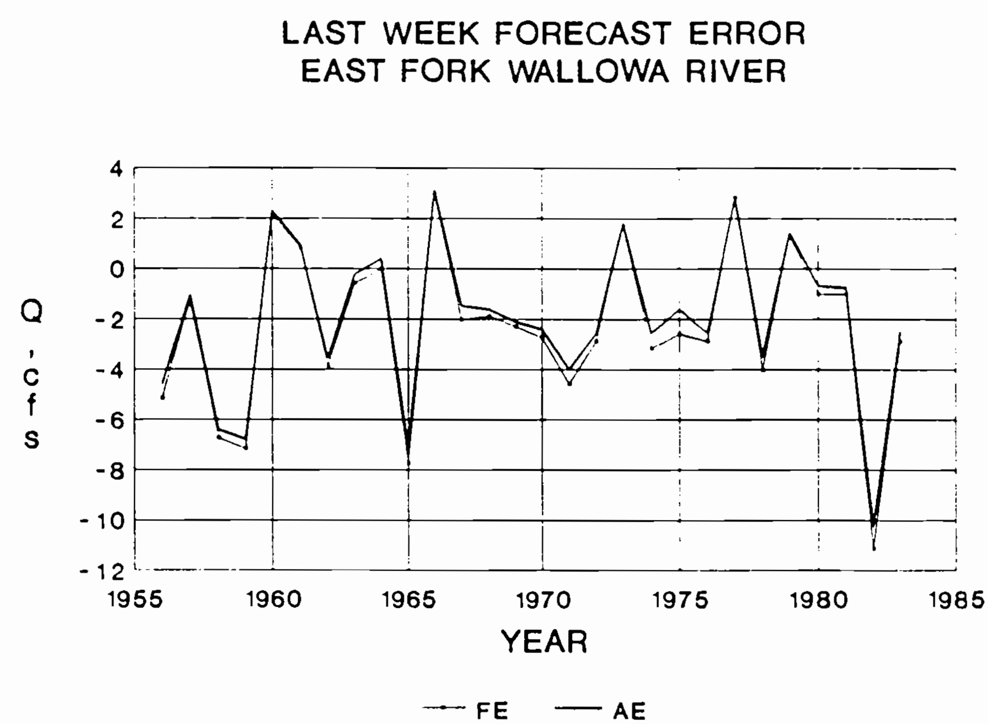

Figure 83. Average and forecast errors for last week of water year for the East Fork Wallowa River.

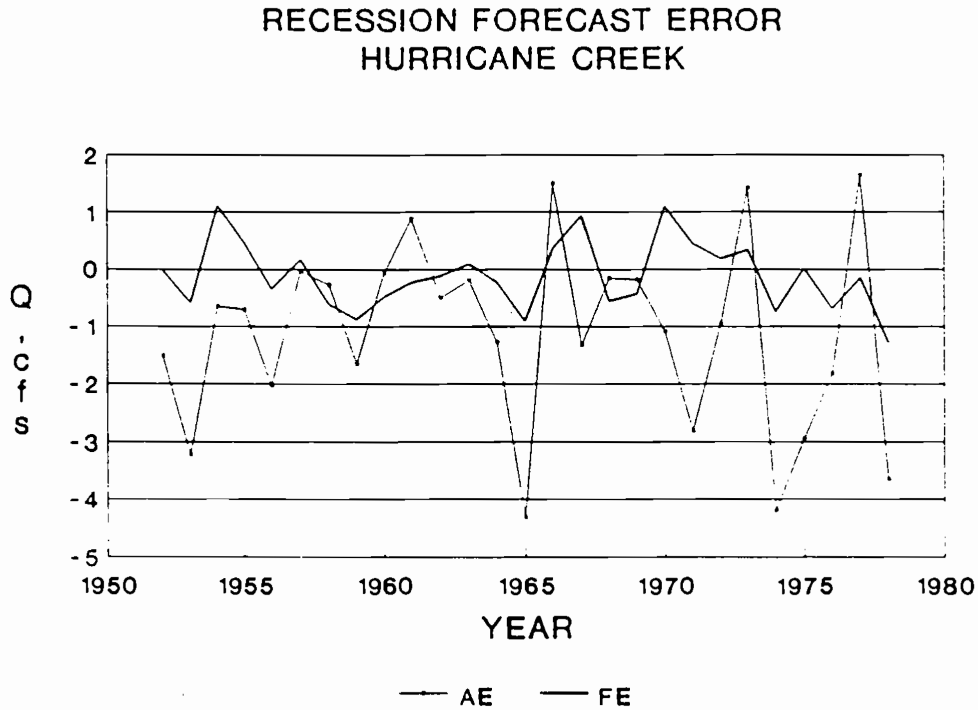

Figure 84. Average and forecast errors for recession volume for Hurricane Creek.

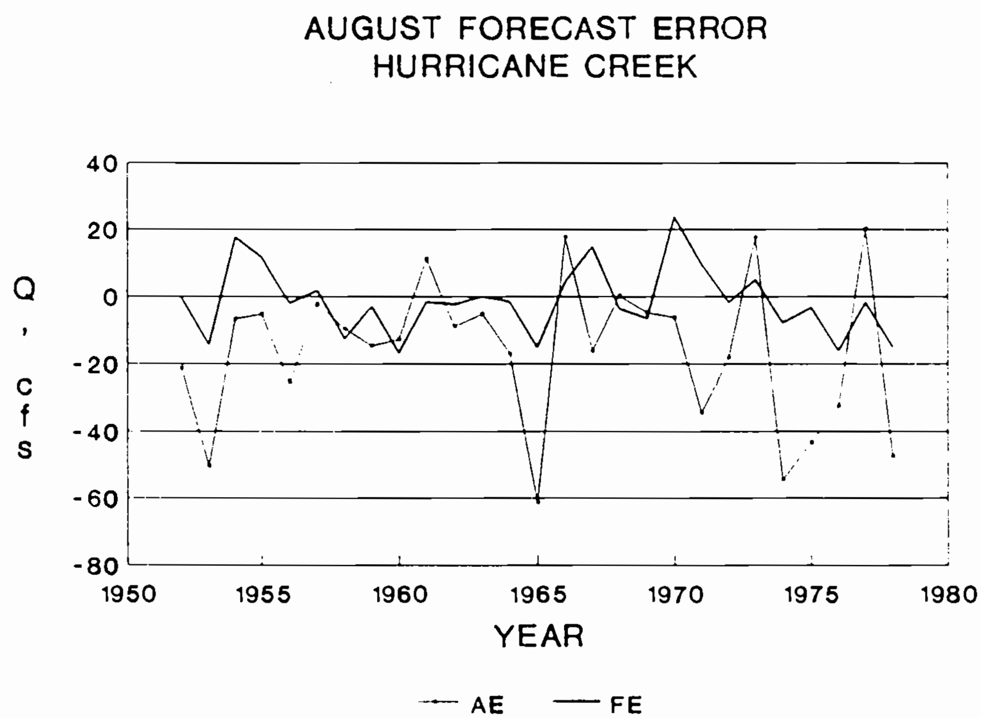

Figure 85. Average and forecast errors for August flow for Hurricane Creek.

SEPTEMBER FORECAST ERROR
HURRICANE CREEK

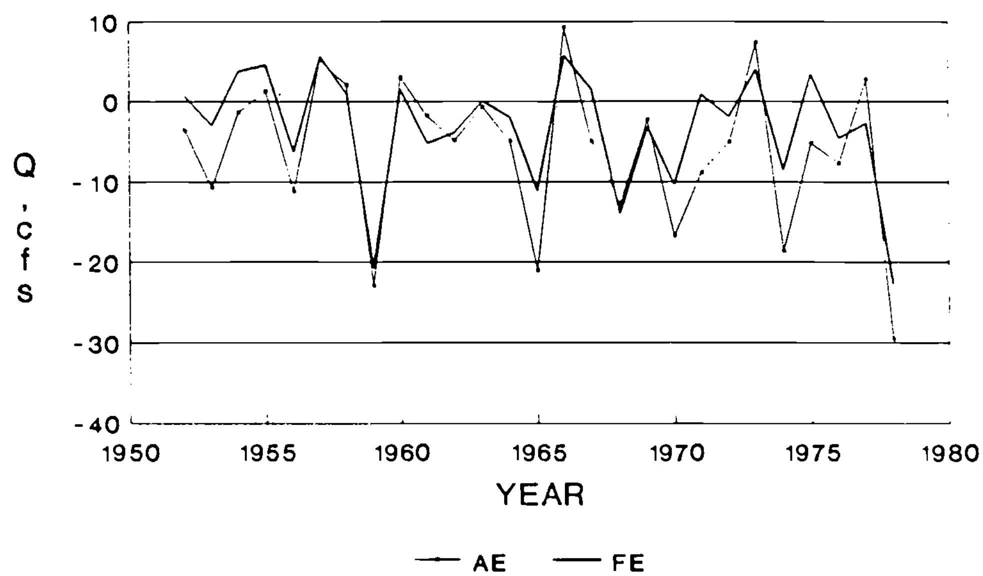

Figure 86. Average and forecast errors for September flow for Hurricane Creek.

LAST WEEK FORECAST ERROR
HURRICANE CREEK

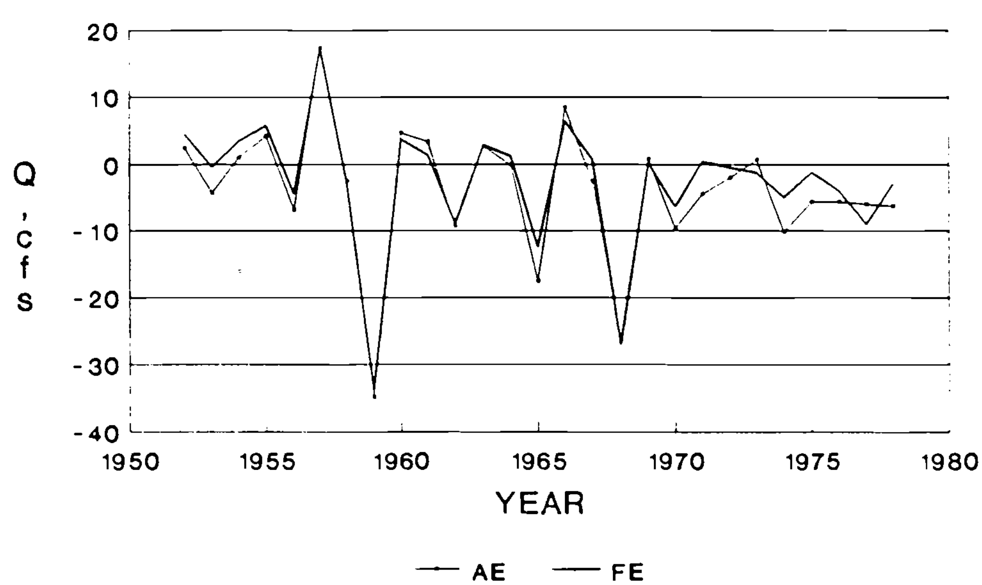

Figure 87. Average and forecast errors for last week of water year for Hurricane Creek.

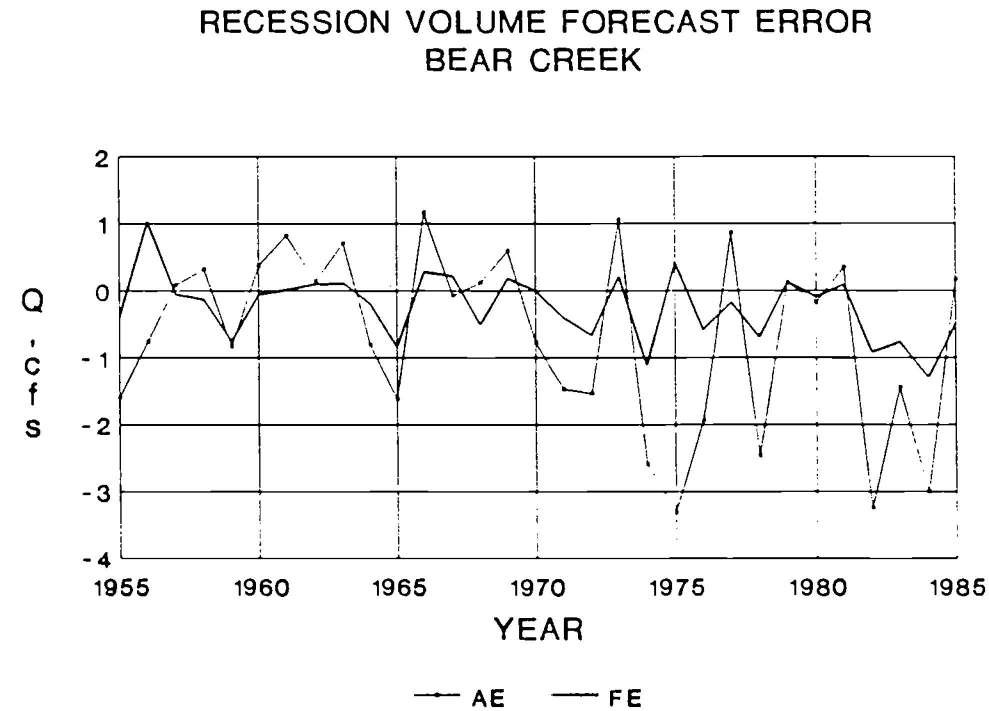

Figure 88. Average and forecast errors for recession volume for Bear Creek.

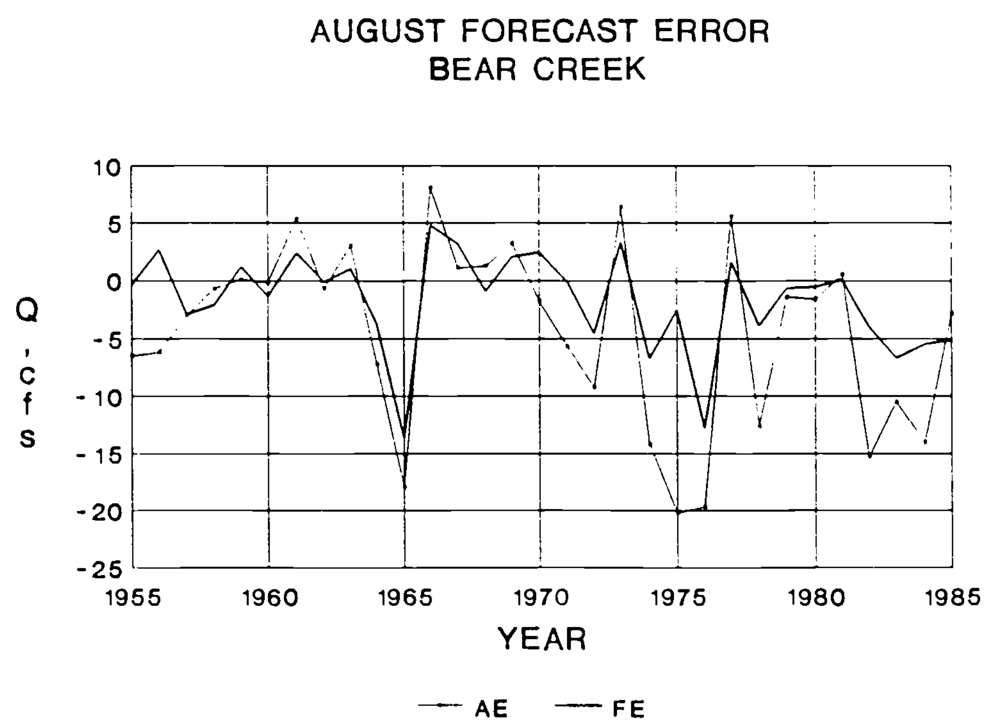

Figure 89. Average and forecast errors for August flow for Bear Creek.

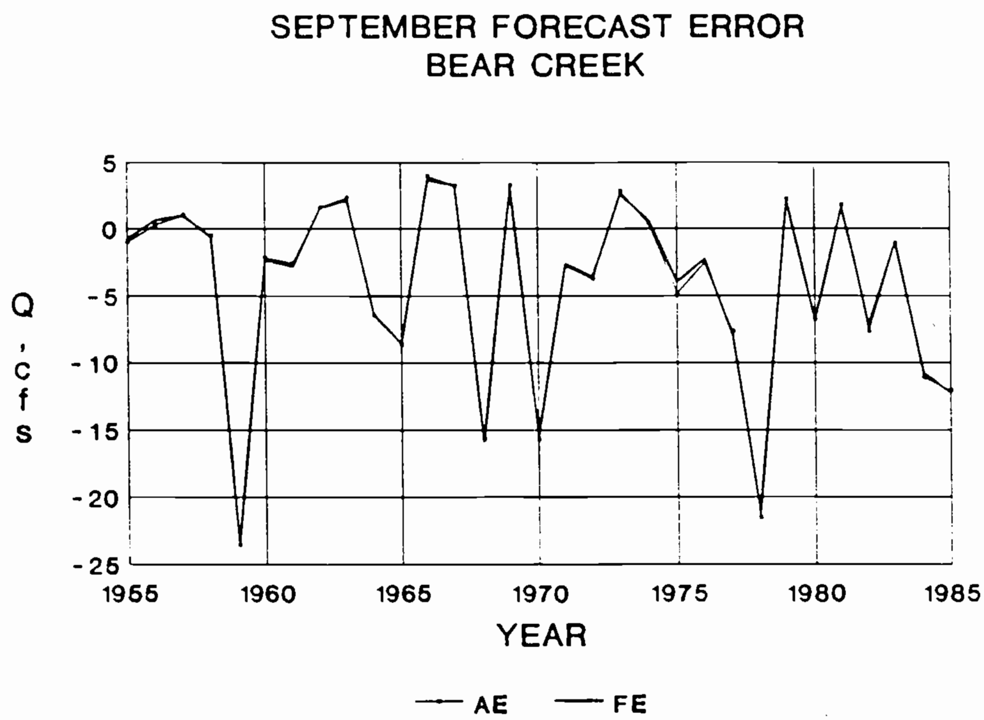

Figure 90. Average and forecast errors for September flow for Bear Creek.

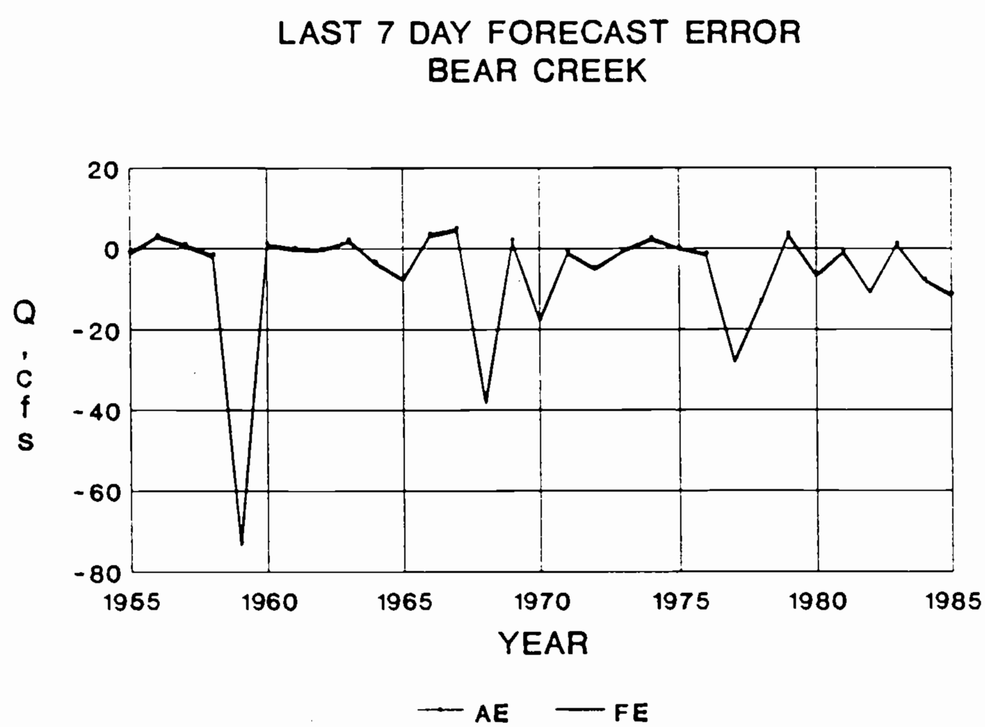

Figure 91. Average and forecast errors for last week of water year for Bear Creek.

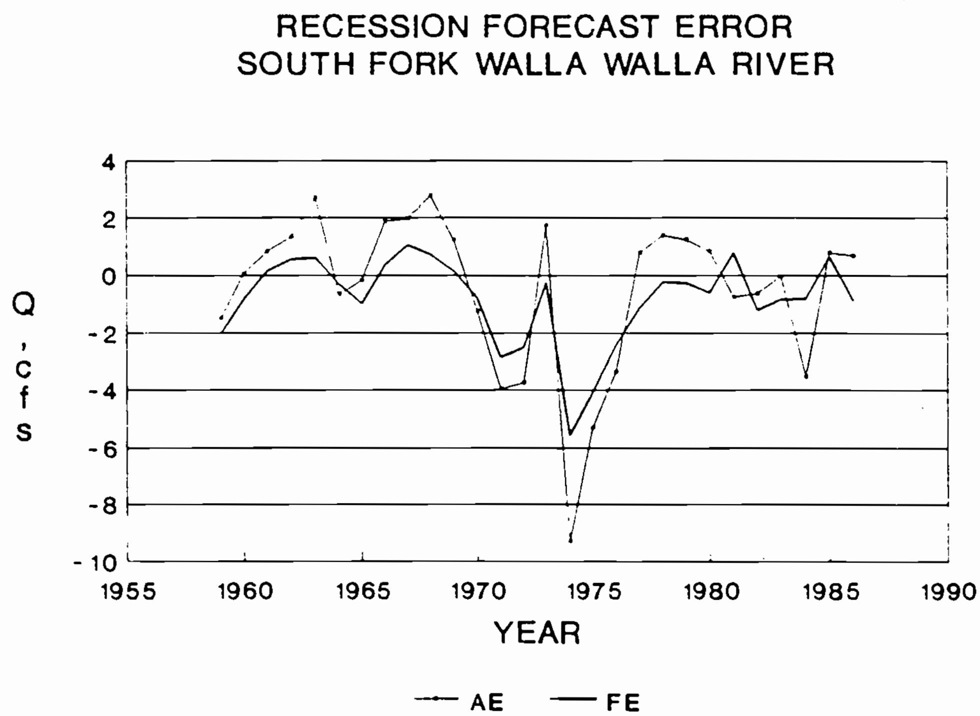

Figure 92. Average and forecast errors for recession volume for the South Fork Walla Walla River.

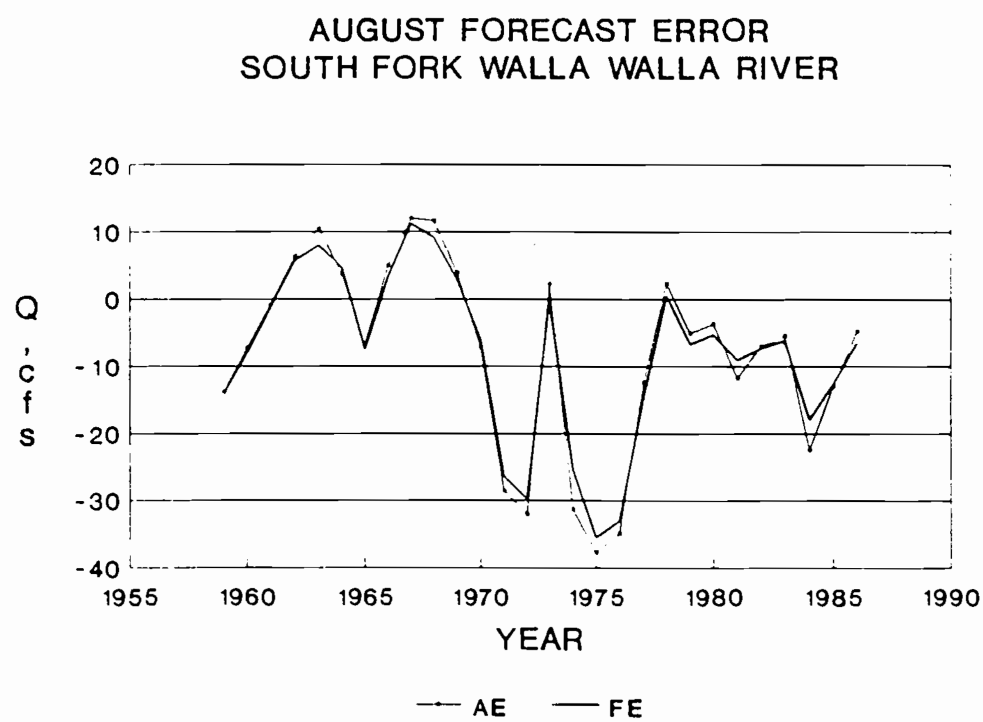

Figure 93. Average and forecast errors for August flow for the South Fork Walla Walla River.

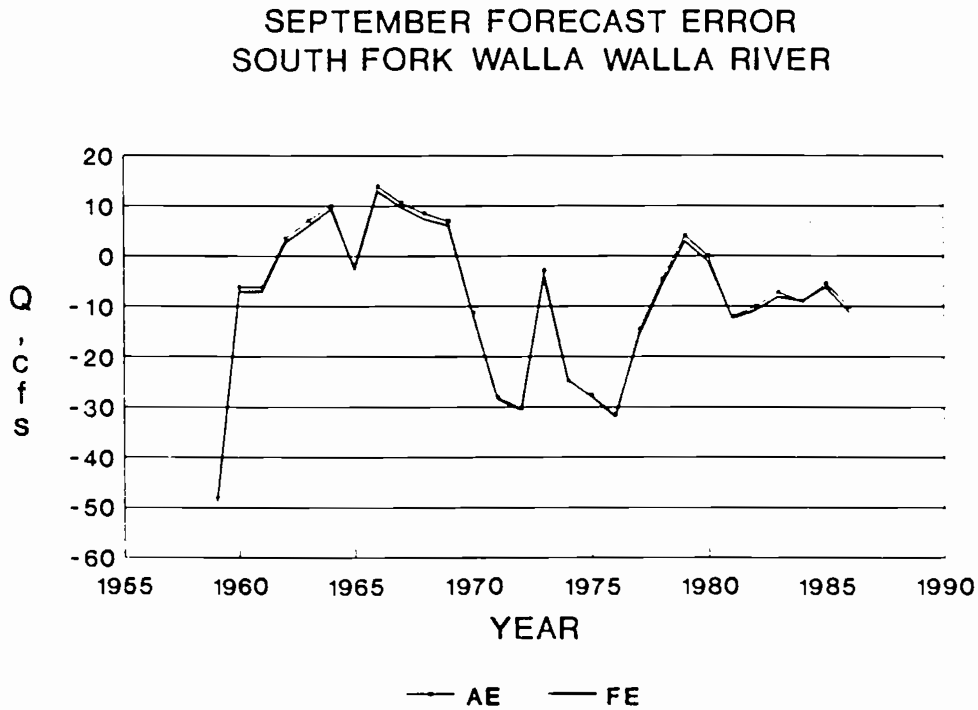

Figure 94. Average and forecast errors for September flow for the South Fork Walla Walla River.

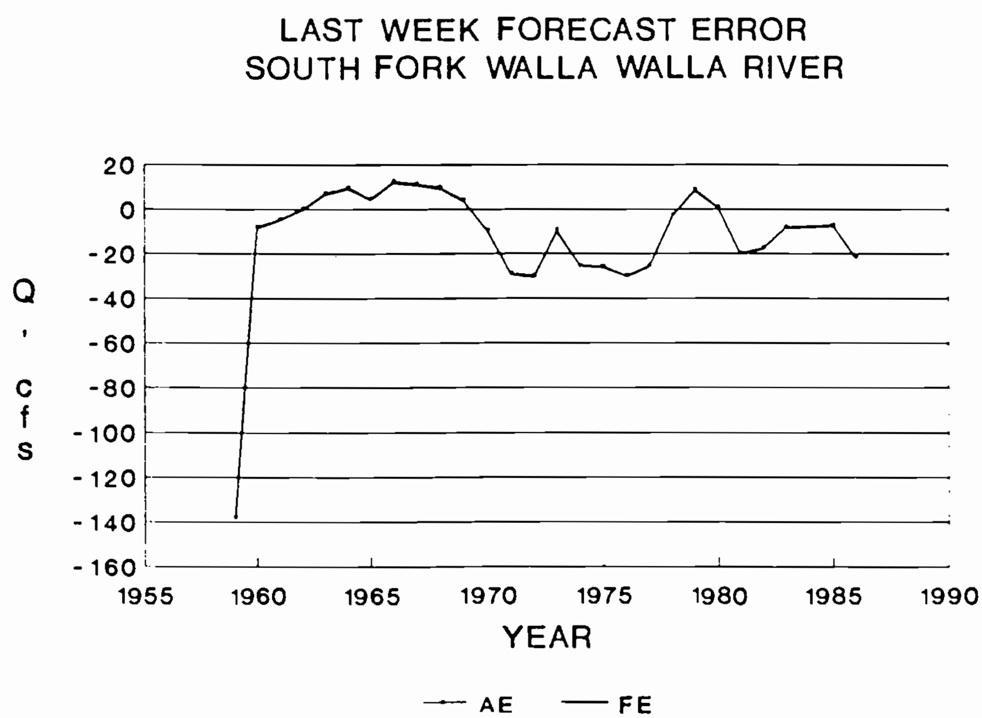

Figure 95. Average and forecast errors for last week of water year for the South Fork Walla Walla River.

RECESSION VLOUME FORECAST ERROR
MILL CREEK

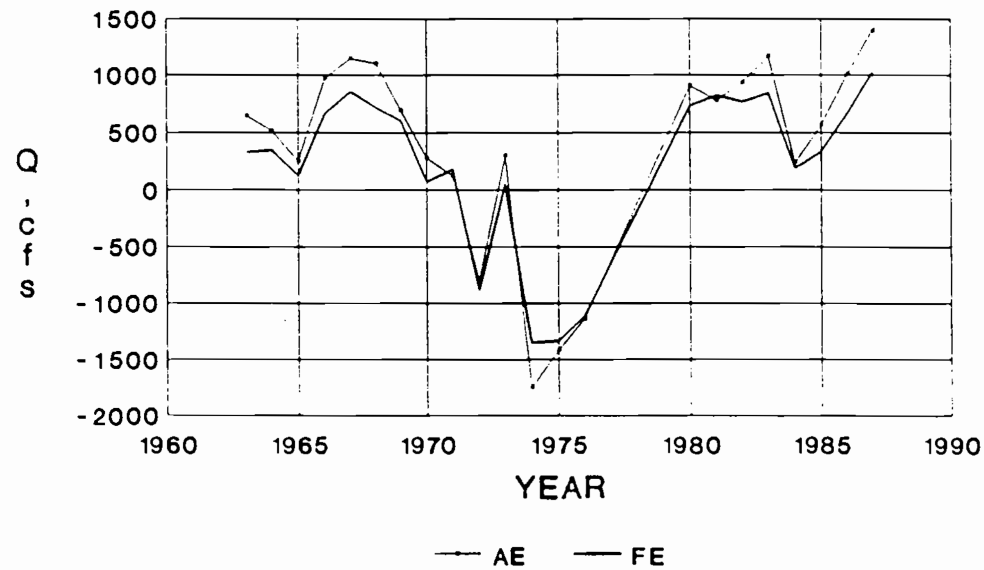

Figure 96. Average and forecast errors for recession volume for Mill Creek.

AUGUST FORECAST ERROR
MILL CREEK

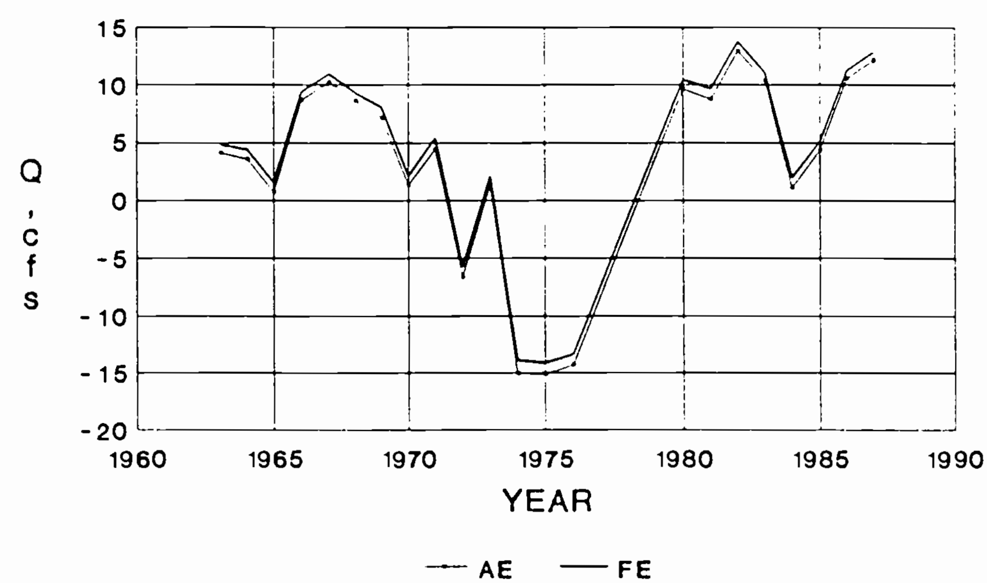

Figure 97. Average and forecast errors for August flow for Mill Creek.

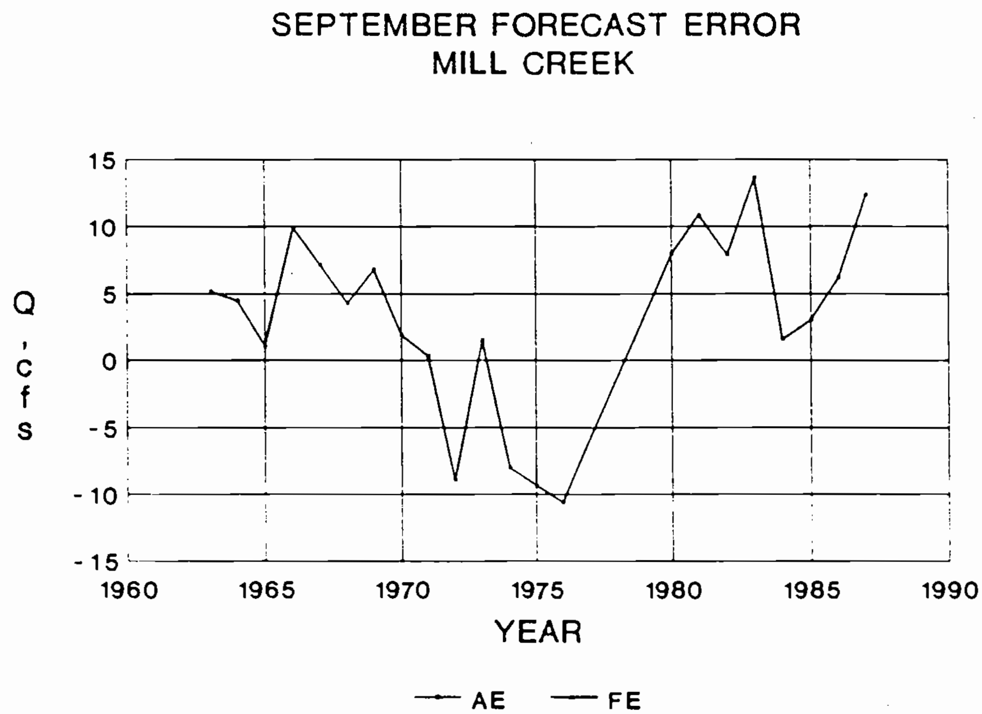

Figure 98. Average and forecast errors for September flow for Mill Creek.

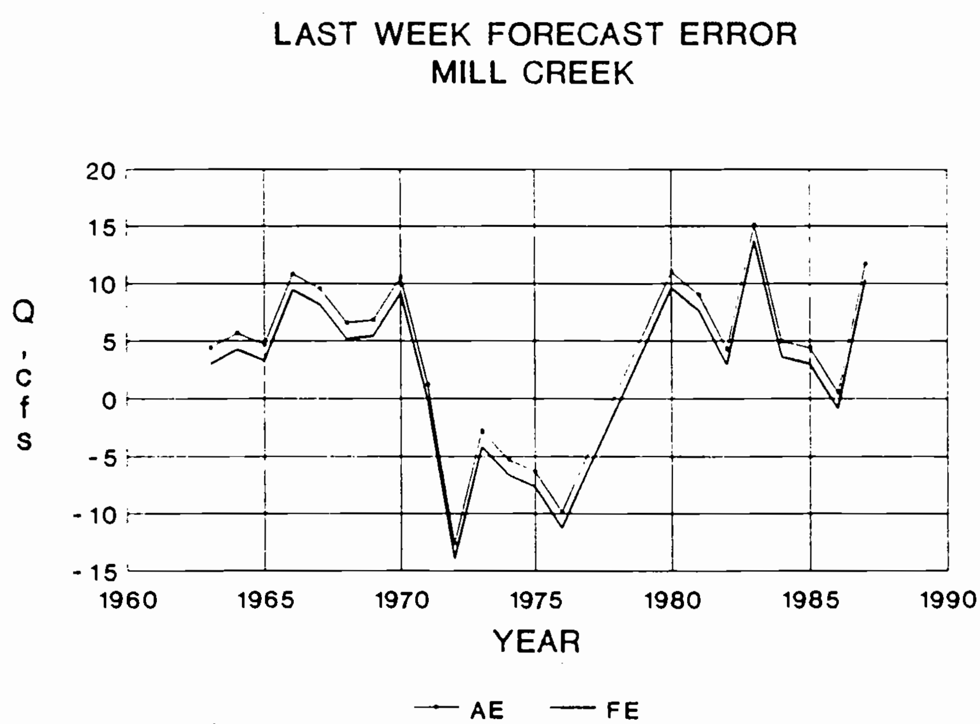

Figure 99. Average and forecast errors for last week of water year for Mill Creek.

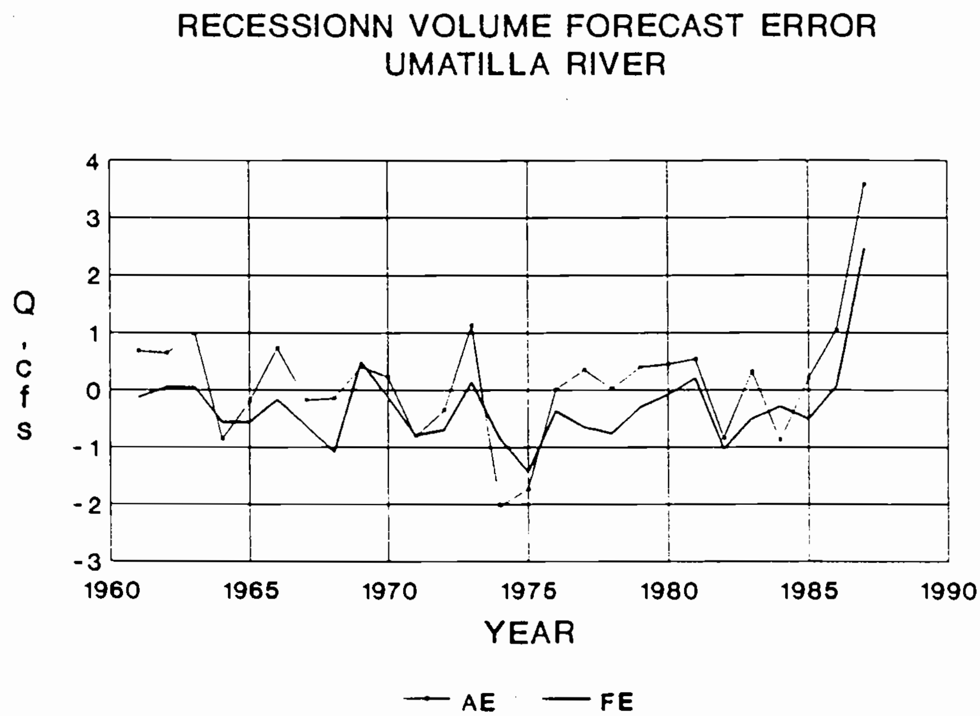

Figure 100. Average and forecast errors for recession volume for the Umatilla River.

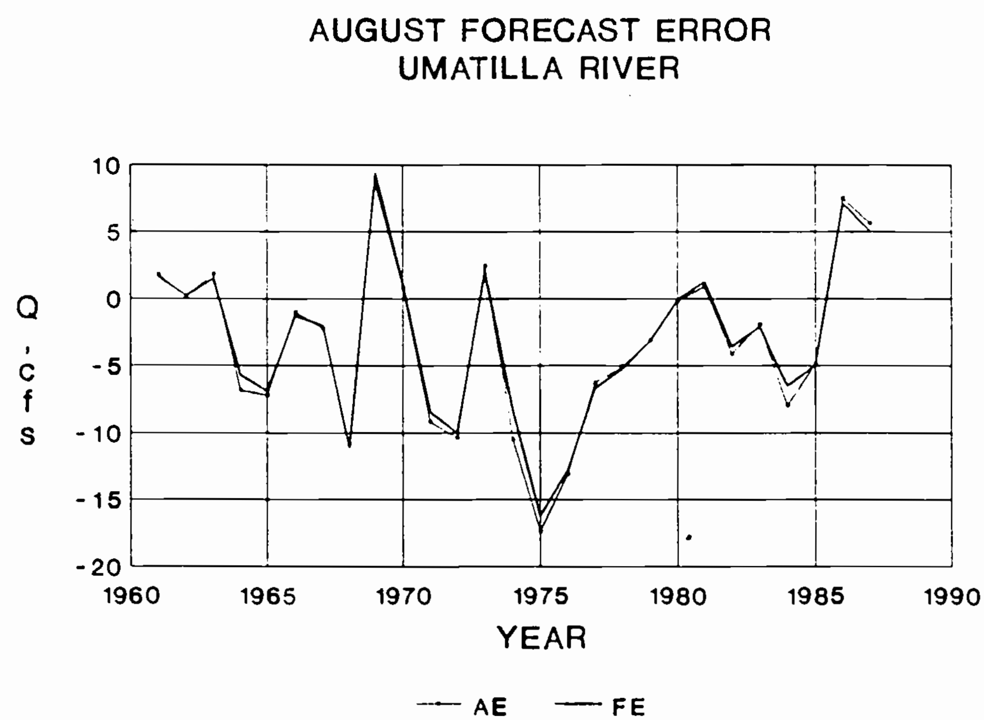

Figure 101. Average and forecast errors for August flow for the Umatilla River.

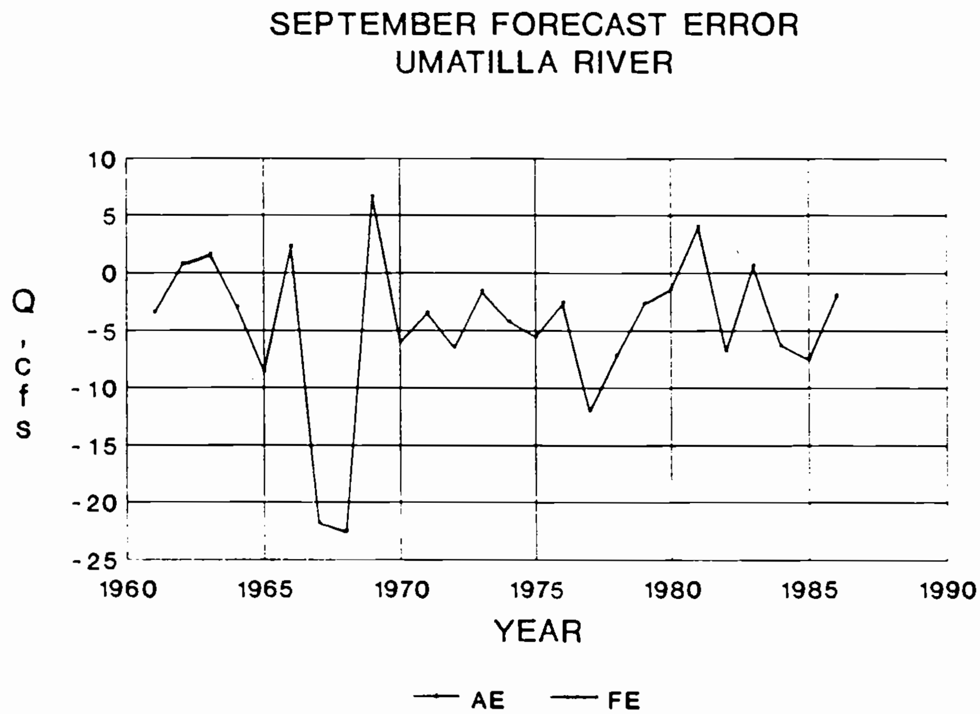

Figure 102. Average and forecast errors for September flow for the Umatilla River.

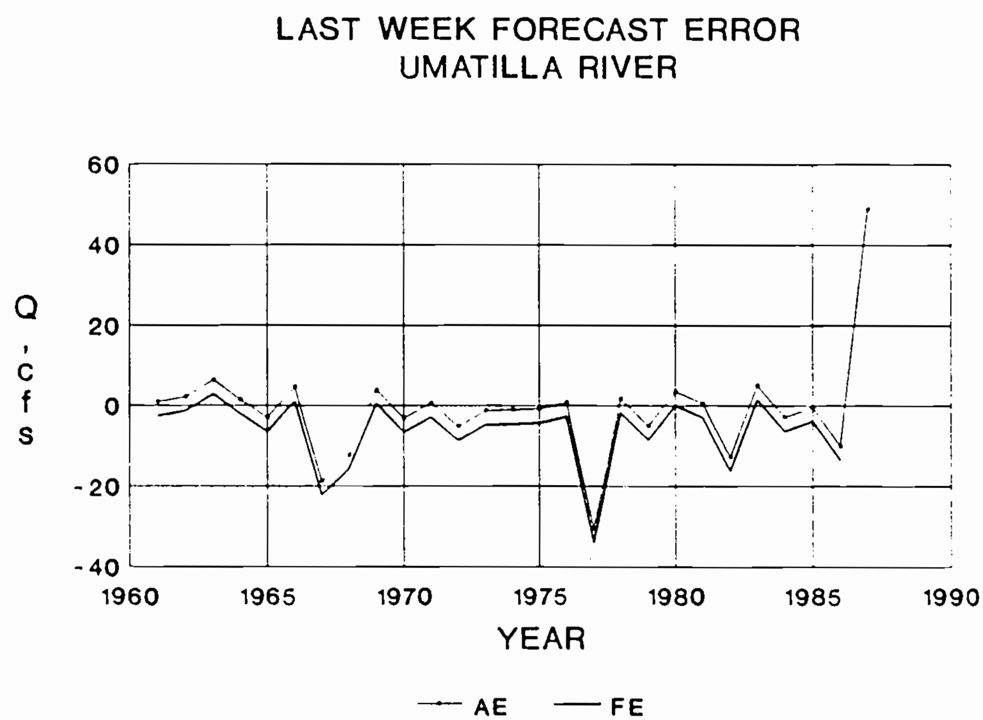

Figure 103. Average and forecast errors for last week of water year for the Umatilla River.

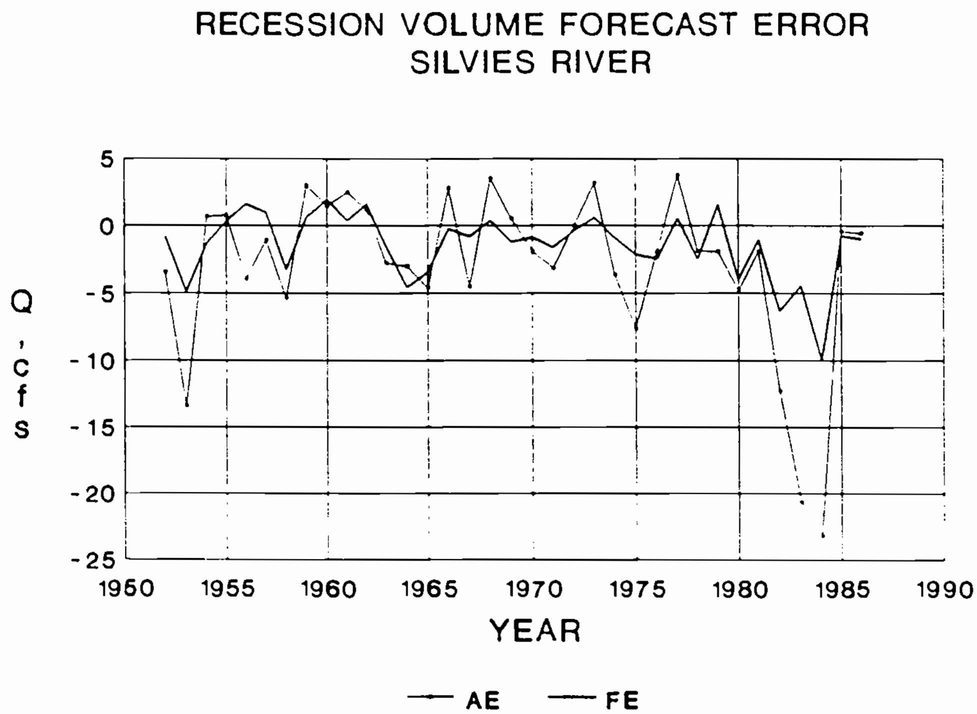

Figure 104. Average and forecast errors for recession volume for the Silvies River.

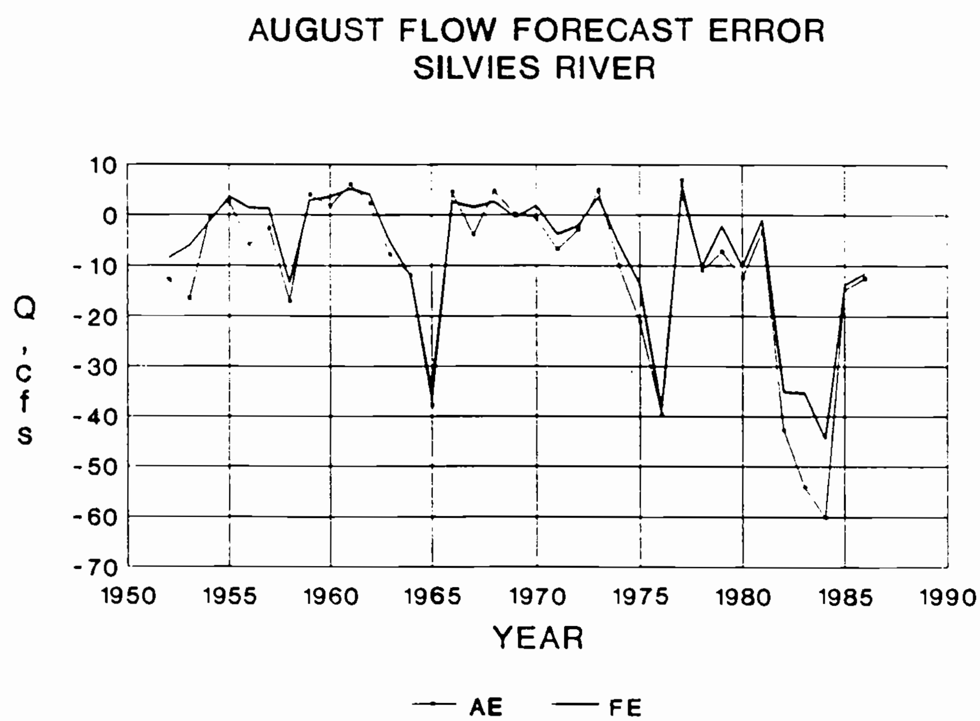

Figure 105. Average and forecast errors for August flow for the Silvies River.

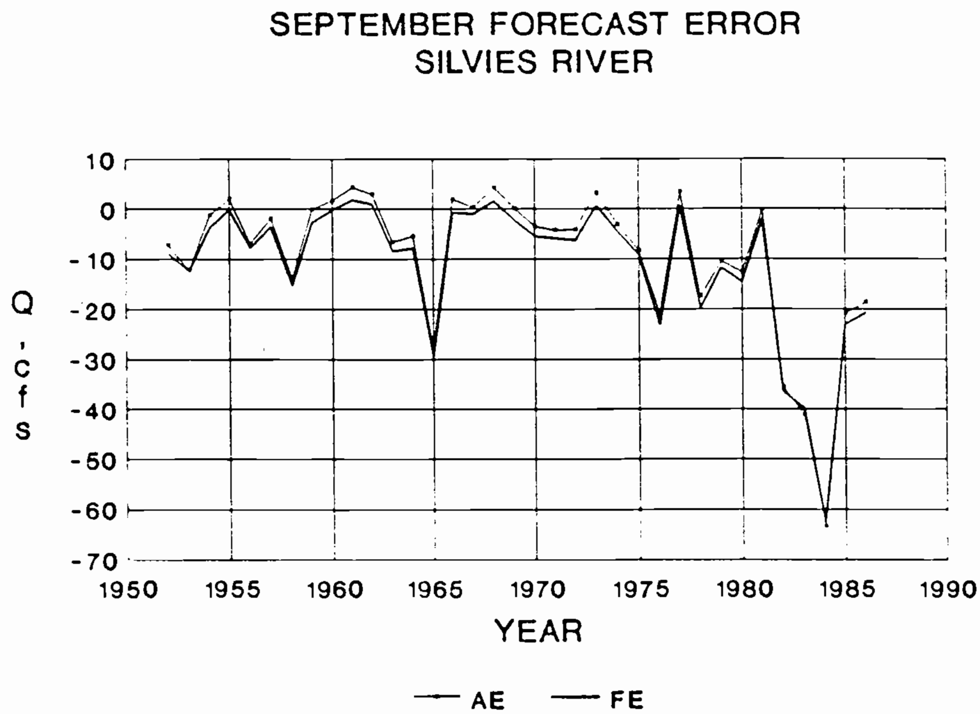

Figure 106. Average and forecast errors for September flow for the Silvies River.

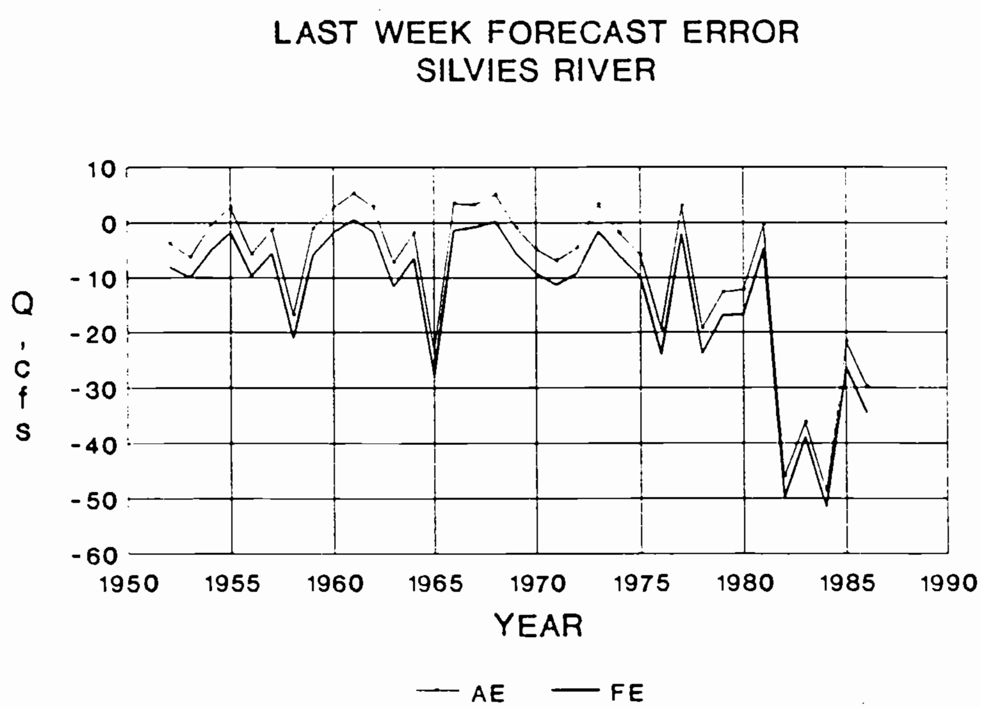

Figure 107. Average and forecast errors for last week of water year for the Silvies River.

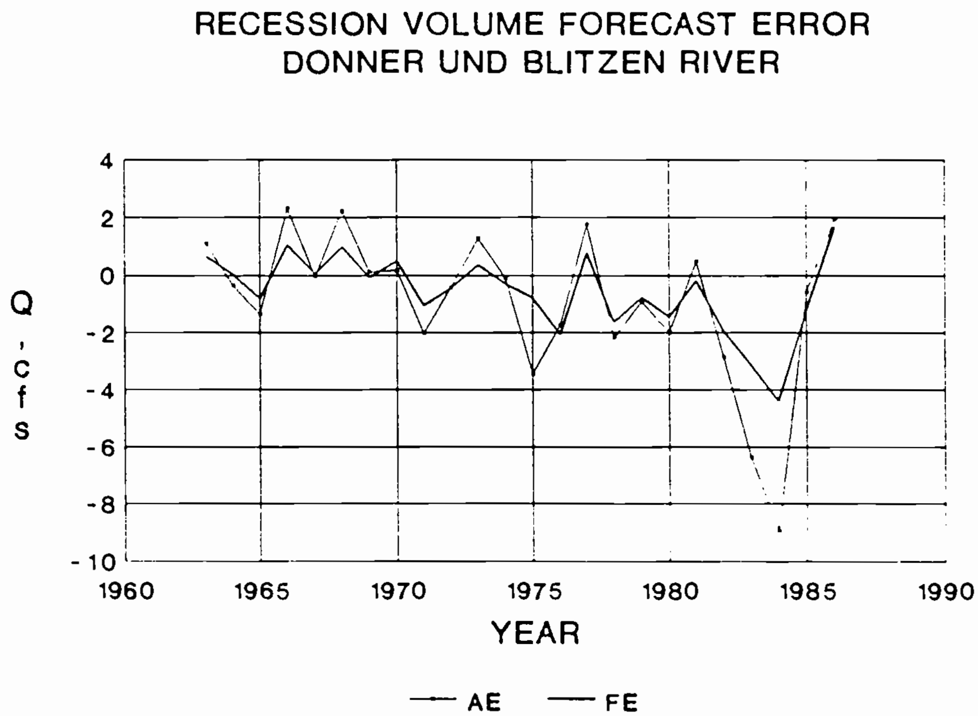

Figure 108. Average and forecast errors for recession volume for the Donner Und Blitzen River.

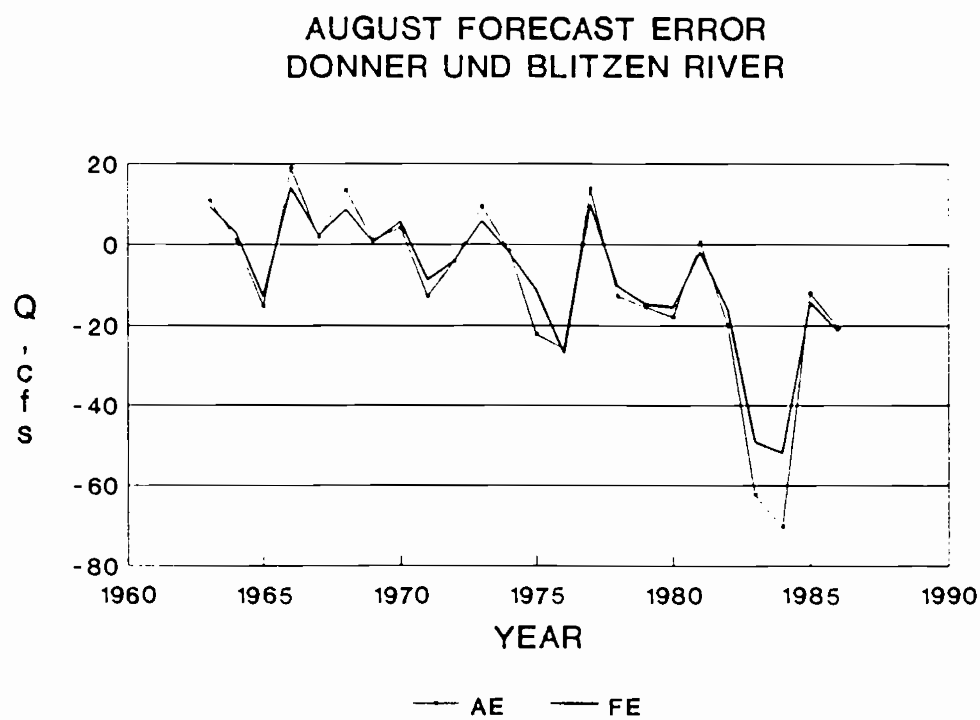

Figure 109. Average and forecast errors for August flow for the Donner Und Blitzen River.

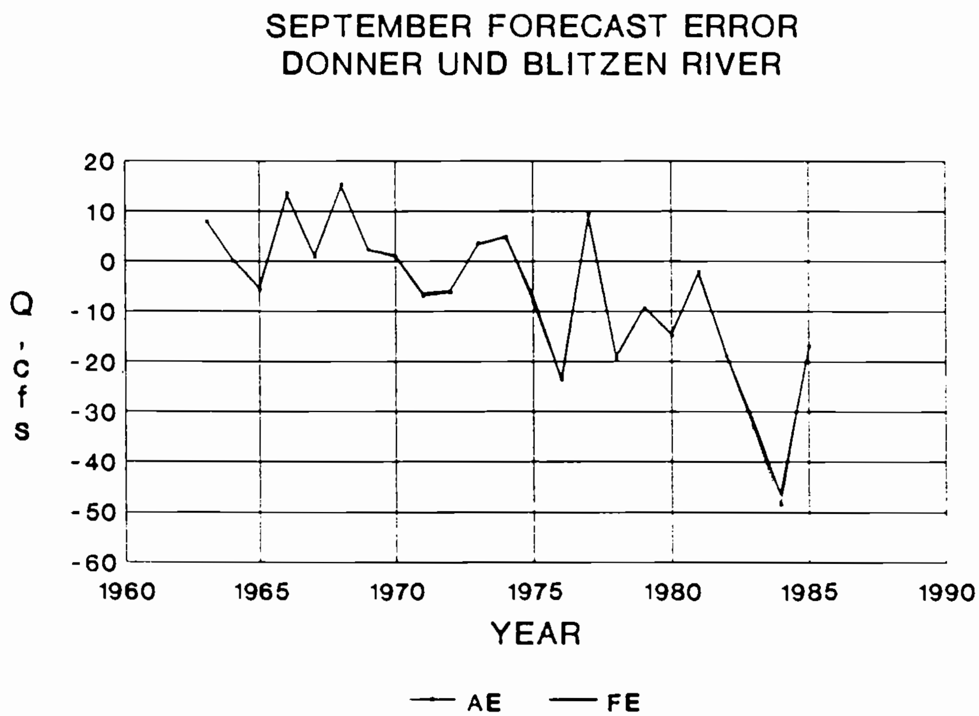

Figure 110. Average and forecast errors for September flow for the Donner Und Blitzen River.

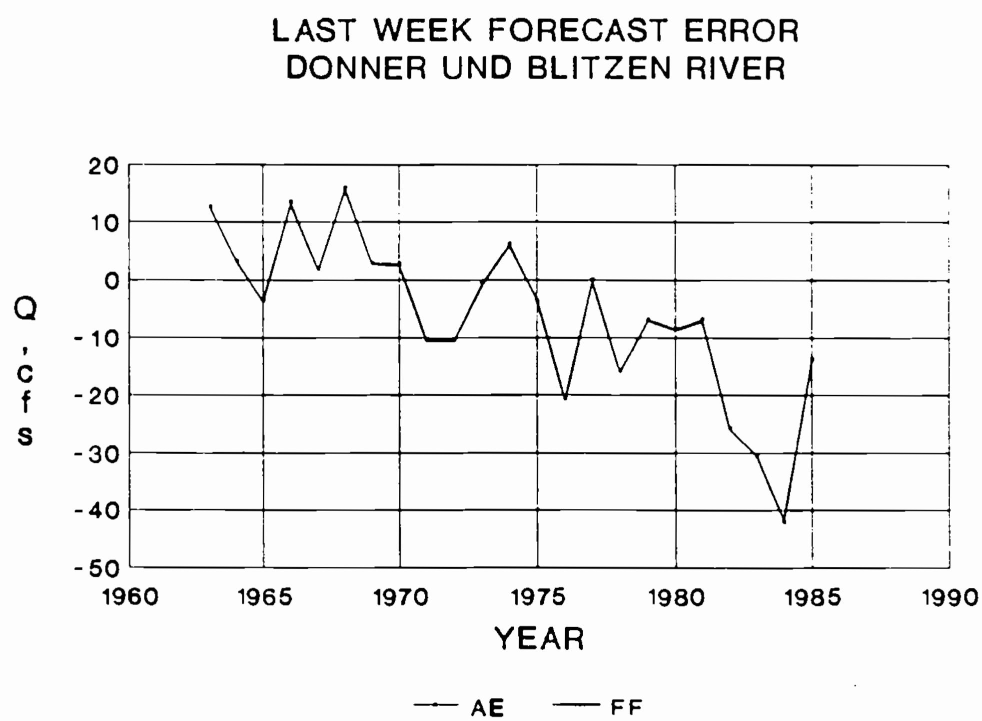

Figure 111. Average and forecast errors for last week of water year for the Donner Und Blitzen River.

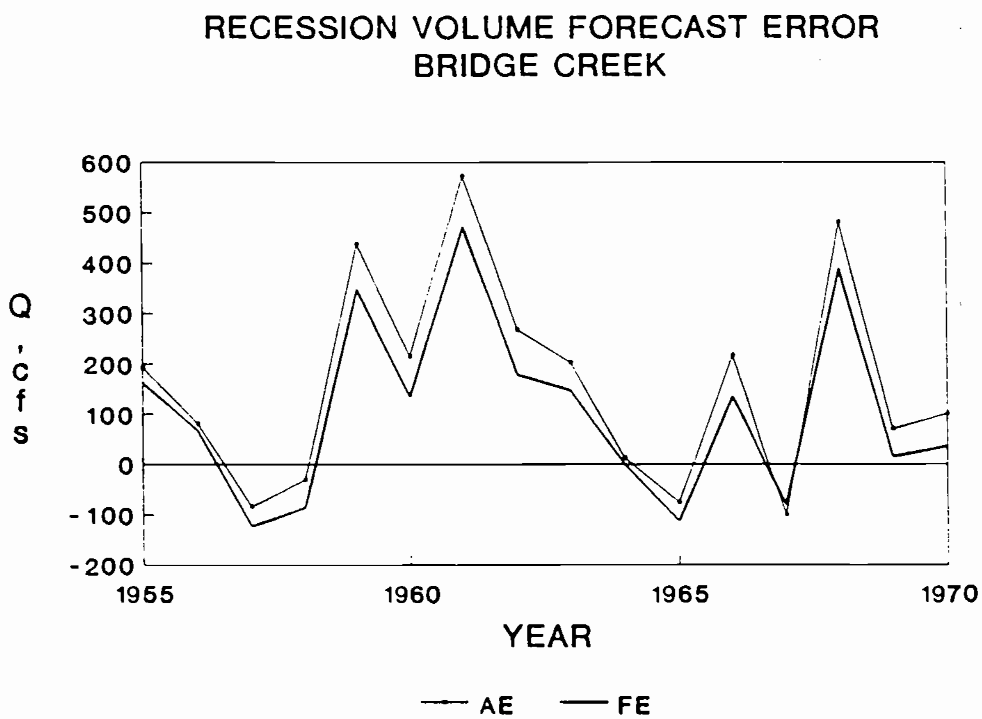

Figure 112. Average and forecast errors for recession volume for Bridge Creek.

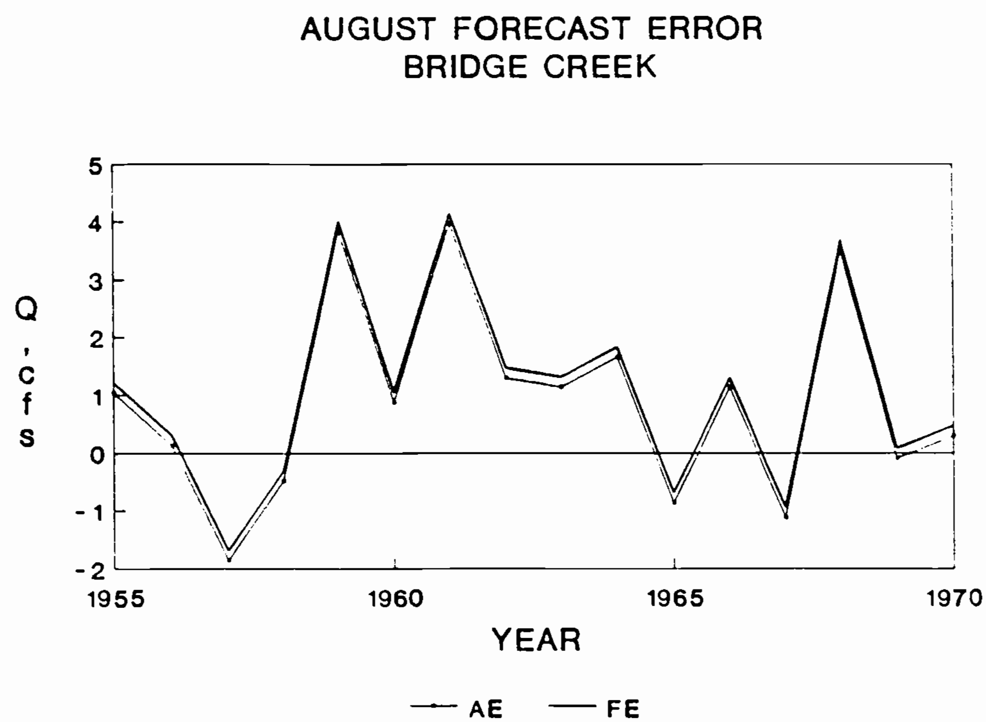

Figure 113. Average and forecast errors for August flow for Bridge Creek.

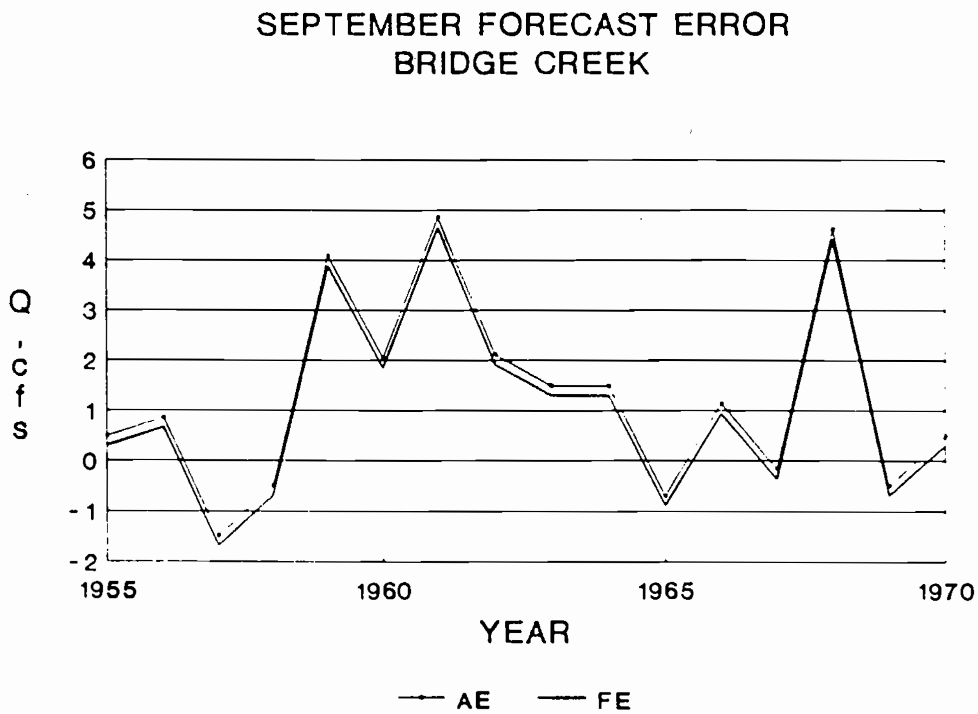

Figure 114. Average and forecast errors for September flow for Bridge Creek.

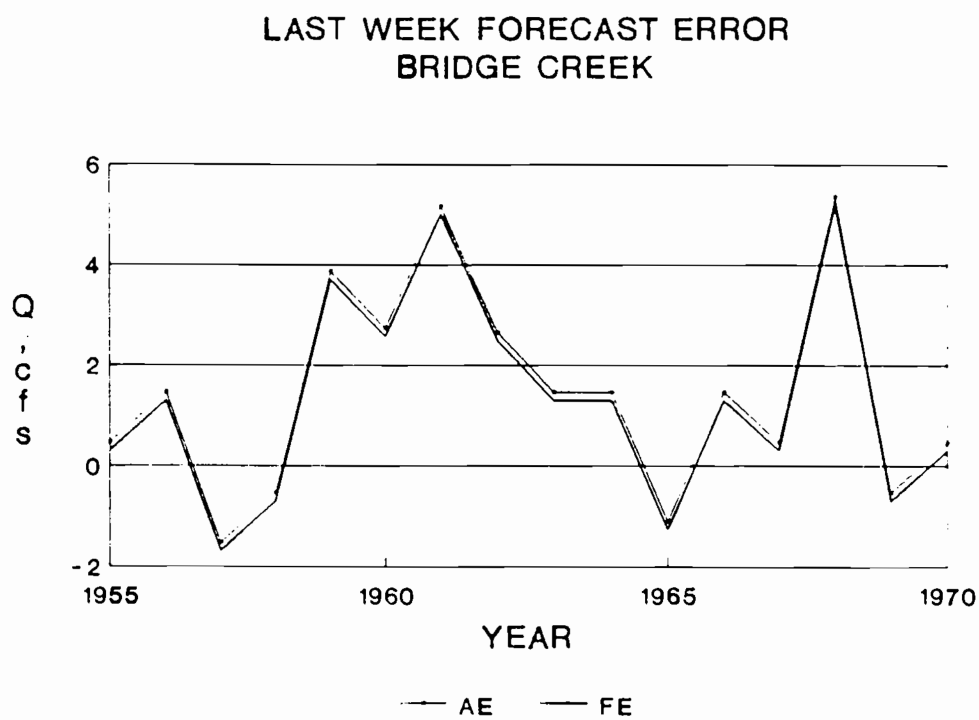

Figure 115. Average and forecast errors for last week of water year for Bridge Creek.

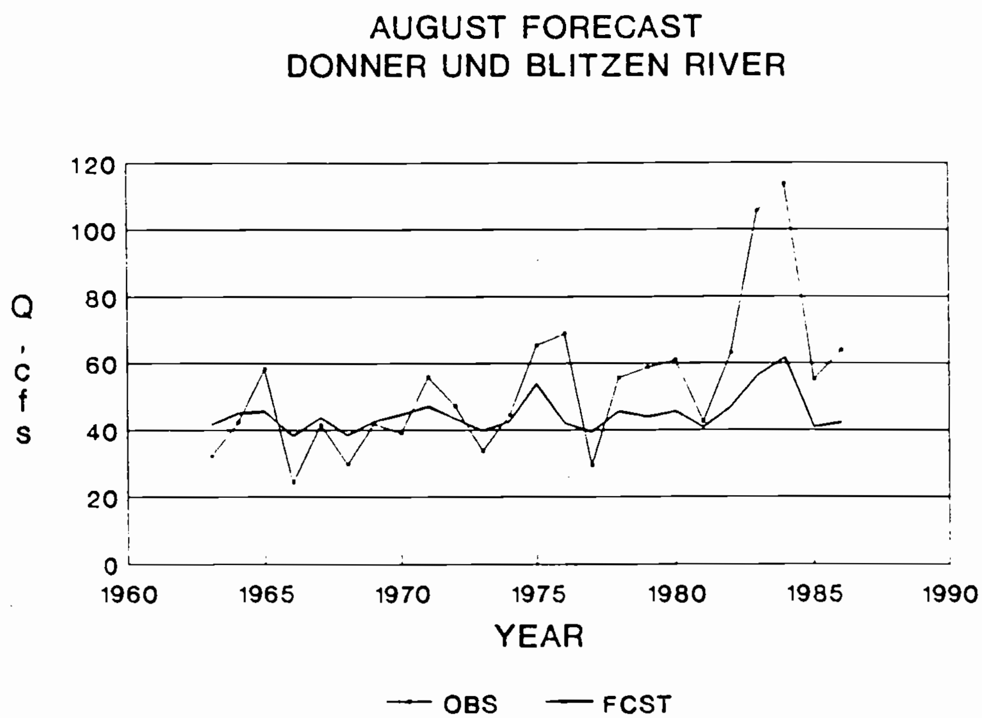

Figure 116. Observed and forecasted August average flows for the Donner Und Blitzen River.

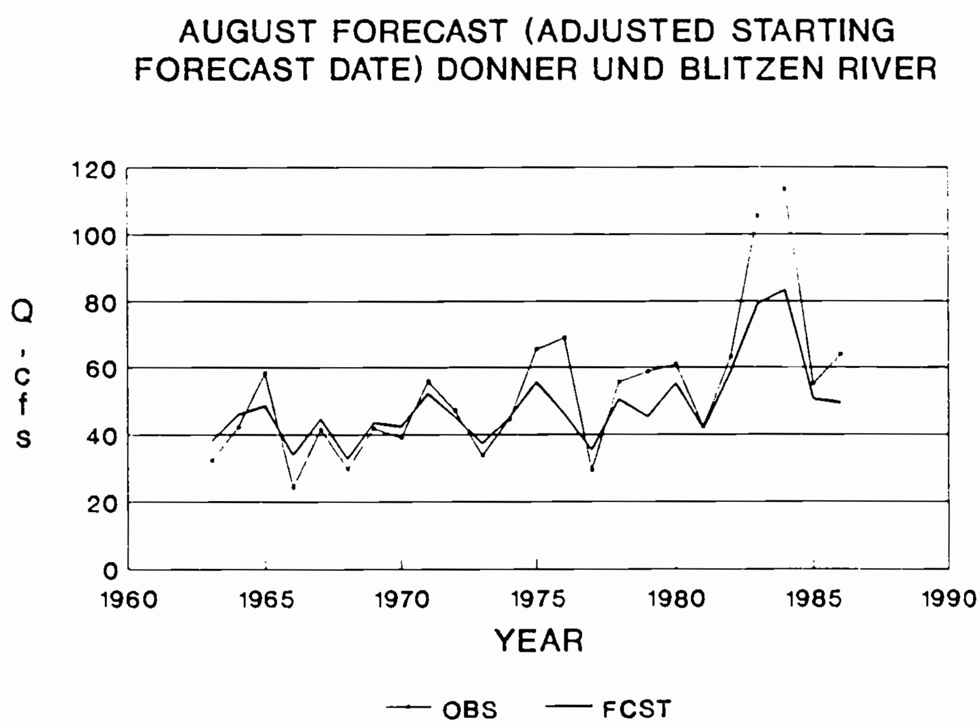

Figure 117. Observerd and forecasted (for shorter period) August average flows for the Donner Und Blitzen River.

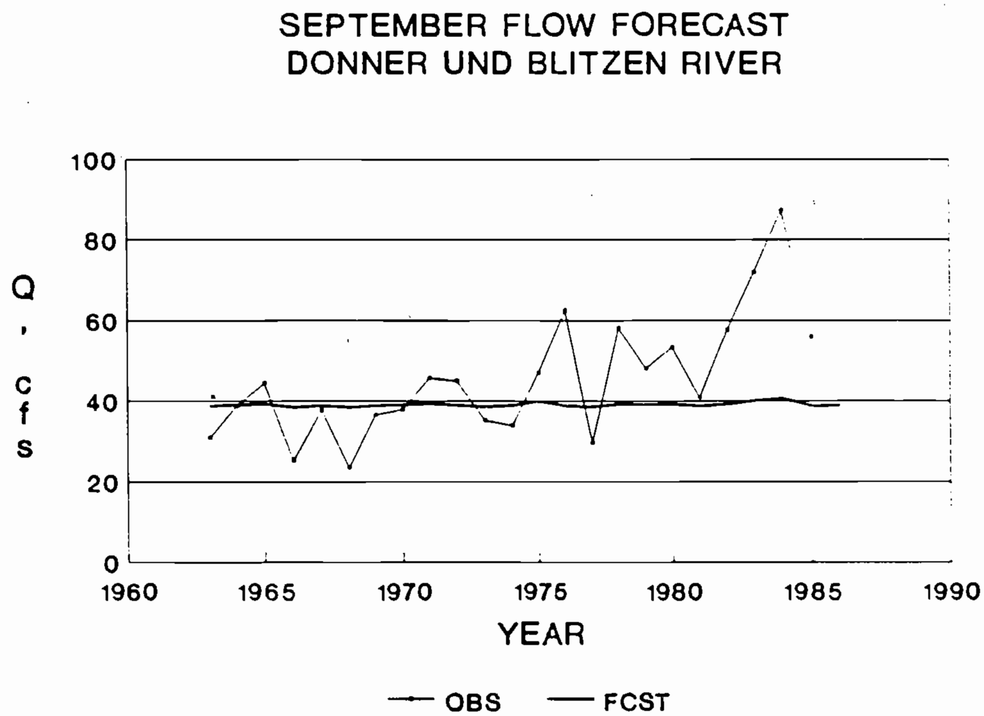

Figure 118. Observed and forecasted September average flows for the Donner Und Blitzen River.

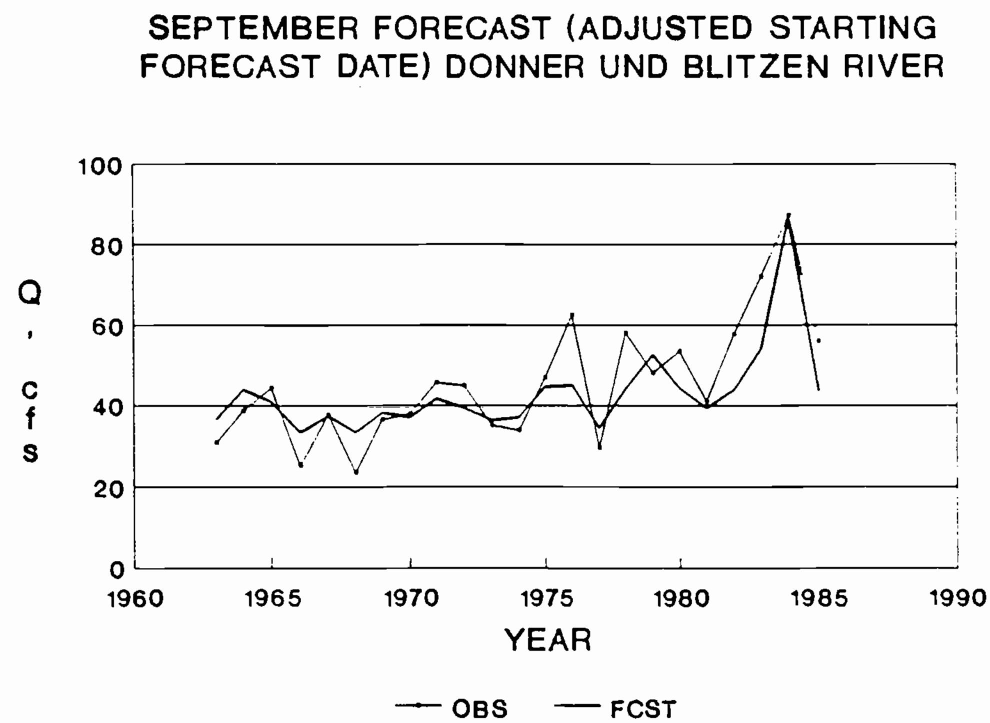

Figure 119. Observerd and forecasted (for shorter period) September average flows for the Donner Und Blitzen River.

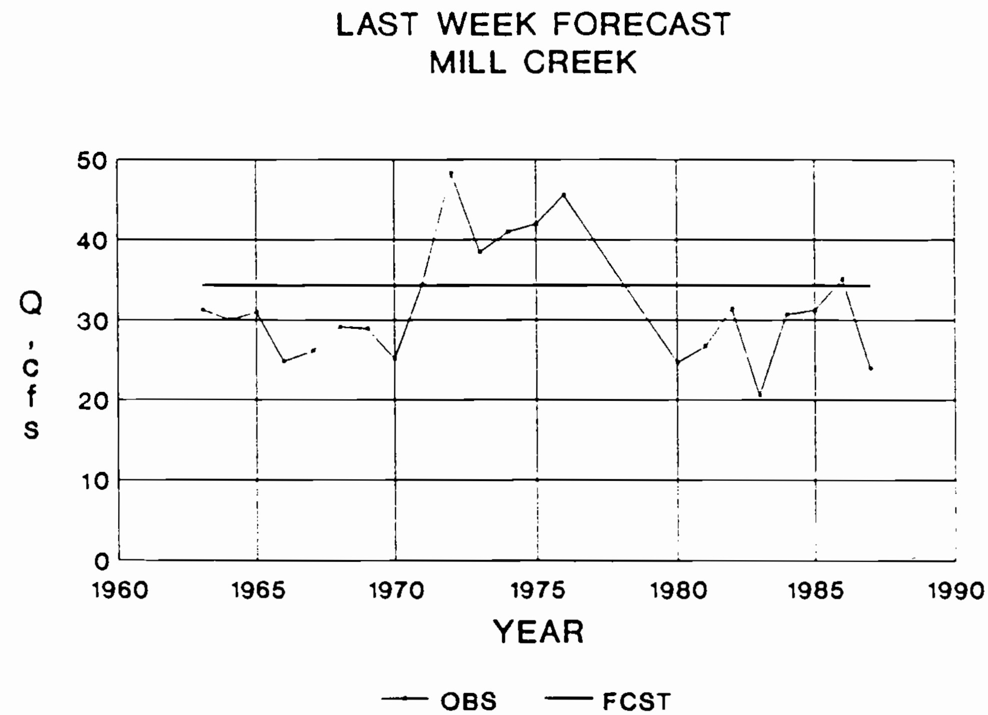

Figure 120. Observed and forecasted last week average flows for Mill Creek.

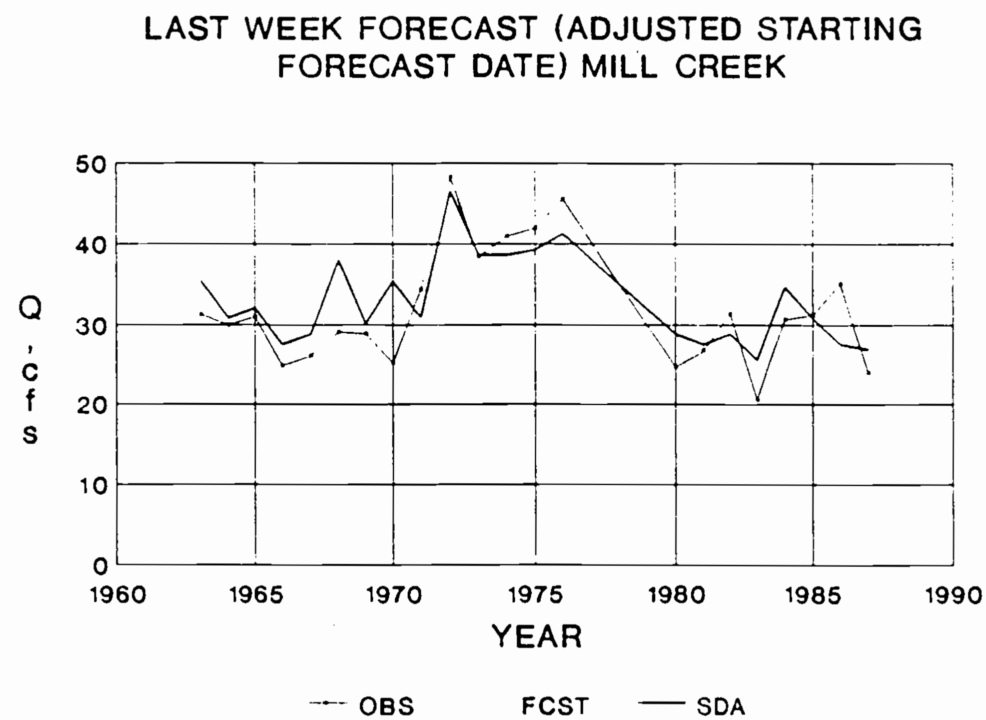

Figure 121. Observerd and forecasted (for shorter period) last week average flows for Mill Creek.

120 & 121). These streams and parameters were picked because they had the poorest accuracy of forecasts made for the longer periods. Forecasts were made for August flows using the flow on 31st of July of that year as starting flow, and for September flows starting with the 31st of August for each year. Similarly, forecasts for the last 7 day of water year were made starting with the flow on the 23rd of September of each year. Forecasts made in this way improved the predictions' accuracy greatly.

It is concluded that forecast models are very good in prediction for recession volume and August average flows. They are not good predictors for September and last week average flow when applied from the starting day of the model period. However, they are accurate, even for September and last week of water year flows, when predictions are made for the individual parameter of the recession period with changed starting forecast day. Due to accumulation of model error, length of forecast period is reduced.

MEAN LOW FLOWS

Mean annual, August, September and October low flows with their standard deviations are calculated for each stream (Table 9). Low flows for streams in the Blue Mountain region have lower variability than streams in the other two regions. Streams in the Southeastern Oregon region showed higher variability in low flows. The Silvies River and the Umatilla River have the maximum and minimum variations in low flow, respectively.

Table 9: Mean low flows (annual (ANN), August (AUG), September (SEP) and October (OCT)) with their standard deviation (St. Dev.) for selected streams in eastern Oregon.

Name of Stream		ANN cfs	AUG cfs	SEP cfs	OCT cfs
Wallowa Mountain region					
East Fork	Mean	9.17	16.05	13.68	12.79
Wallowa River	St.Dev.	1.64	4.12	2.95	2.73
Hurricane Creek	Mean	15.05	40.33	28.20	25.81
	St. Dev.	4.96	11.82	7.13	9.16
Bear Creek	Mean	9.27	12.75	10.79	15.24
	St. Dev.	2.76	4.31	3.34	15.15
Blue Mountain region					
South Fork	Mean	96.96	105.00	102.43	102.79
Walla Walla R.	St. Dev.	12.93	14.27	13.52	14.64
Mill Creek	Mean	26.36	29.49	29.49	29.70
	St. Dev.	6.91	7.23	6.87	7.21
Umatilla River	Mean	40.18	43.05	42.92	45.97
	St. Dev.	4.78	4.53	5.65	7.73
Southeastern Oregon region					
Silvies River	Mean	8.44	8.82	10.40	14.92
	St. Dev.	8.49	9.18	10.37	10.82
Donner Und	Mean	24.00	41.20	38.04	39.21
Blitzen River	St. Dev.	8.44	13.55	10.88	10.12
Bridge Creek	Mean	9.21	11.27	11.49	11.15
	St. Dev.	1.92	1.80	1.98	1.98

5-YEAR MOVING AVERAGE TRENDS

A graph of annual minimum flows does not always provide a clear picture of the trends. To find the stream low flow trends and patterns, 5-year moving averages for minimum annual, August, September and October low flows were calculated for each stream. Their trend similarities were studied regionwise. Again, annual minimum flows are analyzed for a complete picture of minimum flows throughout the year.

WALLOWA MOUNTAIN REGION:

ANNUAL MINIMUM FLOWS

Fig. 122 shows the 5-year moving average annual minimum flow trends for Wallowa Mountain region. In the Wallowa Mountain region, the five year moving averages for annual minimum flows showed much similarity between two of the three streams, namely, the East Fork Wallowa River and Bear Creek. Minimum flows for Hurricane Creek were similar to the East Fork Wallowa River and Bear Creek until the mid 1940's; after that point, the trends were almost opposite to the other two streams. Trends are non stationary (i.e., means change with changing periods) in this region. Hurricane Creek and Bear Creek show a positive trend (i.e., means increase with successive periods) throughout their records. The East Fork Wallowa River showed a positive trend until the late 1960's. The lowest minimum flows on record occurred during the late 1970's. The long term average annual minimum flows for the East Fork Wallowa River and Bear Creek are closer to one another and much lower in magnitude (<10 cfs) than the long-term average annual minimum flow for Hurricane Creek (>15 cfs). From the late 1920's to the mid 1940's, the 5-year moving average is below the long term mean for all three streams. Hurricane Creek and Bear Creek have the lowest minimum flows of record during the late 1930's. Bear Creek has consistently lower minimum flows than the East Fork Wallowa River except during the 1970's. During the early 1950's, the annual minimum flow for Hurricane Creek reached a maximum and then dropped back below average in the late 1950's. During the 1960's and 1970's it remained at or above average. The East Fork Wallowa River and Bear Creek have similar 5-year moving average trends throughout the record, except during a few years in

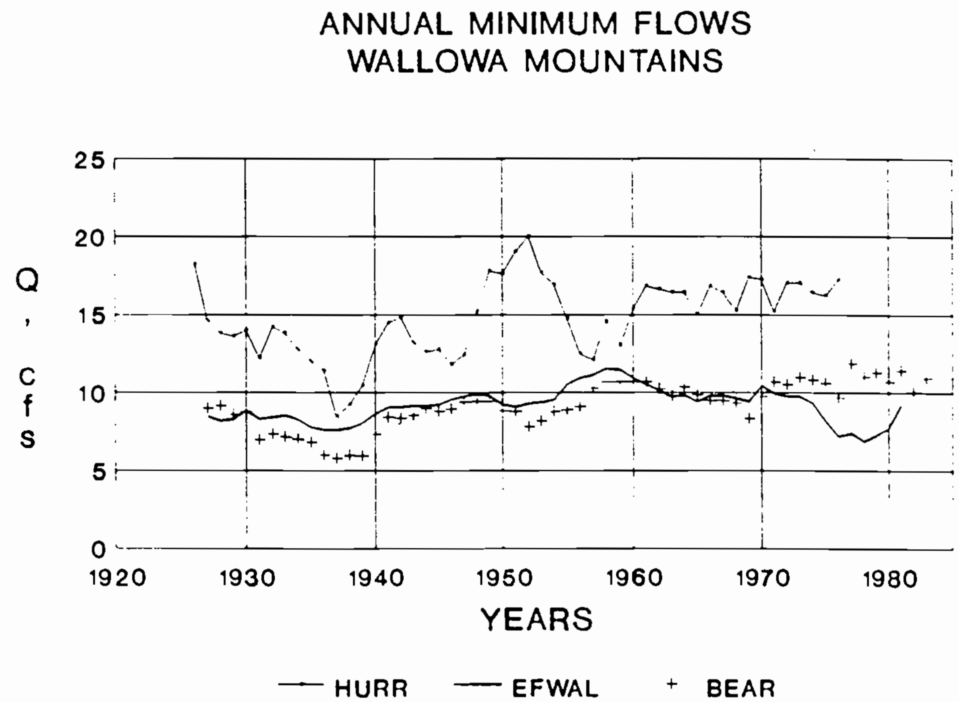

Figure 122. Five-year moving average annual minimum flows for streams in the Wallowa Mountain region.

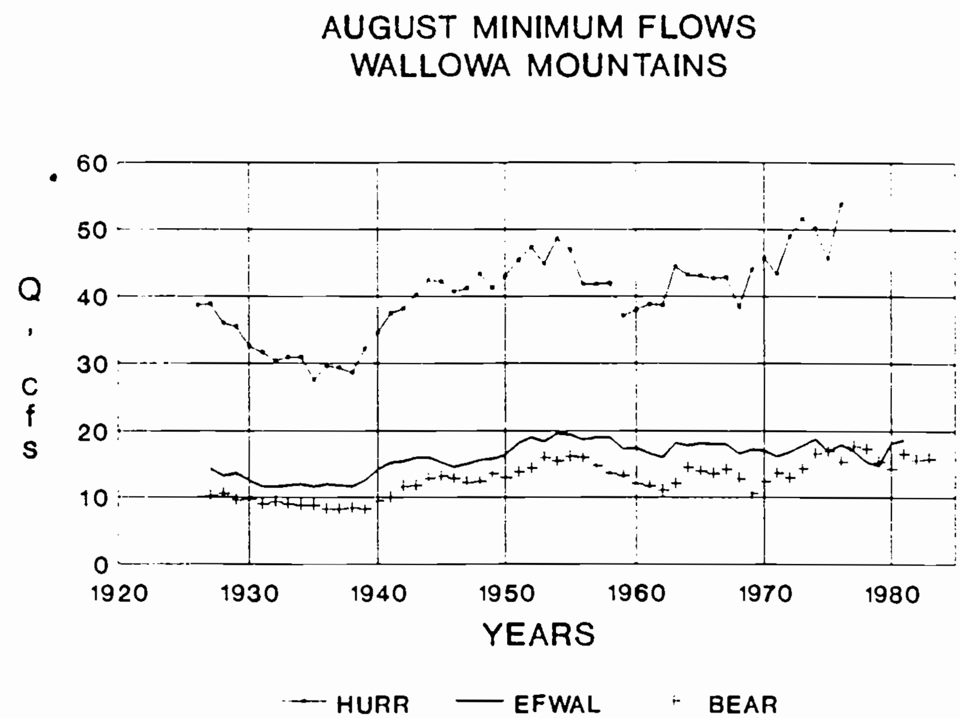

Figure 123. Five-year moving average August minimum flows for streams in the Wallowa Mountain region.

late 1970's.

AUGUST MINIMUM FLOWS

Trends in 5-year moving averages for August minimum flows for the Wallowa Mountain streams are more similar than those in annual minimum flows (Fig. 123). The long term average for minimum August flows for Bear Creek is lower than the East Fork Wallowa River. Hurricane Creek has the highest August minimum flows. For all three streams, flows are below or around average until the late 1940's, fluctuating above or around the mean for rest of the period. August minimum flows for all three streams show positive trends.

SEPTEMBER MINIMUM FLOWS:

Year-to-year variation is slightly increased in September trends. For the majority of the record, trends in minimum September flow for the three streams are similar (Fig. 124). During the 1930's, the flows reached their lowest points for all streams. From the early 1940's to the end of the record, flows have fluctuations above and around average, with increasing trends.

OCTOBER MINIMUM FLOWS:

Variations in October minimum flows for Bear Creek and Hurricane Creek are very high (Fig. 125). The long term mean for Bear Creek is higher than the mean for the East Fork Wallowa River. This reveals a change in catchment behavior during October for this stream. Either the extensive flood plains along Bear Creek release water during October when snow melt is ceased, or reduced evapotranspirational demand over a large catchment area can explain this peculiarity. Except for the East Fork

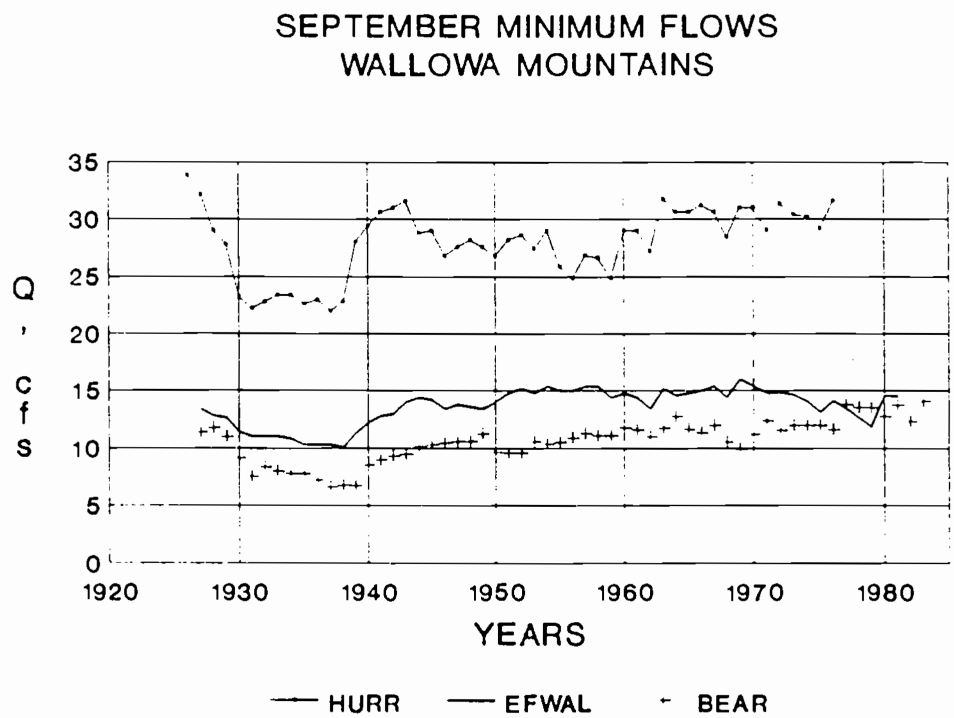

Figure 124. Five-year moving average September minimum flows for streams in the Wallowa Mountain region.

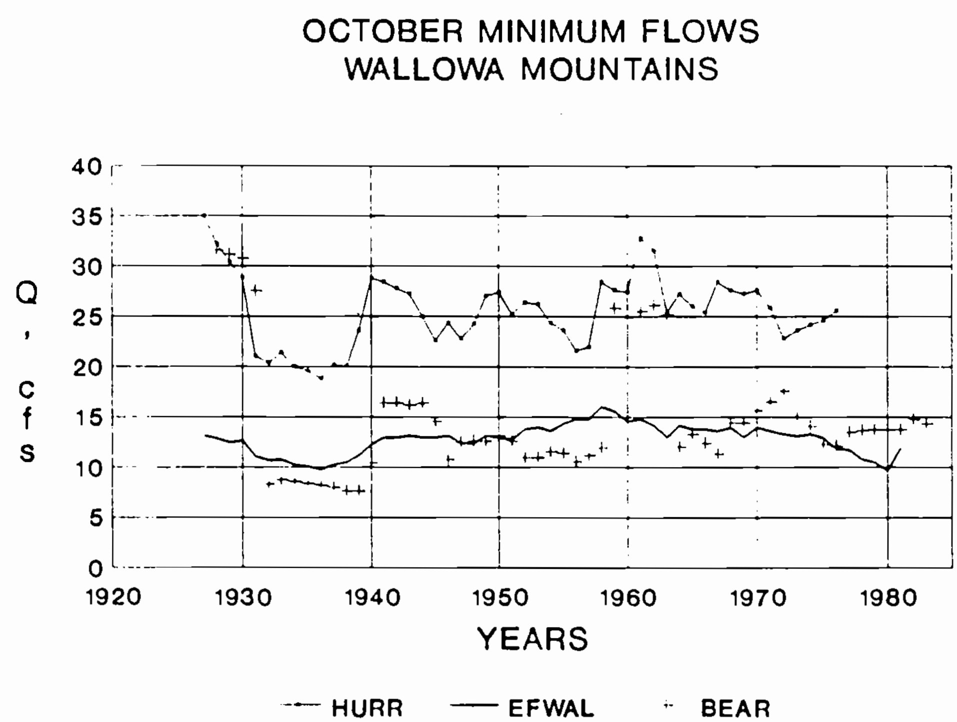

Figure 125. Five-year moving average October minimum flows for streams in the Wallowa Mountain region.

Wallowa River during 1970's, trends are generally the same, increasing over time, for all three streams. Flows are below average during the 1930's.

BLUE MOUNTAIN REGION

ANNUAL MINIMUM FLOWS:

The long-term average minimum annual flows for the South Fork Walla Walla River is much higher than for the Umatilla River and Mill Creek. Mill Creek has the lowest annual minimum flows (Fig. 126). All three streams have smooth trends of below mean annual flows during the 1930's and the mid 1940's. Trends remain above the long term mean for the rest of the period for the Umatilla River. Both the South Fork Walla Walla River and Mill Creek have similar trends from the mid 1940's to the end of the record with some variations, fluctuating above average (during the 1950's and 1970's) and below average (during the late 1960's and early 1980's). These two streams are near one another and have similar vegetative cover conditions.

AUGUST, SEPTEMBER & OCTOBER MINIMUM FLOWS

The 5-year moving average trends for August, September and October minimum flows for all three streams are very similar to the annual minimum flows, but with increased magnitude (Fig. 127, 128 & 129). However, October minimum flows during the late 1950's and early 1960's are much higher than for the rest of the variables (i.e., annual, August, and September minimum flows). Generally, minimum flows increase in magnitude from annual minimum flows to August to September to October minimum flows.

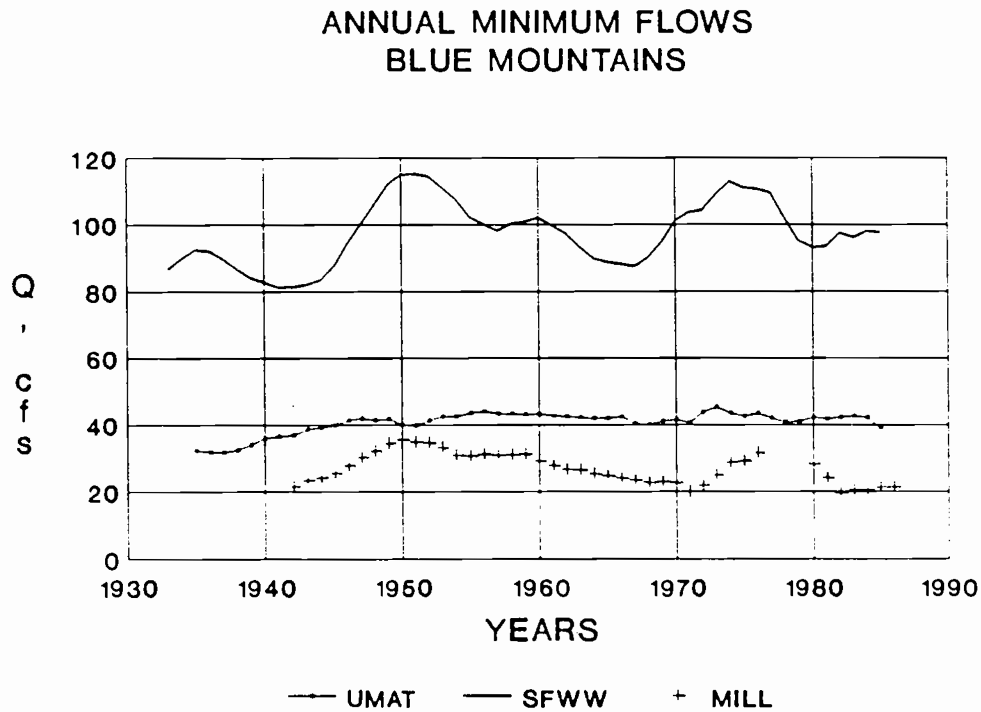

Figure 126. Five-year moving average annual minimum flows for streams in the Blue Mountain region.

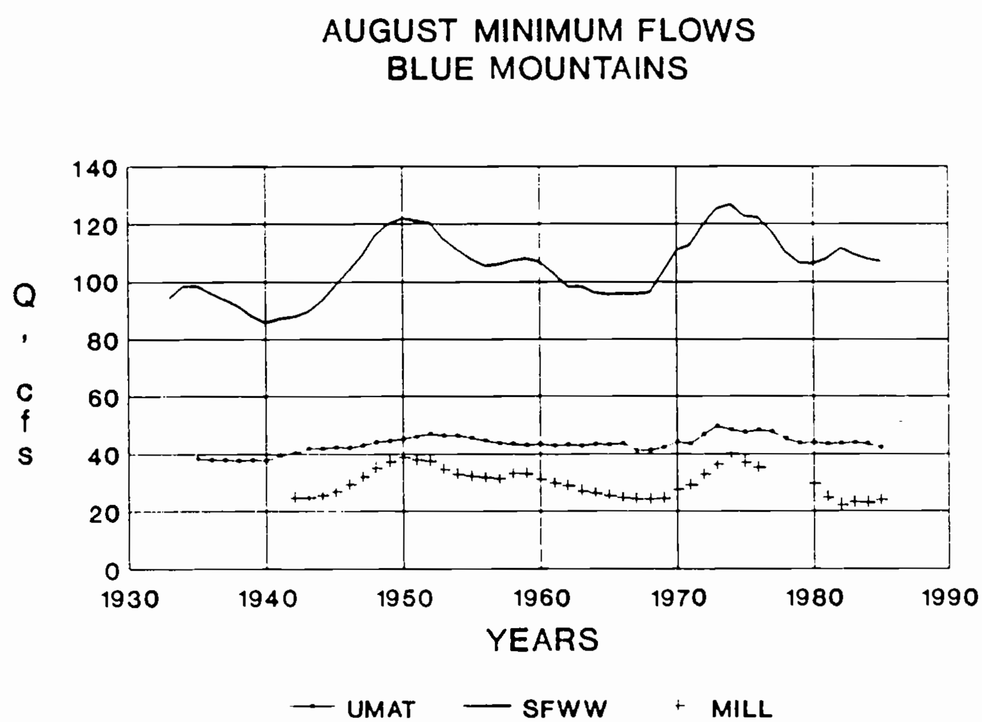

Figure 127. Five-year moving average August minimum flows for streams in the Blue Mountain region.

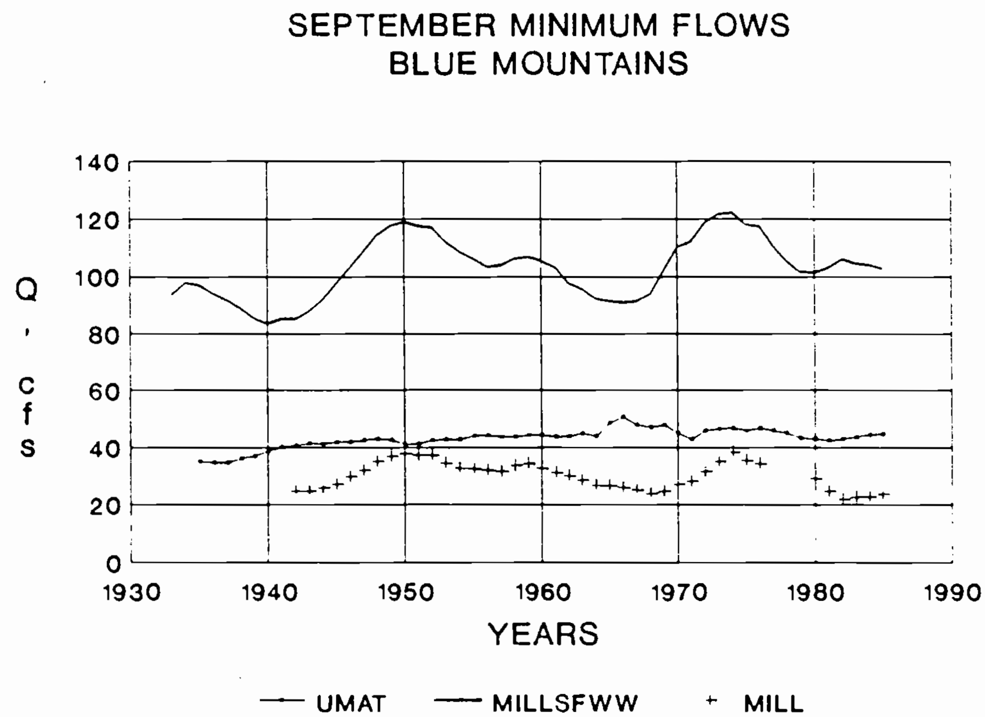

Figure 128. Five-year moving average September minimum flows for streams in the Blue Mountain region.

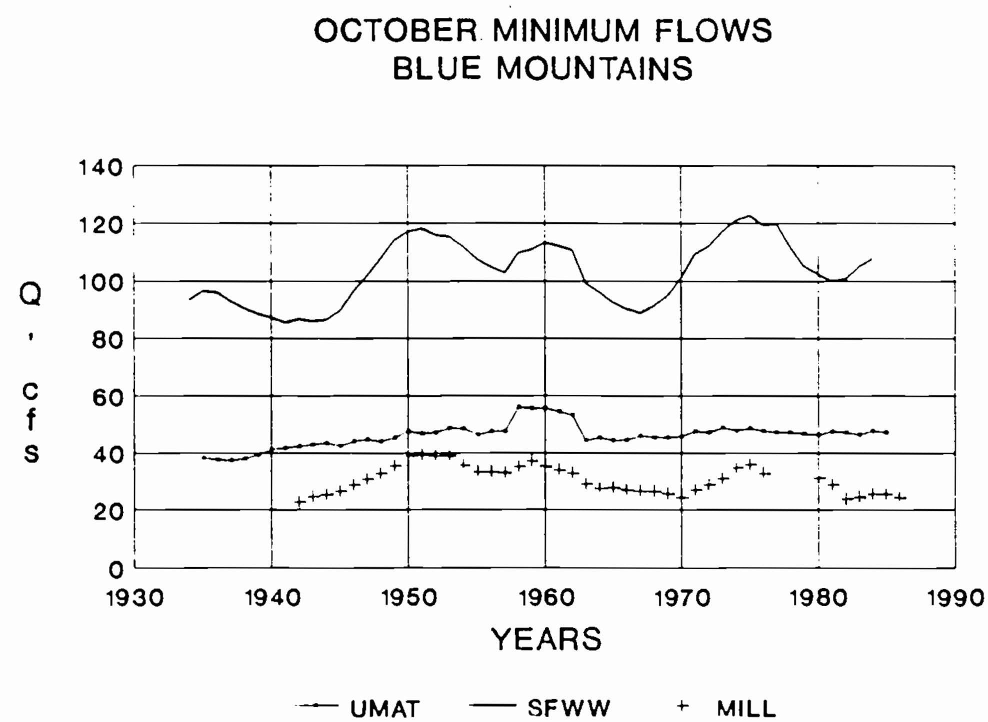

Figure 129. Five-year moving average October minimum flows for streams in the Blue Mountain region.

SOUTHEASTERN OREGON REGION

ANNUAL, AUGUST, SEPTEMBER AND OCTOBER MINIMUM FLOWS:

The 5-year moving average trends in annual minimum flows for the Donner Und Blitzen River and the Silvies River are similar, with some minor variations (Fig. 130). Magnitudes of minimum flows for the Silvies River are lowest of all streams in the region, in spite of having the largest catchment area. Its minimum annual flow from the mid 1920's through the early 1950's is below the long-term mean, and then fluctuates around or below the mean until the late 1970's. Minimum flows reach a maximum at the end of the record. The Donner Und Blitzen River has fluctuations near or below the mean flow during the 1940's and 1950's, remaining well below the mean in the 1960's and 1970's. In the early 1980's, it increased to its maximum of record, similar to the Silvies River. Bridge Creek has a trend which followed the trends of the other two streams to a certain extent, with the amount of departure from the mean very small, compared to the other streams. This indicates its dependence on a water source which is not affected by the year-to-year variability of climate. Ground water supply seems to be a reasonable explanation. For all three streams, trends for August, September and October minimum flows closely followed the annual minimum flow trends, with comparatively greater magnitudes of discharges than annual minimums (Fig. 131, 132 & 133). For the Donner Und Blitzen River, flows increased from annual to September to August to October minimum flows. For the Bridge Creek, flows during these months are almost the same. For the Silvies River, magnitudes of discharges increased from annual minimums to August to September to October minimum flows. The long-term average October flow for the Silvies River is greatly

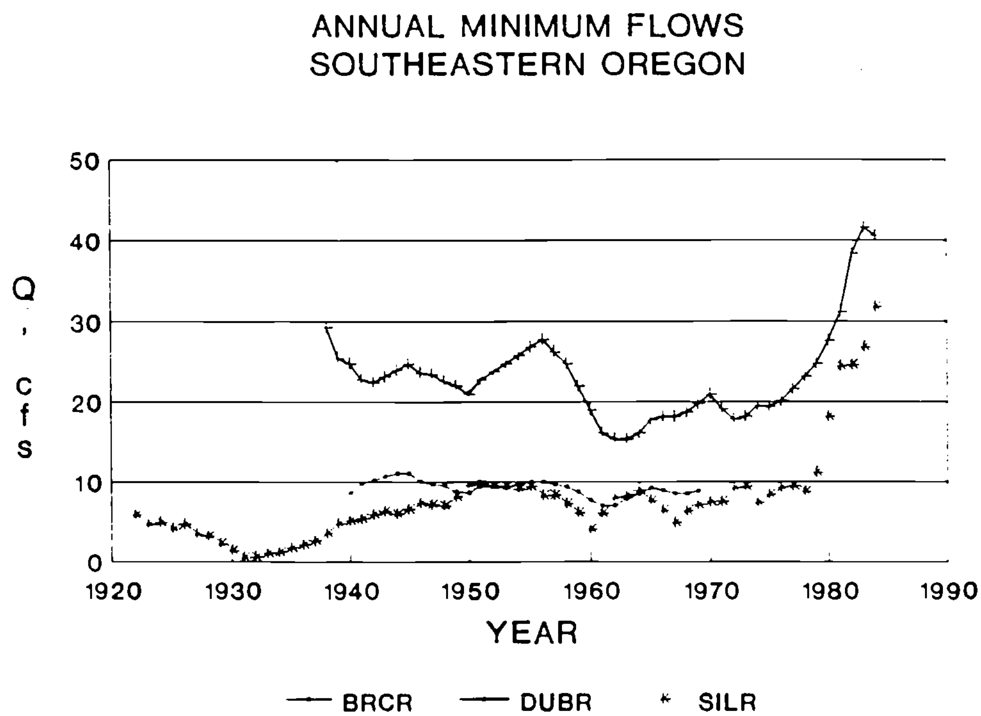

Figure 130. Five-year moving average annual minimum flows for streams in the southeastern Oregon region.

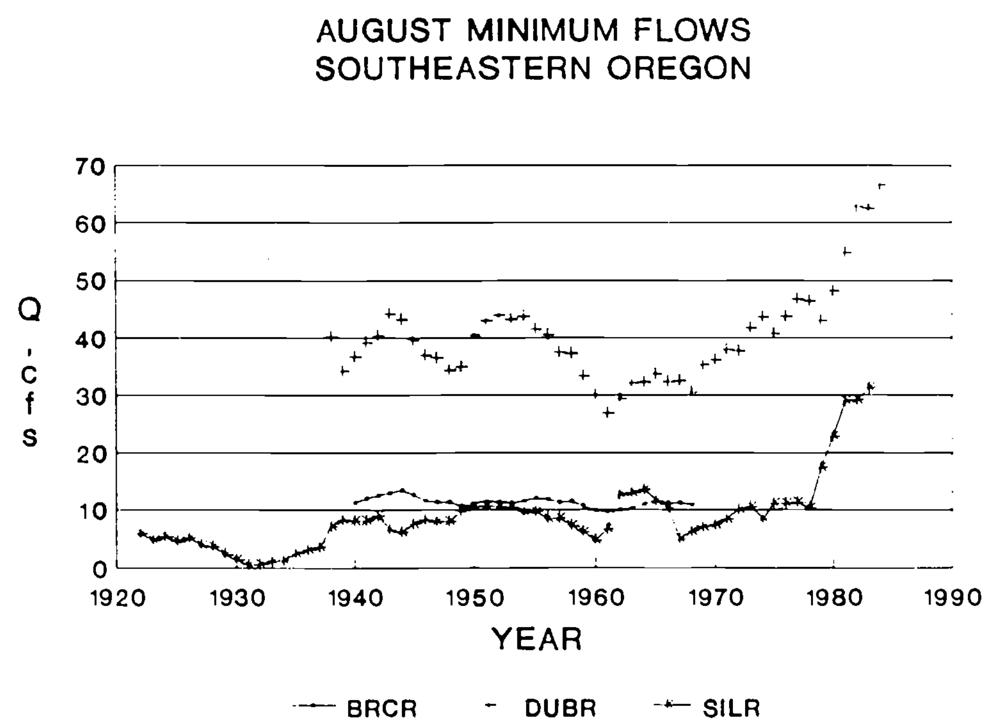

Figure 131. Five-year moving average August minimum flows for streams in the southeastern Oregon region.

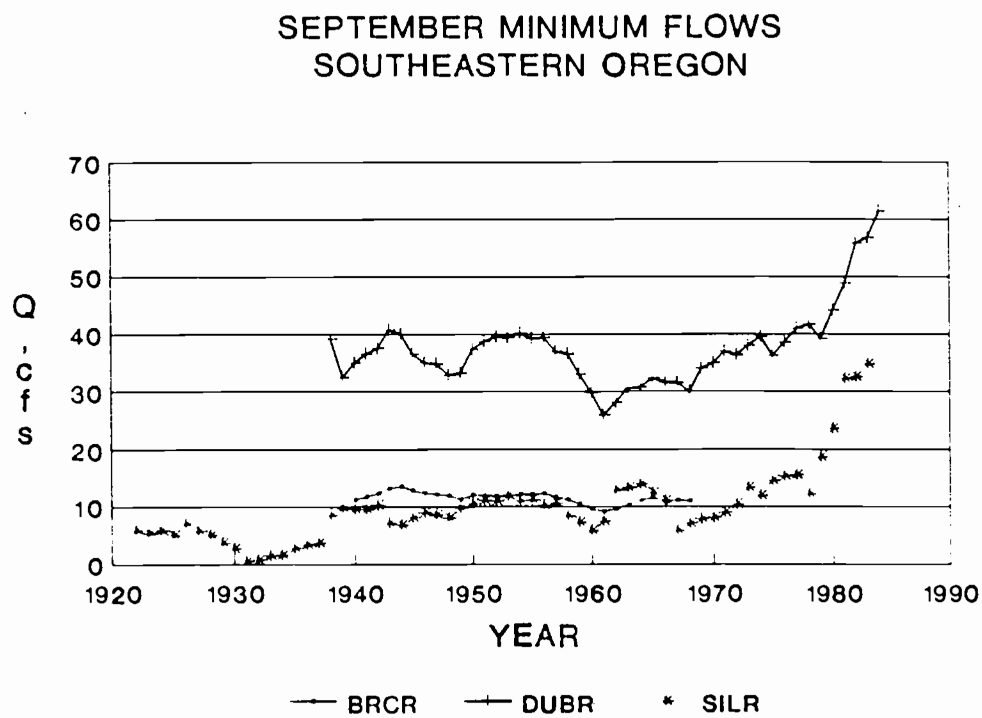

Figure 132. Five-year moving average September minimum flows for streams in the southeastern Oregon region.

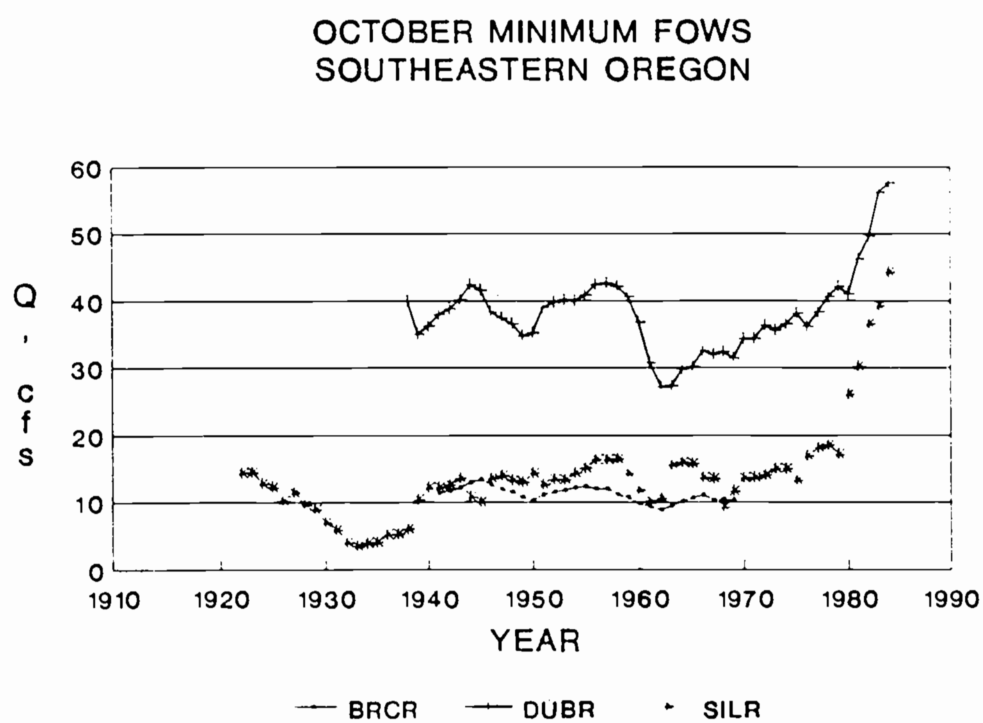

Figure 133. Five-year moving average October minimum flows for streams in the southeastern Oregon region.

increased than those of August and September, and is higher than Bridge Creek's, while for other variables it is lower. This behavior is similar to Bear Creek in the Wallowa Mountains region, which reveals either onset of rainy season for the Silvies River catchment earlier or reduced evapotranspiration over a larger catchment area, compared to other streams.

CUMULATIVE DEPARTURES FROM THE LONG TERM MEAN

WALLOWA MOUNTAIN REGION

ANNUAL MINIMUM FLOWS:

The cumulative departure from the mean for the East Fork Wallowa River was negative from the mid 1920's until the late 1950's and was positive from the early 1960's to the late 1970's. The cumulative departure from the mean for Bear Creek is negative for the whole period of record. Hurricane Creek has a departure similar to Bear Creek, except from the mid 1920's to the mid 1930's when it becomes positive (Fig. 134). The negative cumulative departures increased until early 1940's for all streams in the region. In spite of some wet years, departures for Hurricane Creek and Bear Creek increased until the late 1940's and mid-1950's, respectively. From there onward, minimum flows recovered until the end of record for both streams, though with much variability in the trend during that period.

AUGUST MINIMUM FLOWS:

All three streams have a negative departure from the mean for August minimum flows for the whole period of record (Fig. 135). The East Fork Wallowa River and Bear Creek have similar magnitudes of departure. All streams

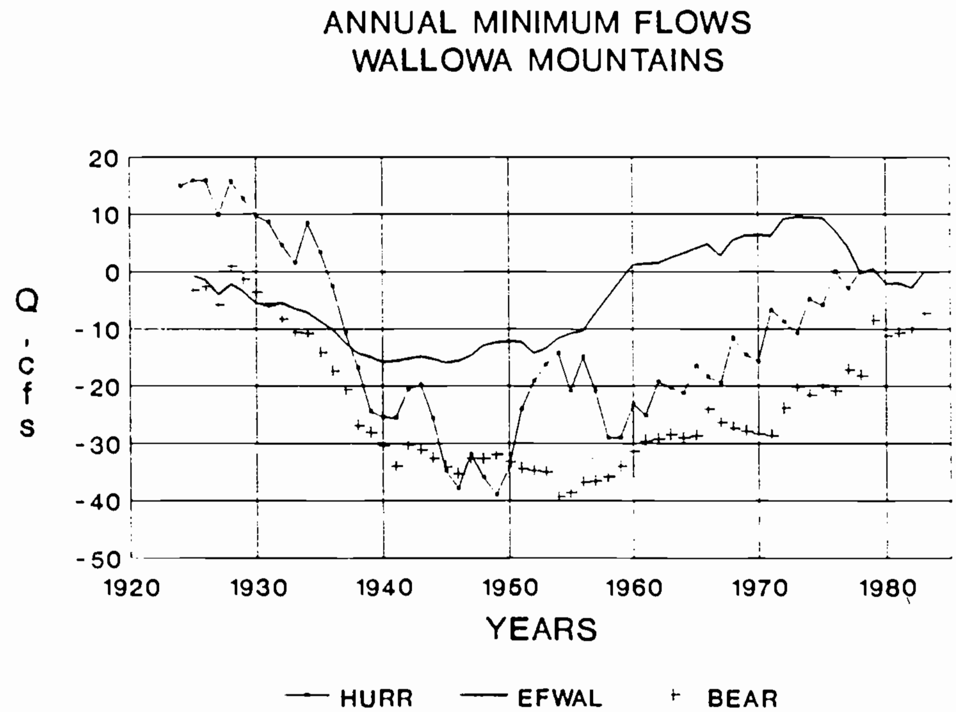

Figure 134. Cumulative departures from means for annual minimum flows for streams in the Wallowa Mountain region.

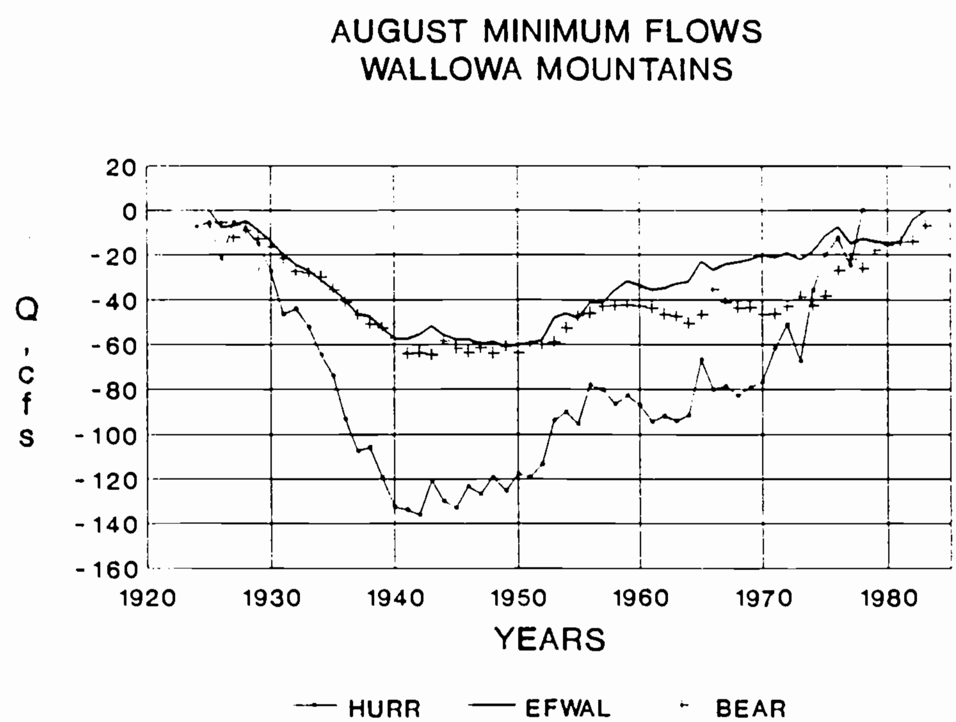

Figure 135. Cumulative departures from means for August minimum flows for streams in the Wallowa Mountain region.

reached their maximum negative departures during the 1940's. General trends in August cumulative departures are similar to annual departures for all three streams, with varying magnitudes.

SEPTEMBER MINIMUM FLOWS:

The cumulative departures for all three streams are negative for the whole record, except during the late 1920's. The cumulative departures are below normal until the early 1940's for all streams in the region, showing a decade long drought period (Fig. 136). From there onward, minimum flows recovered until the end of record, though with much fluctuation. This recovery process is smoother for Hurricane Creek and Bear Creek, compared to the East Fork Wallowa River.

OCTOBER MINIMUM FLOWS

Hurricane Creek and Bear Creek have a maximum positive departure from the mean during the late 1920's, which decreased rapidly back to zero during the late 1930's. It fluctuated above and below zero cumulative departure for the rest of the period. For the East Fork Wallowa River, October minimum flow cumulative departures closely resembled the September cumulative departures trends (Fig. 137).

BLUE MOUNTAIN REGION

ANNUAL, AUGUST, SEPTEMBER AND OCTOBER MINIMUM FLOWS

The Umatilla River and the South Fork Walla Walla River have negative cumulative departures from the 1930's to the mid 1970's (Fig. 138). From the mid-1970's to the mid 1980's it remained near zero. A drought period extended from the early 1930's to the mid 1940's in this

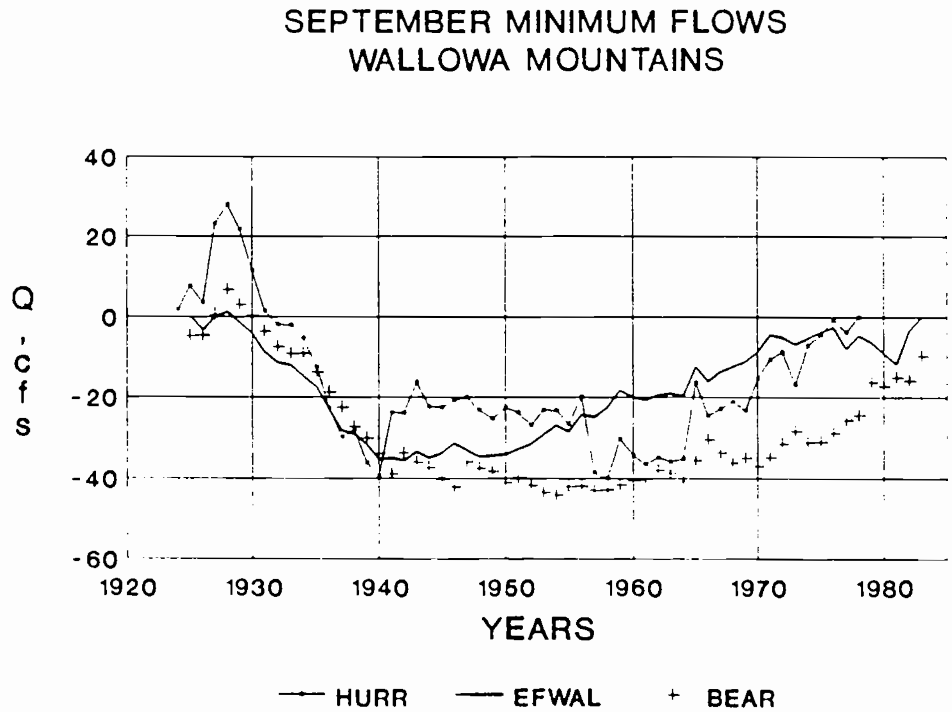

Figure 136. Cumulative departures from means for September minimum flows for streams in the Wallowa Mountain region.

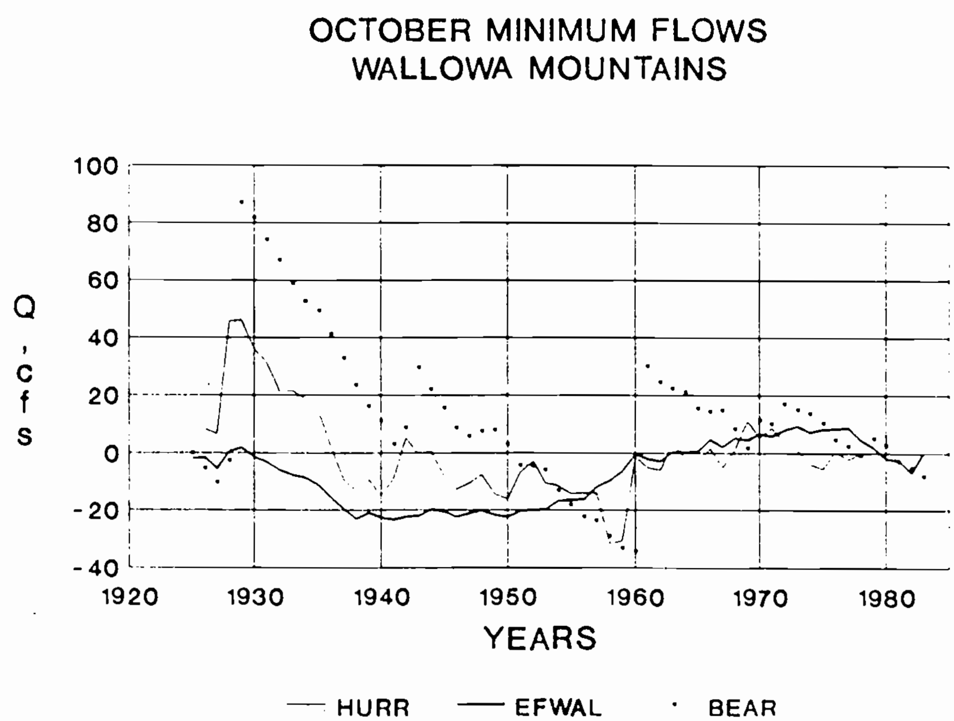

Figure 137. Cumulative departures from means for October minimum flows for streams in the Wallowa Mountain region.

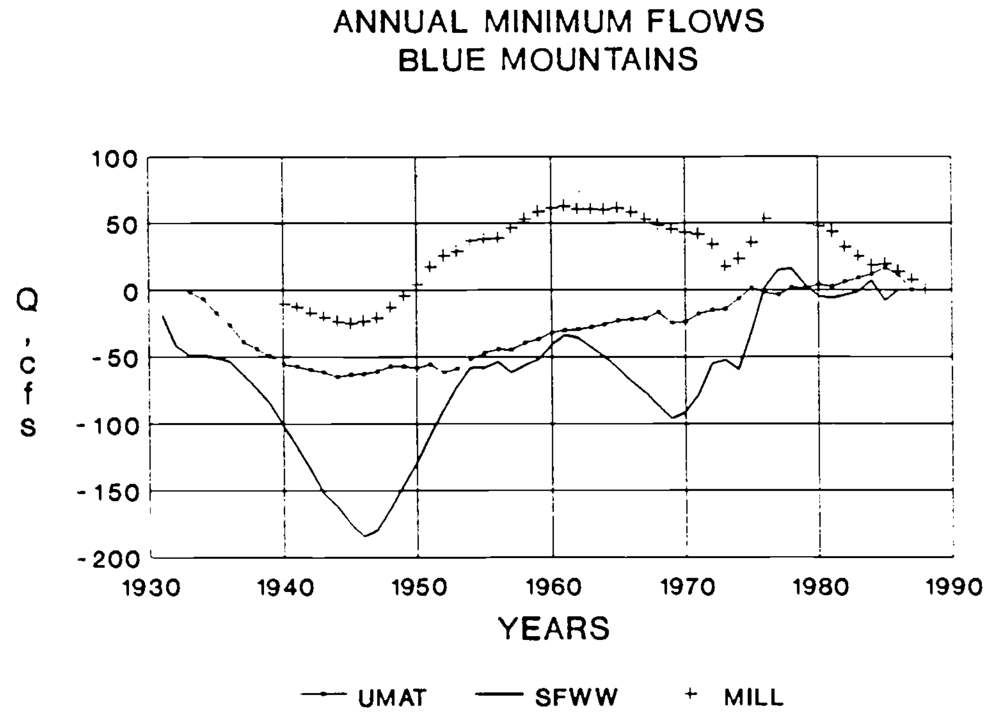

Figure 138. Cumulative departures from means for annual minimum flows for streams in the Blue Mountain region.

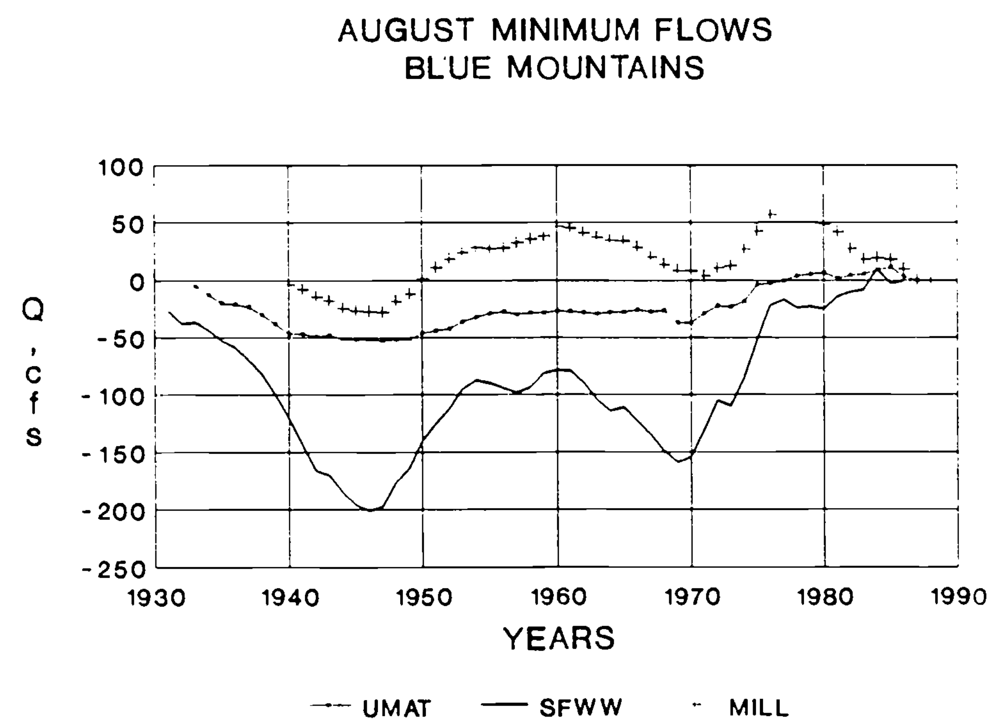

Figure 139. Cumulative departures from means for August minimum flows for streams in the Blue Mountain region.

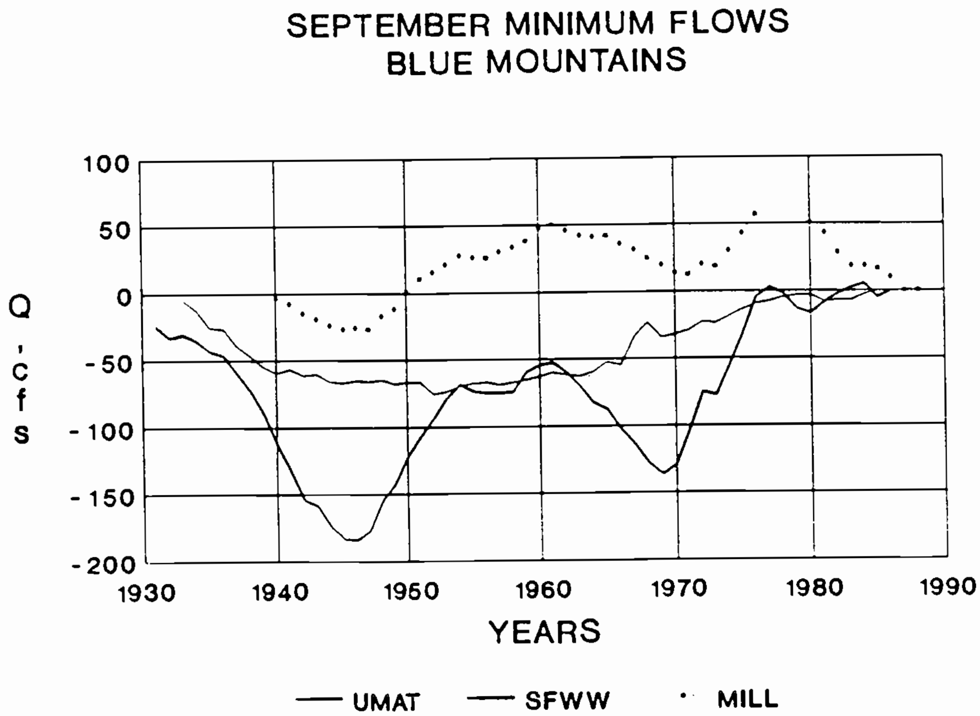

Figure 140. Cumulative departures from means for September minimum flows for streams in the Blue Mountain region.

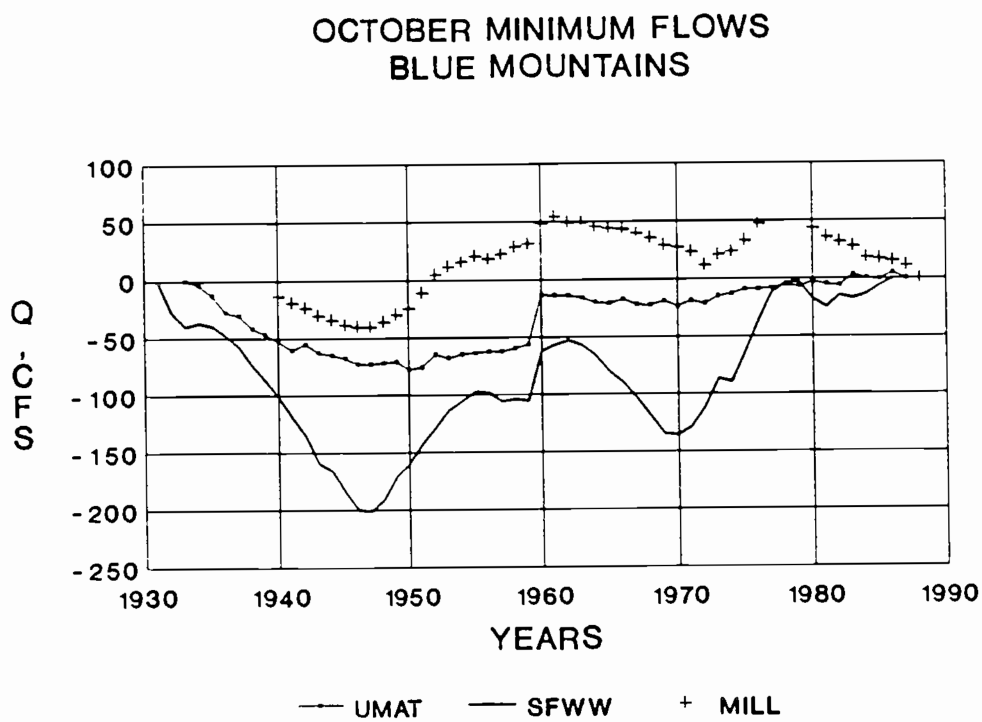

Figure 141. Cumulative departures from means for October minimum flows for streams in the Blue Mountain region.

region. The Umatilla River showed a gradual recovery until the mid 1970's, with smaller fluctuations. The other two streams experienced a shorter drought period during the late 1960's. With the exception of the 1940's, Mill Creek has positive cumulative departures, reaching a maximum during the early 1960's. General cumulative departure trends for all three streams are in good harmony. For August, September and October, trends in cumulative departures are similar to the annual cumulative departure trends, with little variation in magnitude (Fig. 139, 140 & 141).

SOUTHEASTERN OREGON REGION

ANNUAL, AUGUST, SEPTEMBER AND OCTOBER MINIMUM FLOWS

The cumulative departures for annual, August, September and October minimum flows are all negative for the Donner Und Blitzen River and the Silvies River for the majority of the record. The cumulative departures from the mean are similar for both the Silvies River and the Donner Und Blitzen River in all parameters, reaching the largest negative values during the 1970's. The negative cumulative departures for the Silvies River are most severe during the 1930's, indicating a severe low flow period. However, the record for this period is not available for the other two streams. For the Donner Und Blitzen River, the most severe low flow period was during the 1960's. From the late 1970's to the mid 1980's, these streams had higher low flow periods due to a wet period. The August cumulative departures for the Donner Und Blitzen River reached a maximum negative departure during the 1960's. Bridge Creek has positive cumulative departures for the majority of the record, except for the short periods at the beginning and end of the record (Fig.

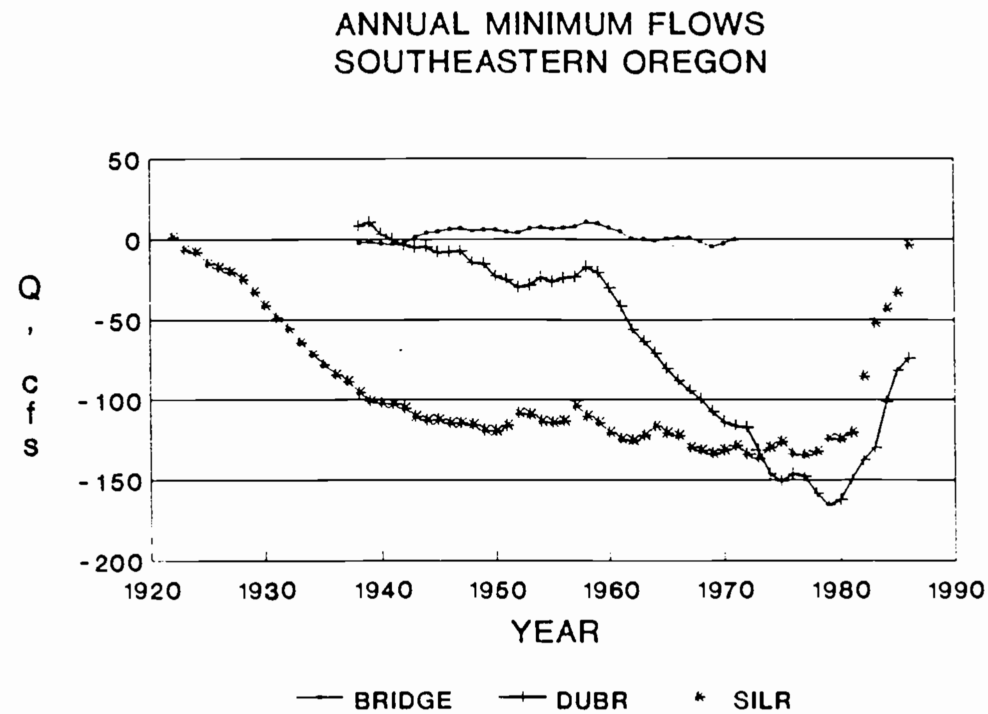

Figure 142. Cumulative departures from means for annual minimum flows for streams in the southeastern Oregon region.

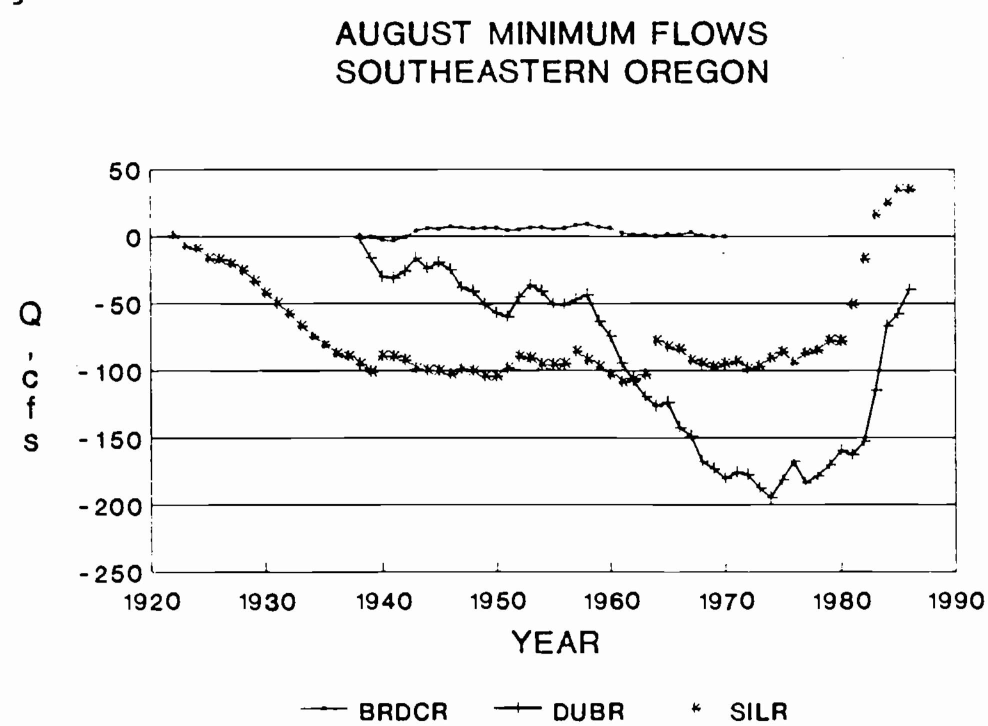

Figure 143 Cumulative departures from means for August minimum flows for streams in the southeastern Oregon region.

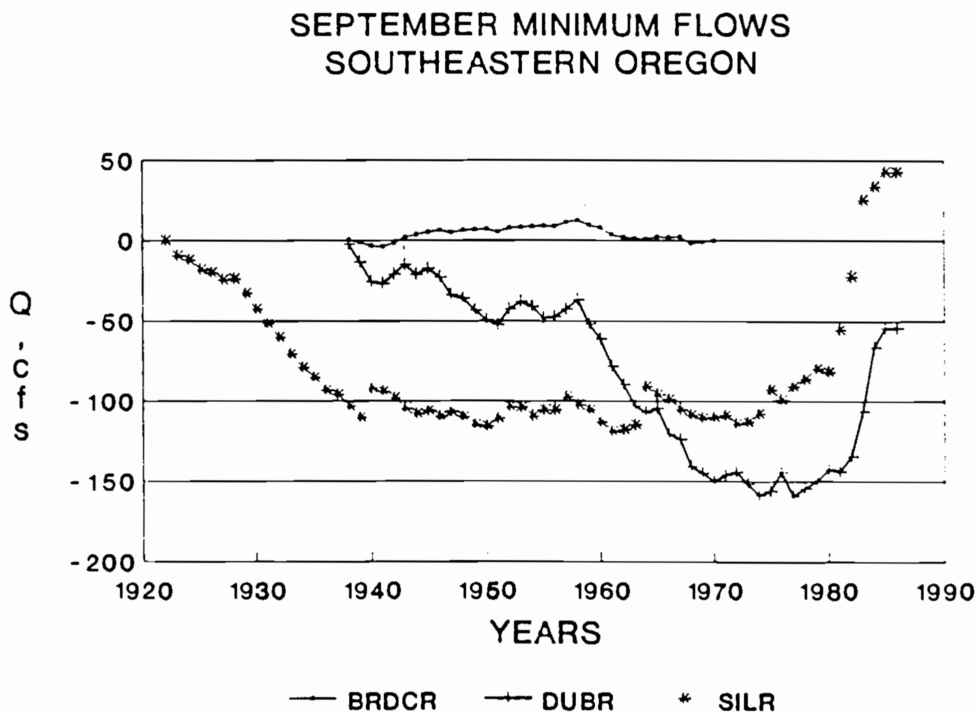

Figure 144. Cumulative departures from means for September minimum flows for streams in the southeastern Oregon region.

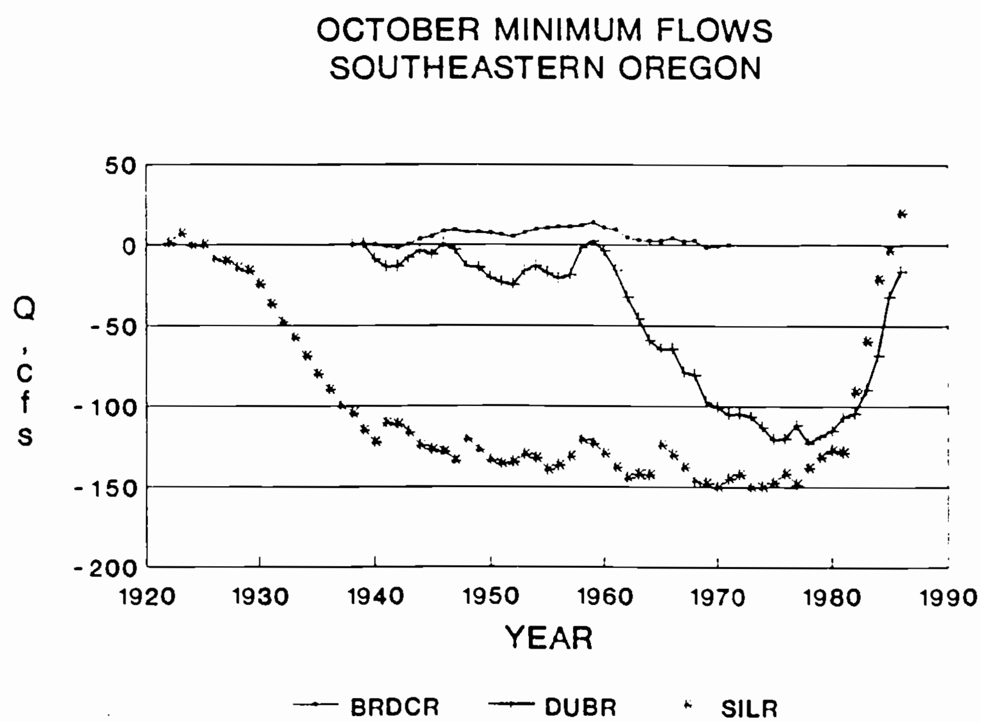

Figure 145. Cumulative departures from means for October minimum flows for streams in the southeastern Oregon region.

142 to 145). However, the magnitudes of these departures are very small, compared to the other two streams. It consistently shows a trend which has minimum year-to-year variability, suggesting that the flow is regulated by a source of water little affected by year-to-year climatic variations. The source may be groundwater or a confined aquifer, contributing subsurface flow.

PRECIPITATION

MONTHLY AVERAGE PRECIPITATION

PRECIPITATION AT UNION EXPERIMENTAL STATION

Scatter of annual average precipitation over the whole year at Union Experimental Station has much in common with Wallowa' annual precipitation. However, May receives the maximum average monthly precipitation at Union. It is followed by June, April, November, December, March, October and January' monthly average precipitations, respectively. July receives the lowest precipitation followed by August, September and February, respectively (Fig. 146).

PRECIPITATION AT WALLOWA

Average annual precipitation at Wallowa is also spread over the whole year, with maximum of 2" in November and minimum of 0.7 inches in July and August. Seven months receive 1.5 inches or more of average monthly precipitation, while, ten months receive more than one inch of monthly average precipitation. July and August are the driest months in the area (Fig. 147).

PRECIPITATION AT LA GRANDE

Most of the annual precipitation is received in

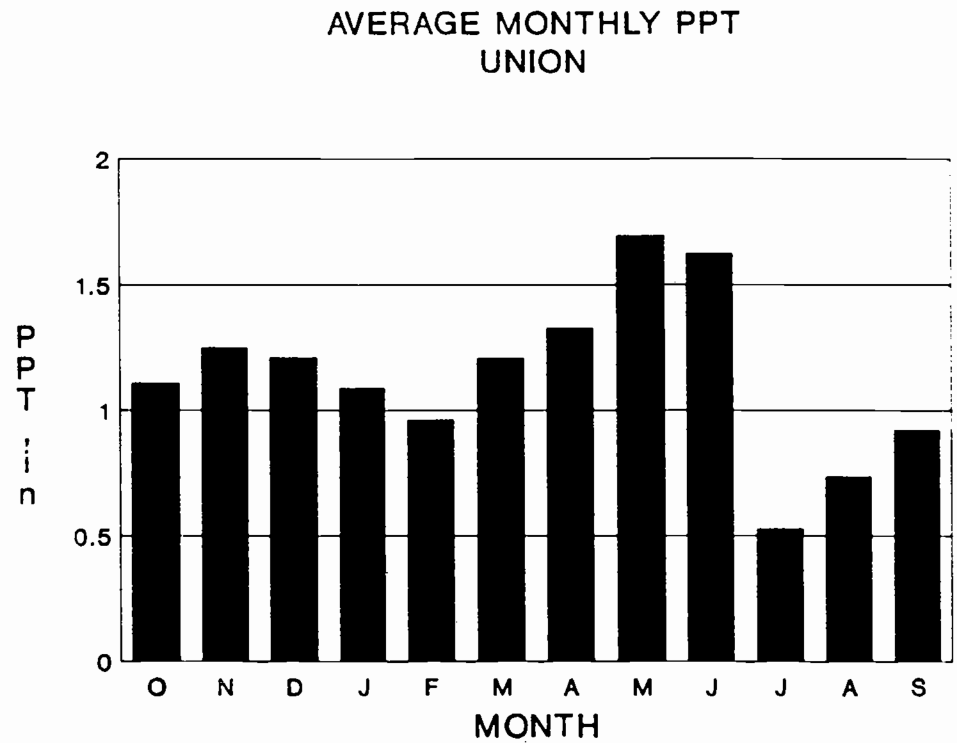

Figure 146. Average monthly precipitation at Union, Oregon.

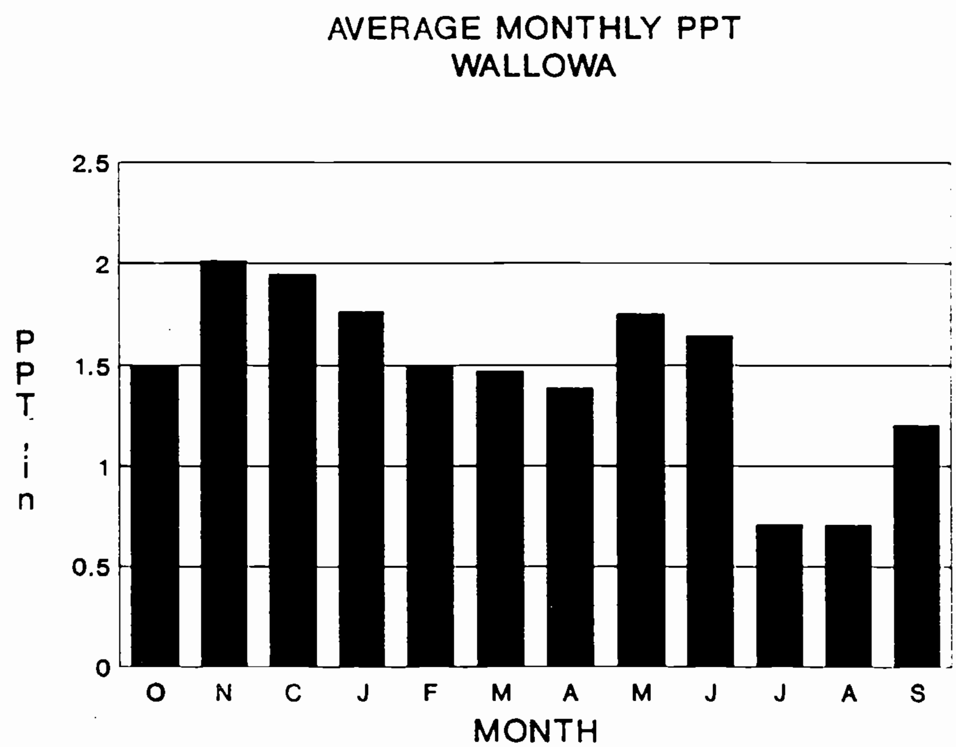

Figure 147. Average monthly precipitation at Wallowa, Oregon.

winter (November-March). However, precipitation is well distributed over the whole year. Nine months receive close to 1.5 inches or more of precipitation. Only summer months of July, August and September receive less precipitation. July receives the minimum precipitation (0.6") followed by August, September and October, respectively. November, December and January receive the maximum precipitation (over 2" each month) followed by March, May, February, April and June, with decreasing precipitation, respectively (Fig. 148).

PRECIPITATION AT BURNS

Monthly average precipitation has a different pattern at Burns Station than that of P-Ranch Refuge. Most of the precipitation is received in winter, November to March, a pattern similar to that of La Grande station (Fig. 149). Maximum precipitation falls in December (>1.65") followed by January, November, February and March average monthly precipitations with decreasing magnitudes, respectively. Minimum average monthly precipitation is received in July (0.4"), followed by August, September, April and October average monthly precipitations, respectively.

In general, annual average precipitation is fairly well- distributed throughout the year, with minor variations, over the whole of eastern Oregon. Either November and December or May and June receive maximum average monthly precipitation. July is the driest month followed by August, September and October, respectively, throughout eastern Oregon.

P-RANCH REFUGE STATION

Average monthly precipitation pattern at the P-Ranch Refuge Station is similar to that of Union experimental

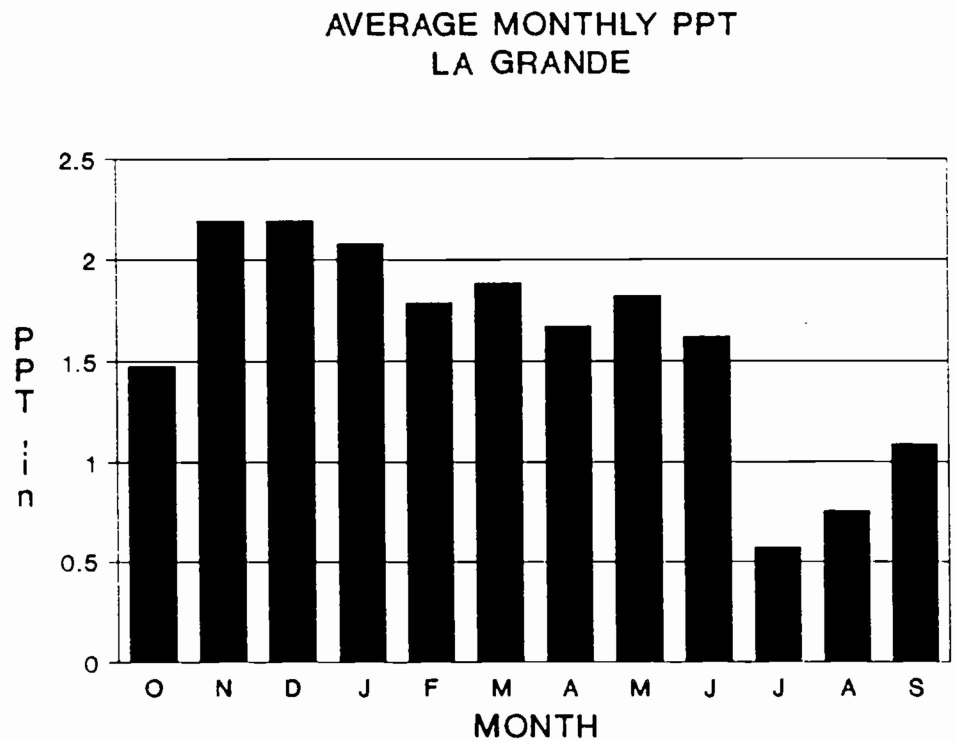

Figure 148. Average monthly precipitation at La Grande, Oregon.

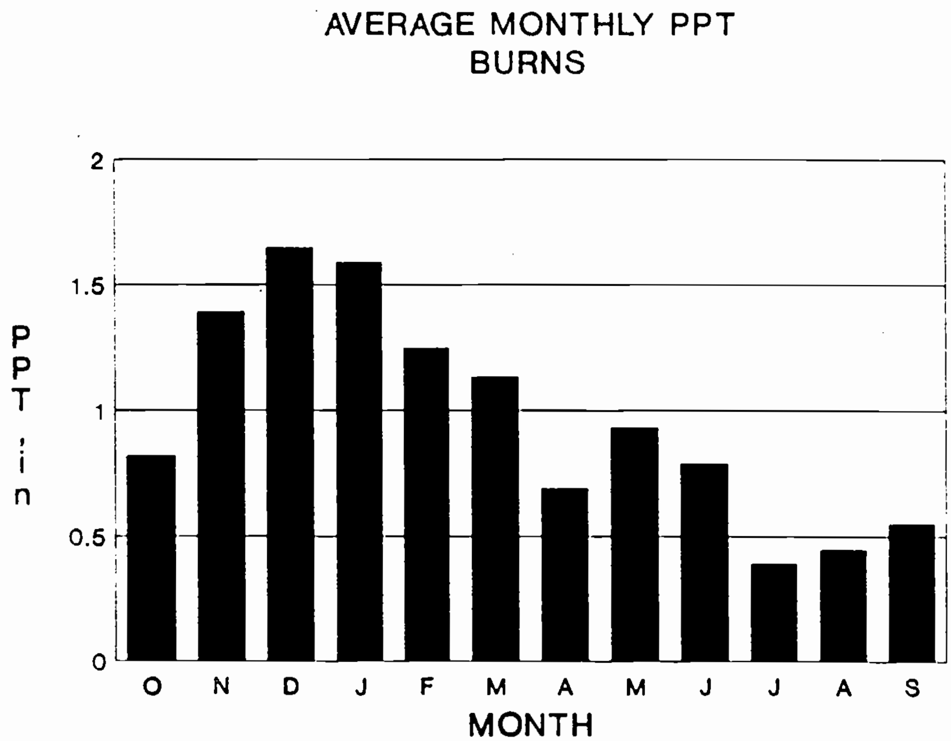

Figure 149. Average monthly precipitation at Burns, Oregon.

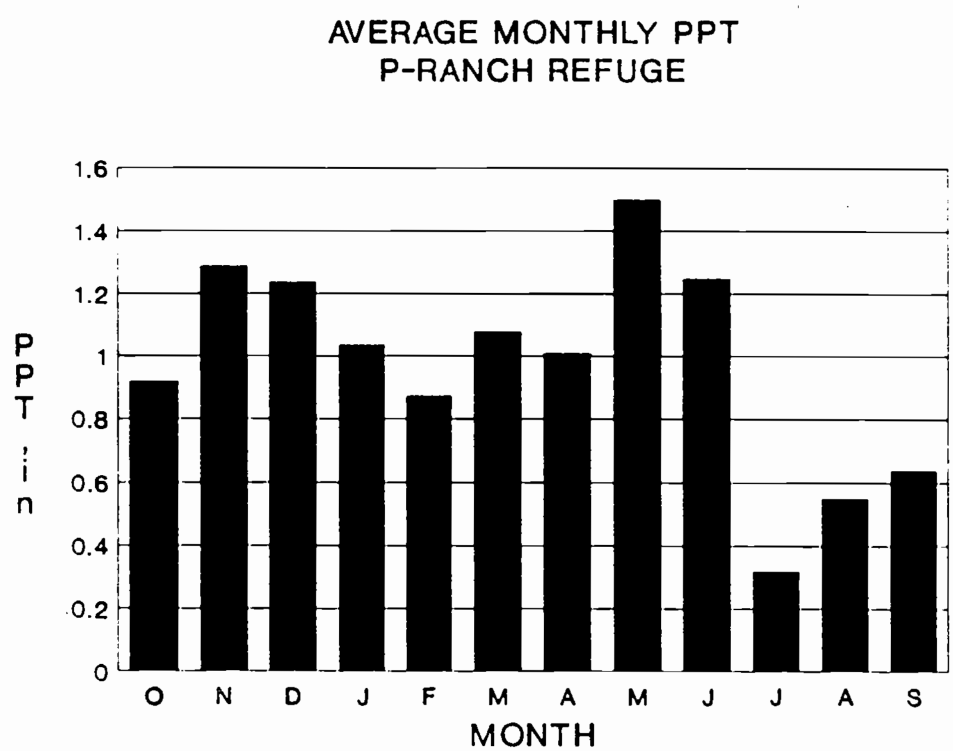

Figure 150. Average monthly precipitation at P-Ranch Refuge, Oregon.

station, however, with lower magnitudes (Fig. 150). May receives the maximum precipitation followed by November, June, December, March and January average monthly precipitations, respectively. July receives the minimum precipitation followed by August, September, February, October and April monthly average precipitations with increasing magnitudes, respectively.

MEAN ANNUAL PRECIPITATION

Mean annual precipitation with their standard deviations for each precipitation station are calculated (Table 10). Mean annual precipitation changes with latitude in eastern Oregon. Annual average precipitation

Table 10. Mean annual precipitation, standard deviation (St. Dev.) and coefficient of variance for five precipitation stations selected.

STATION	MEAN PPT(in)	ST.DEV. (in)
Union	13.62	3.02
Wallowa	17.14	3.62
La Grande	18.92	3.62
Burns	11.61	2.73
P-ranch Refuge	11.49	2.92

is minimum at P-ranch Refuge and maximum at La Grande. Variability in annual precipitation is maximum at P-ranch Refuge and minimum at La Grande.

5-YEAR MOVING AVERAGE PRECIPITATION

Magnitudes of annual precipitation are different, increasing from lower latitudes and elevations (Union) to higher elevations and latitudes (La Grande).

NORTHEASTERN OREGON REGION

Five-year moving average precipitations for Wallowa, La grande and Union precipitation stations are plotted against each other. Long term annual precipitation increases from Union (14 inches) to Wallowa (17 inches) to La Grande (19 inches). Five-year moving average trends for all three stations in the region are similar. Rises and falls in the trends for wet and dry years are closely matching for all three stations (Fig. 151). Comparatively, trends are more similar for precipitation at Union and Wallowa stations. Five-year moving average precipitation at Union and Wallowa stations remained below long-term mean during the 1920's and the 1930's. Five-year moving average precipitation at Union was below average also during the 1960's and the mid 1970's. Five-year moving average precipitation at Wallowa remained close to normal during the rest of the period, except during the early 1950's. However, it closely followed the year-to-year changes in 5-year moving average precipitation trend at Union. La Grande station received close to or above average precipitation from the early period of the record until the late 1950's, except during the late 1930's. From the 1960's until the end of the record, it received close to or below average precipitation, with a lot of year-to-year noise. The extent of similarities between precipitation trends for the three stations is greater, compared to the low flow trends for different streams in the northeastern Oregon.

SOUTHEASTERN OREGON REGION

Five-year moving average precipitation trends for Burns and P-Ranch Refuge stations showed much similarity throughout the period of record (Fig. 152). At Burns, 5-

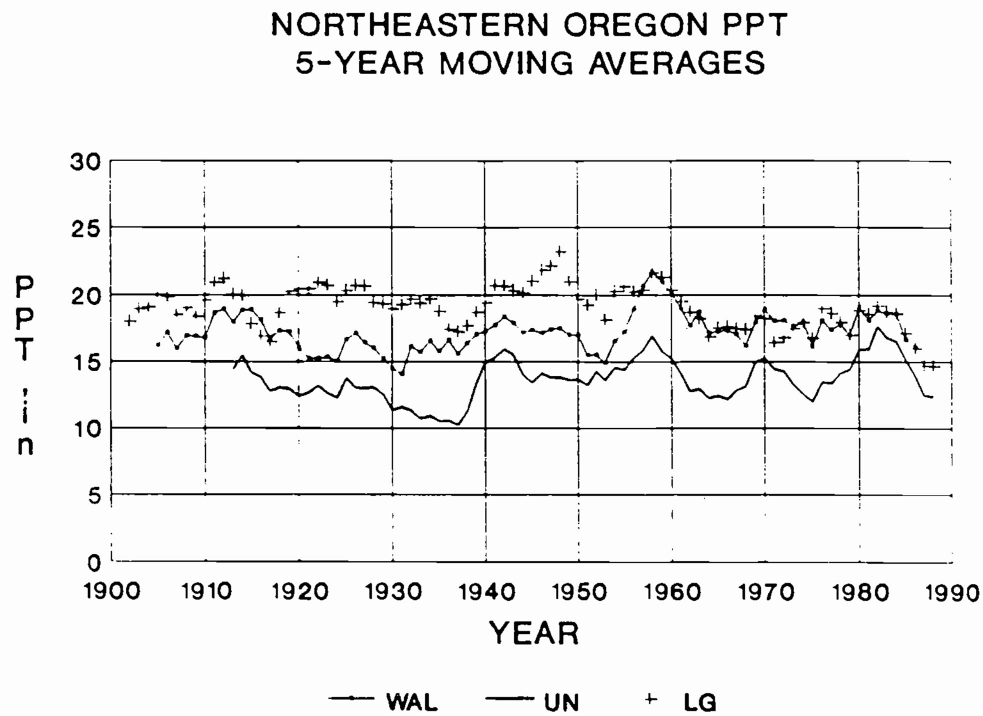

Figure 151. Five-year moving average precipitation at different stations in the northeastern Oregon.

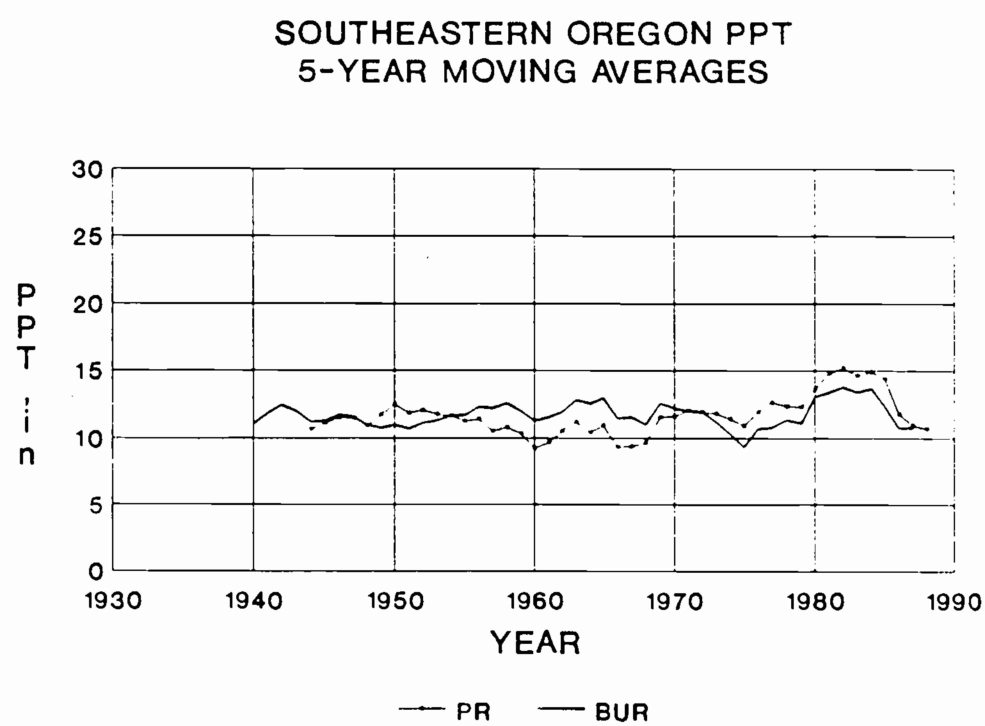

Figure 152. Five-year moving average precipitation at different stations in the southeastern Oregon.

year moving average precipitation was below normal during the 1940's and the early 1950's. For the rest of the period it remained above normal, except in the later half of the 1970's and the mid 1980's. Five-year moving average precipitation trends for P-Ranch station followed year-to-year changing trends for 5-year moving average precipitation at Burns. However, drought during the mid 1950's to the late 1960's was severe at P-Ranch Refuge as compared to that at Burns.

CUMULATIVE DEPARTURE FROM MEAN PRECIPITATION

NORTHEASTERN OREGON

The cumulative departures more clearly showed the pattern and trends of precipitation (Fig. 153). It showed close resemblance in the trends and patterns of precipitation at Union and Wallowa. Prior to the mid 1920's, the cumulative departures from long-term means are close to zero for all three stations in northeastern Oregon. After that, there is a clear separation of the cumulative departure trends between La Grande and other two stations in the region. The cumulative departures from the mean annual precipitation for La Grande is positive for rest of the record. However, year-to-year trend fluctuations are similar to those of the other two precipitation stations. From the mid 1920's onward, it has an increasing positive cumulative departures trend, attaining maximum during the early 1960's, then gradually decreasing until the end of 1980's. For Union and Wallowa, the cumulative departures from mean precipitation remained negative for the rest of the record until the mid 1980's. Downward trends for these two stations continued until the late 1930's, indicating the severity of the

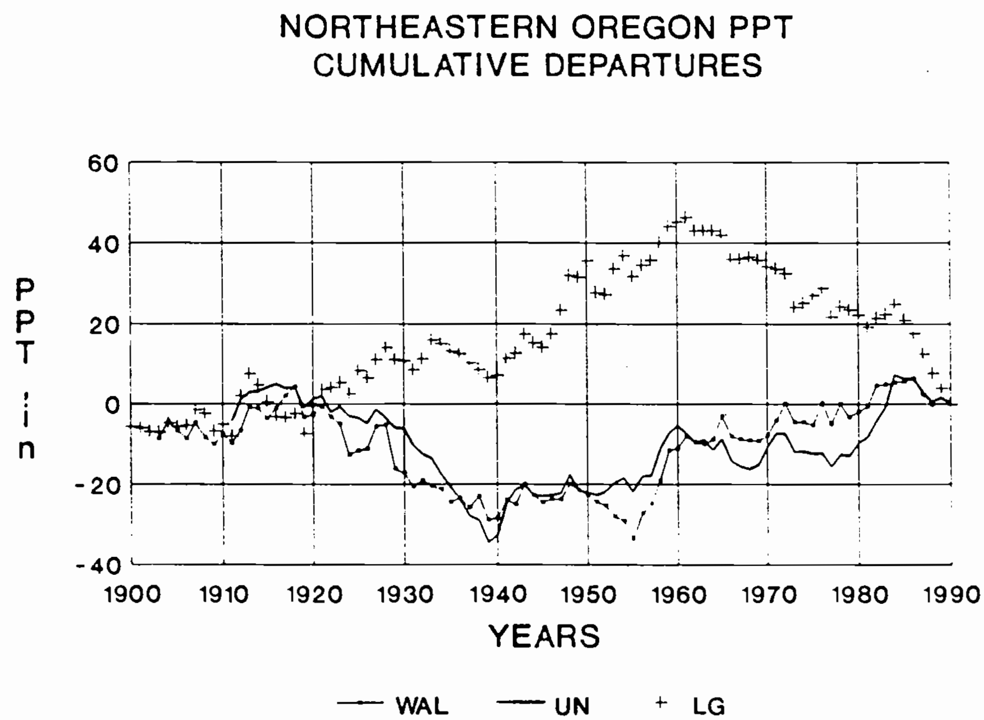

Figure 153. Cumulative departures from means for precipitation at different stations in the northeastern Oregon.

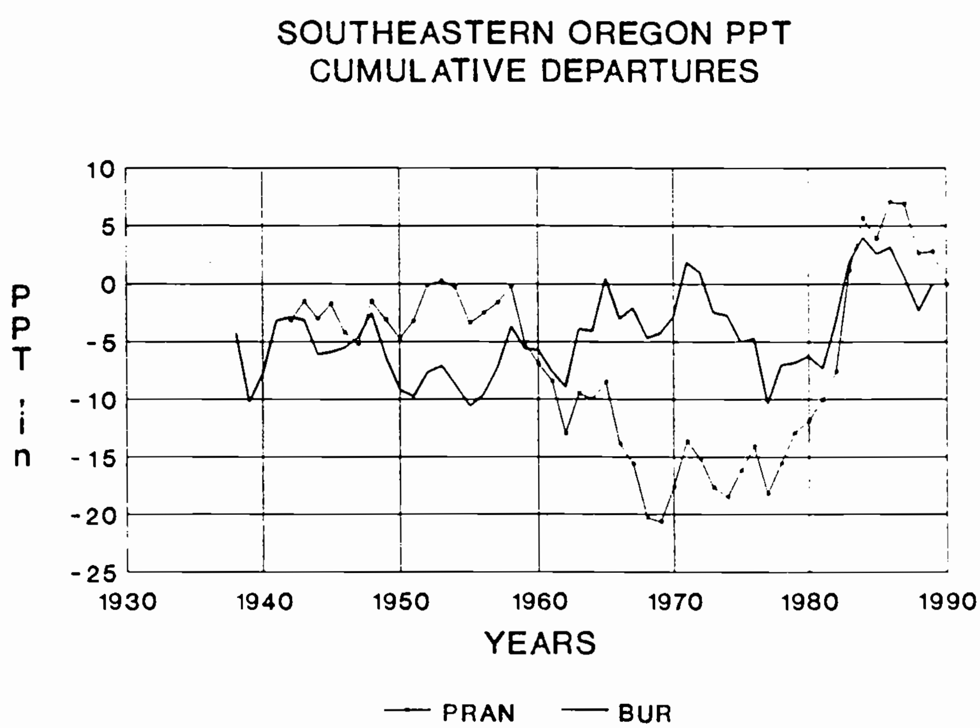

Figure 154. Cumulative departures from means for precipitation at different stations in the southeastern Oregon.

drought. After that long drought period, these two stations showed an upward trend until the mid 1980's. All the precipitation stations in northeastern Oregon showed considerable year-to-year fluctuation around the normal.

SOUTHEASTERN OREGON

The cumulative departures for two precipitation stations in the southeastern Oregon region remained negative for the majority of the record (Fig. 154). These stations had a moderate drought in the earlier period. This is particularly true for P-Ranch precipitation station, which underwent a longer drought during the late 1950's to the late 1960's. During the late 1970's and the early 1980's, it had a wet period. At Burns precipitation station, shorter drought periods are scattered over the late 1930's, the 1950's and the late 1970's. However, most of the time, the cumulative departure trends as well as year-to-year fluctuations at both precipitation stations are quite similar.

Precipitation data during the 1930's was not available for these stations, therefore, severity of droughts during the 1950's and 1960's couldn't be compared with that of 1930's in the southeastern Oregon.

LOW STREAMFLOWS AND PRECIPITATION TREND COMPARISONS

Summer and annual low streamflows and base flows depend upon a number of factors. However, precipitation is one of the most important factors for determining the amount and timing of low streamflows. Analysis of low flows for each parameter (annual, August, September and October) for each stream indicated some similarities and some inconsistencies in low flow trends over the years of record, within and among three regions. These discrepancies can be explained with the help of watershed parameters and climate. It may be due to a change in management strategy, harvesting pattern, disease, fire hazard etc. in respective catchments over this period. Better similarities for most of the low flow parameters are shown during the early periods of record. This raised questions about precipitation trends during the whole period. How much are the trends similarities between precipitation and low flows during the earlier and later periods. If the precipitation trends have similarities with low streamflows during the major portion of the record but not during some decades, it is guessed that a change in some of the watershed variables has affected the relationship between stream low flows and precipitation.

5-YEAR MOVING AVERAGE LOW STREAMFLOWS AND PRECIPITATION TREND COMPARISON

WALLOWA MOUNTAIN REGION

ANNUAL MINIMUM FLOWS AND ANNUAL PRECIPITATION:

Five-year moving average annual low flow trends for Bear Creek and the East Fork Wallowa River closely followed the regional precipitation trends during the late 1920's to the mid- 1970's. For Bear Creek, annual low streamflow trends followed the precipitation trends until the end of the record (Fig. 155). However, for the East Fork Wallowa River, annual low streamflow showed trends opposite to the precipitation trends during the mid-1970's. For the later period of record, trends for precipitation and annual low streamflow are quite similar. Annual low streamflow trends for Hurricane Creek followed the precipitation trends throughout the record, except

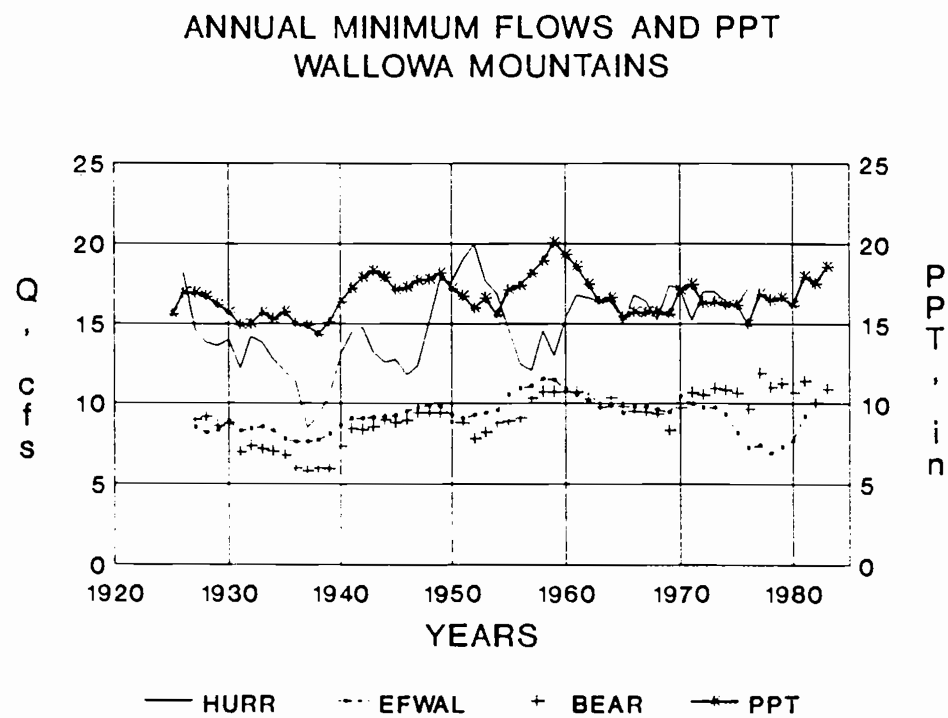

Figure 155. Five-year moving averages for annual minimum flows and annual precipitation in the Wallowa Mountain region.

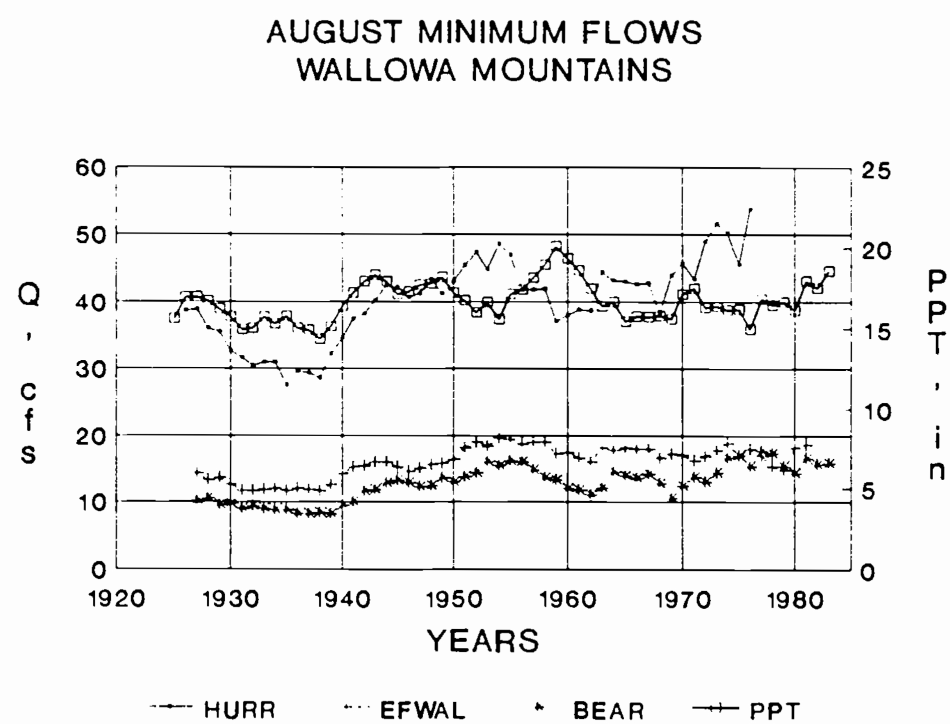

Figure 156. Five-year moving averages for August minimum flows and annual precipitation in the Wallowa Mountain region.

during the late 1940's to the early 1960's. During this period, annual low flow trends for Hurricane Creek remained opposite to the precipitation trends. Explanation for this distinctive behavior may be revealed by looking into the management history of that watershed during the late 1940's and the 1950's.

AUGUST MINIMUM FLOWS AND ANNUAL PRECIPITATION:

For all three streams, August low streamflow trends followed the regional precipitation trends very closely until the 1950's. For the rest of the period, similarities between low streamflows and precipitation are not as good

as previously. This change in the behavior of stream low flows is more clear during the late 1950's and the mid-1960's (Fig. 156).

SEPTEMBER MINIMUM FLOWS AND PRECIPITATION:

Trend similarities between September low streamflows and regional precipitation are similar to those for August low streamflows. September low streamflows for Hurricane Creek showed trends clearly opposite to regional precipitation trends during the late 1950's. For the rest of the period, September low streamflows for Hurricane Creek are closely following the year-to-year changing trends in regional precipitation (Fig. 157).

OCTOBER MINIMUM FLOWS AND ANNUAL PRECIPITATION:

October low streamflows have much year-to-year variability for Hurricane Creek and Bear Creek. October low streamflow trends for the East Fork Wallowa River followed the regional precipitation trends closely, except during the late 1970's. In general, October low

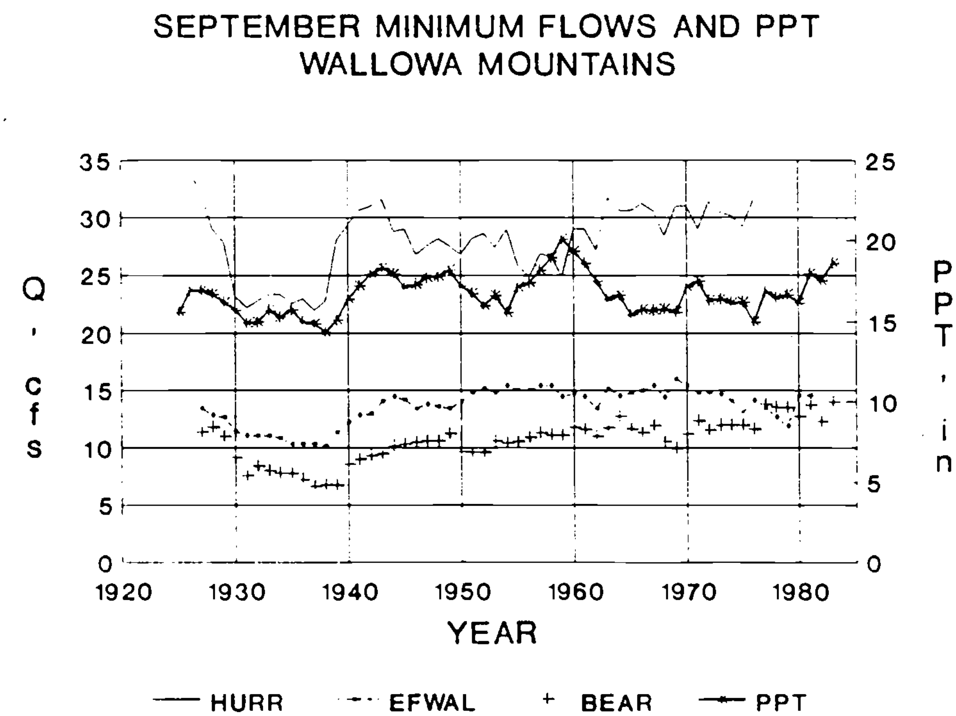

Figure 157. Five-year moving averages for September minimum flows and annual precipitation in the Wallowa Mountain region.

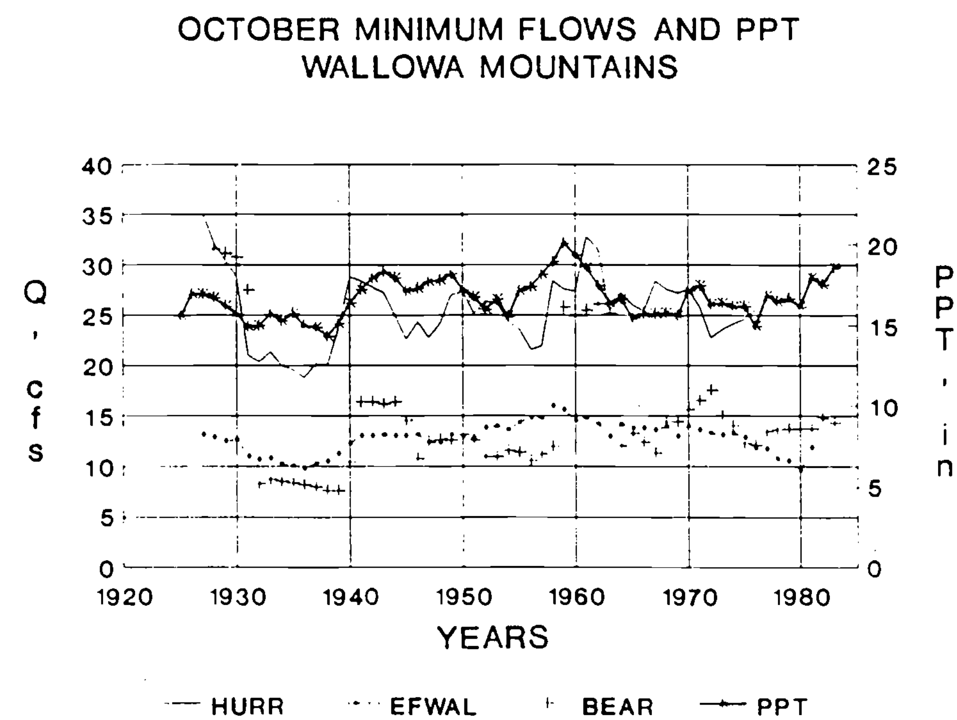

Figure 158. Five-year moving averages for October minimum flows and annual precipitation in the Wallowa Mountain region.

streamflows trends showed good similarity to the precipitation trends - like the other variables (Fig. 158).

BLUE MOUNTAIN REGION

ANNUAL LOW FLOWS AND ANNUAL PRECIPITATION:

Of the three Blue mountains streams, annual low streamflows for the Umatilla River and Mill Creek have lower magnitudes and less fluctuations in trends. The South Fork Walla Walla River has relatively high low flows, with bigger swings in trends. Mill Creek followed the precipitation trends closely during the 1940's and the 1950's. During the 1960's, stream low flow has a downward trend even during the wet first half of the decade. For the rest of the record, annual stream low flow trends are comparable to precipitation trends.

The Umatilla River followed the precipitation trends more closely than Mill Creek throughout the record. Year-to-year peaks and troughs in the precipitation trends are followed by the annual low streamflow trends. The South Fork Walla Walla River showed annual low streamflow trends quite similar to the precipitation trends until the late 1950's. During the 1960's, annual low streamflow trends for the Umatilla River were opposite to those of precipitation trends. For rest of the period, trend similarities in annual stream low flows and the regional precipitation remained poor to medium. There seems to be a major change in the catchment areas of Mill Creek and the South Fork Walla Walla River during the late 1950's and the early 1960's. That may have caused a change in the characteristic of low flows in the streams. The change may be a large scale harvesting, disease, insect infestation or fire. This may indicate that during the

ANNUAL MINIMUM FLOWS AND PPT
BLUE MOUNTAINS

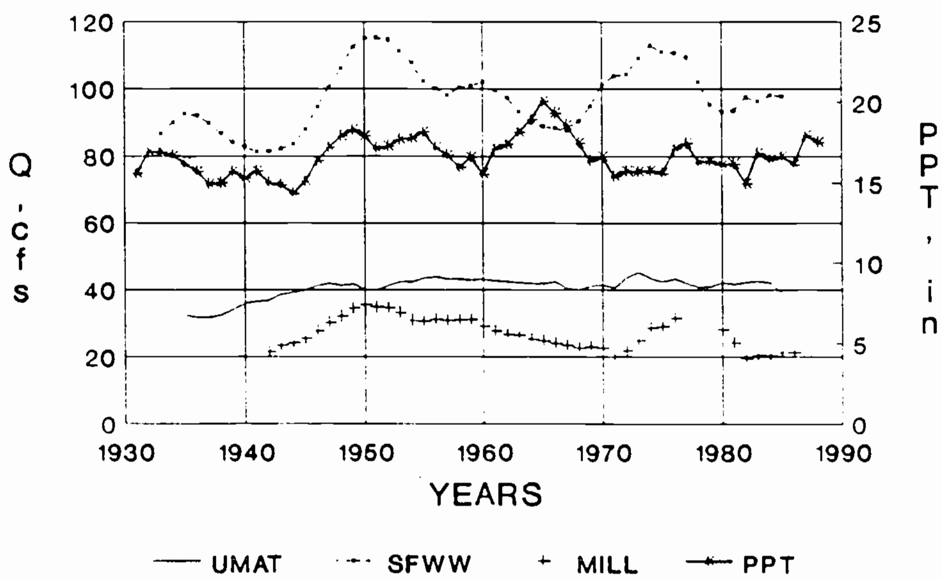

Figure 159. Five-year moving averages for annual minimum flows and annual precipitation in the Blue Mountain region.

AUGUST MINIMUM FLOWS AND PPT
BLUE MOUNTAINS

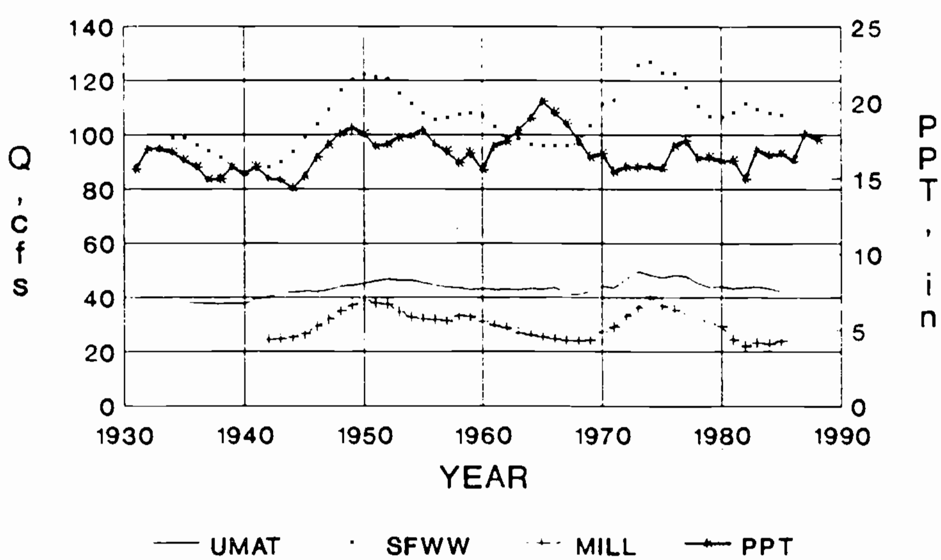

Figure 160. Five-year moving averages for August minimum flows and annual precipitation in the Blue Mountain region.

1970's, the newly established vegetation increased the ground cover and brought the low streamflow characteristics back to normal (Fig. 159).

AUGUST LOW FLOWS AND ANNUAL PRECIPITATION:

The August stream low flow trends similarities with the regional precipitation trends are similar to those of annual stream low flow trends for all three streams in the region. During the 1960's and the early 1970's, August low streamflow trends for Mill Creek and the South Fork Walla Walla River are opposite to the precipitation trends. The Umatilla River' August low flows showed better similarities with the precipitation trends (Fig. 160).

SEPTEMBER LOW FLOWS AND ANNUAL PRECIPITATION:

The extent of resemblance of September low flow trends with the regional precipitation is the same as August low flow trends. However, for a couple of years during the early 1960's, the Umatilla River also showed trends opposite to the precipitation trends (Fig. 161).

OCTOBER LOW FLOWS AND ANNUAL PRECIPITATION:

For the October low flow trends, all three streams closely followed the precipitation trends until the mid-1950's. During the late 1950's and the early 1960's, the Umatilla River had trends opposite to the regional precipitation trends. Mill Creek and the South Fork Walla Walla River' October low flow trends followed the precipitation trends until the early 1950's. During the mid-1950's to the early 1970's, October low flow trends for these two streams have poor fit with the precipitation trends. During the late 1970's and the 1980's, trends

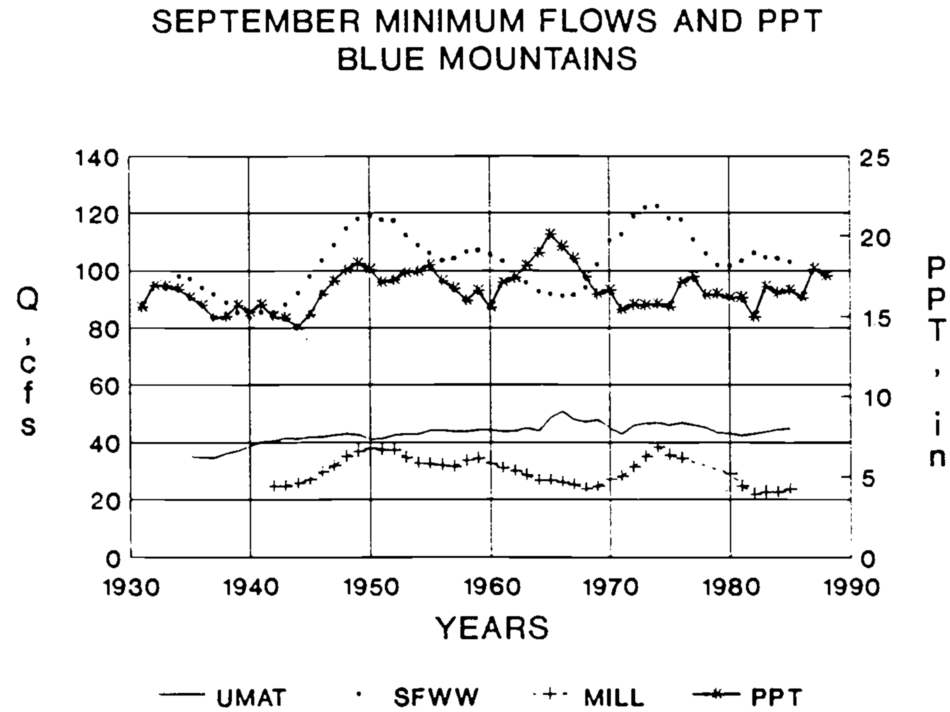

Figure 161. Five-year moving averages for September minimum flows and annual precipitation in the Blue Mountain region.

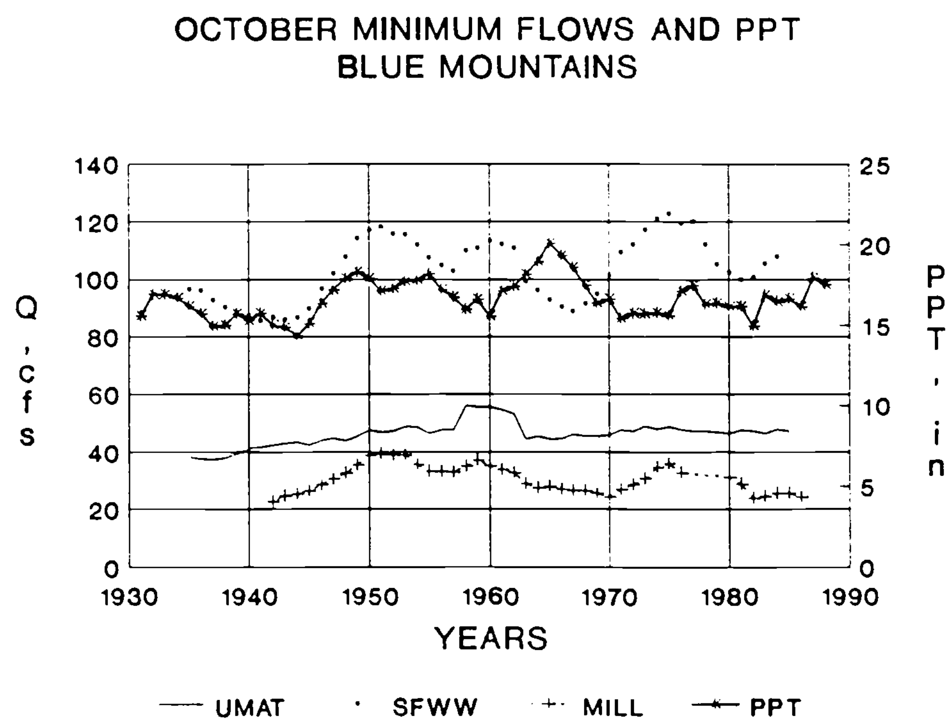

Figure 162. Five-year moving averages for October minimum flows and annual precipitation in the Blue Mountain region.

similarities between October low flows and regional precipitation for all three streams are moderate (Fig. 162).

SOUTH EASTERN OREGON REGION

ANNUAL MINIMUM FLOWS AND ANNUAL PRECIPITATION:

Five-year moving average annual precipitation for southeastern Oregon has small year-to-year variations. Troughs and rises in trends are smaller, compared to northeastern Oregon' 5-year average annual precipitation trends. The 5-year moving average annual minimum flow trends for the Silvies River have the best similarities with the 5-year moving average annual precipitation trends in the southeastern Oregon region. For the better part of the record, there appeared a lag of about one year between precipitation trends and the Silvies River' minimum flow trends. The same is true for Bridge Creeks' annual minimum flow trends. Five-year moving average annual minimum flow trends for the Donner Und Blitzen River have the least similarities with the regional annual 5-year moving average precipitation trends in the southeastern Oregon' region (Fig. 163).

AUGUST, SEPTEMBER AND OCTOBER MINIMUM FLOWS AND ANNUAL PRECIPITATION:

August and September minimum flow trends similarities with annual precipitation for each stream, followed the same pattern as shown by respective annual minimum flow trends. However, the extent of trends similarities for summer months' minimum flows were slightly better, compared to annual minimum flows. August and September minimum flows trends for Bridge Creek showed better fit with annual precipitation trends than the other two

ANNUAL MINIMUM FLOWS AND PPT
SOUTHEASTERN OREGON

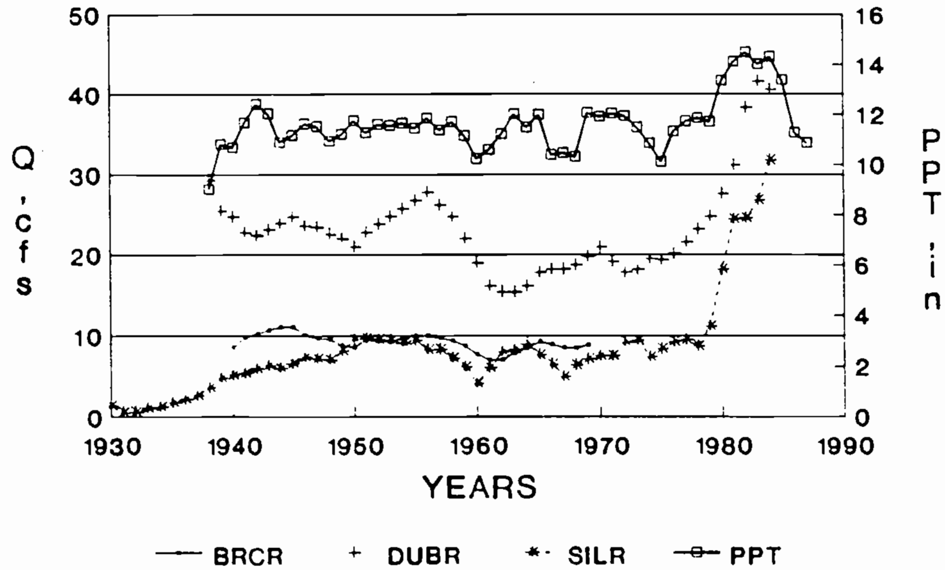

Figure 163. Five-year moving averages for annual minimum flows and annual precipitation in the southeastern Oregon region.

AUGUST MINIMUM FLOWS AND PPT
SOUTHEASTERN OREGON

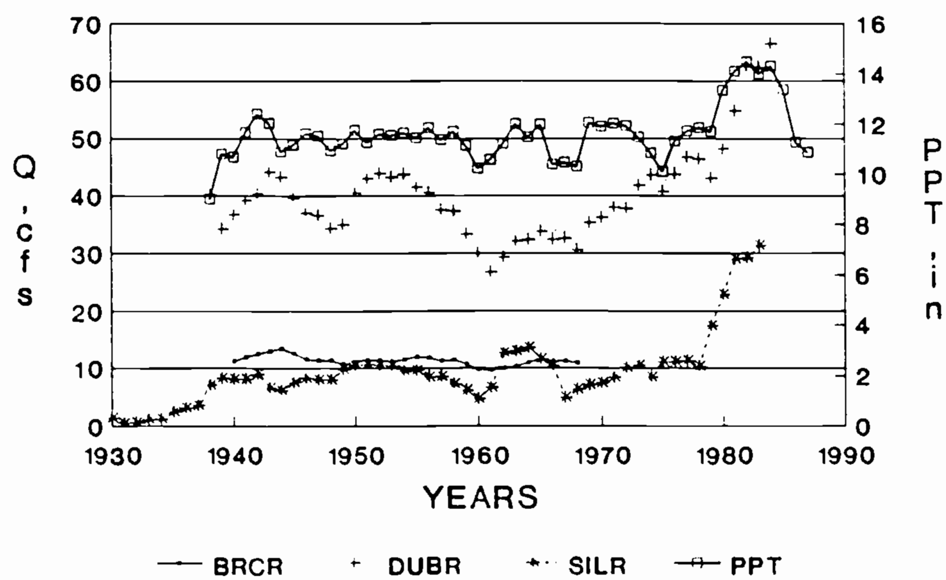

Figure 164. Five-year moving averages for August minimum flows and annual precipitation in the southeastern Oregon region.

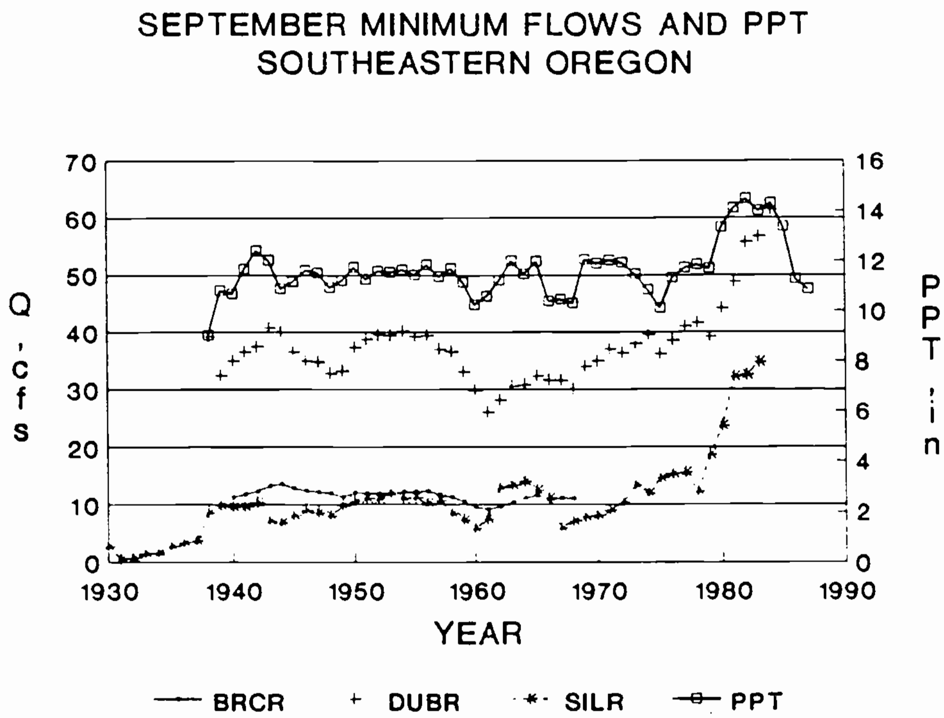

Figure 165. Five-year moving averages for September minimum flows and annual precipitation in the southeastern Oregon region.

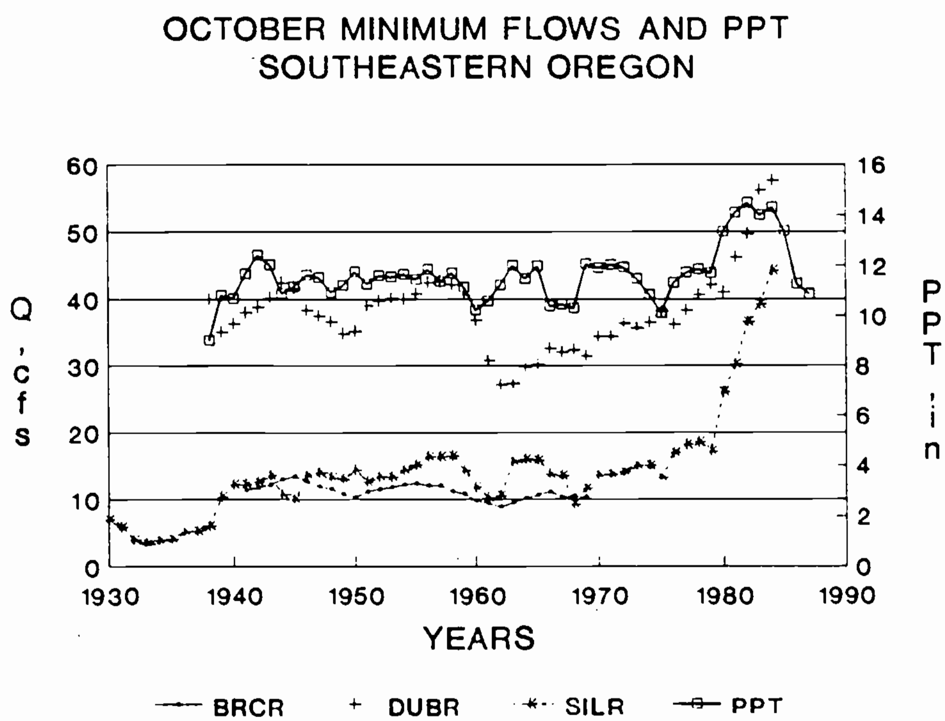

Figure 166. Five-year moving averages for October minimum flows and annual precipitation in the southeastern Oregon region.

streams in the region. October minimum flow trends poorly matched with the 5-year moving average annual precipitation trends (Fig. 164, 165 & 166).

CUMULATIVE DEPARTURES: PRECIPITATION AND LOW FLOWS TREND COMPARISON

WALLOWA MOUNTAIN REGION:

ANNUAL MINIMUM FLOWS:

The cumulative departures increase the ease in understanding the severeness of dry ant wet periods. Year-to-year variations shown in the 5-year moving average trends are minimized in the cumulative departures trends. All three streams in the Wallowa Mountain region showed annual minimum flow cumulative departures trends similar to the annual precipitation cumulative departure trends during the whole period, except during the late 1970's. During the late 1970's, the East Fork Wallowa River showed annual minimum flow cumulative departures trends opposite to the annual precipitation cumulative departures trends. During the mid-1930's to the mid-1940's, annual precipitation showed negative cumulative departures. However, during the rest of the period it showed mostly positive cumulative departures. The cumulative departures for annual minimum flows for all three streams in the region remained negative throughout their records, except for the East Fork Wallowa River. The East Fork Wallowa River showed positive cumulative departures during the 1960's through the late 1970's (Fig. 167).

AUGUST, SEPTEMBER AND OCTOBER MINIMUM FLOWS:

For the August and September minimum flows cumulative

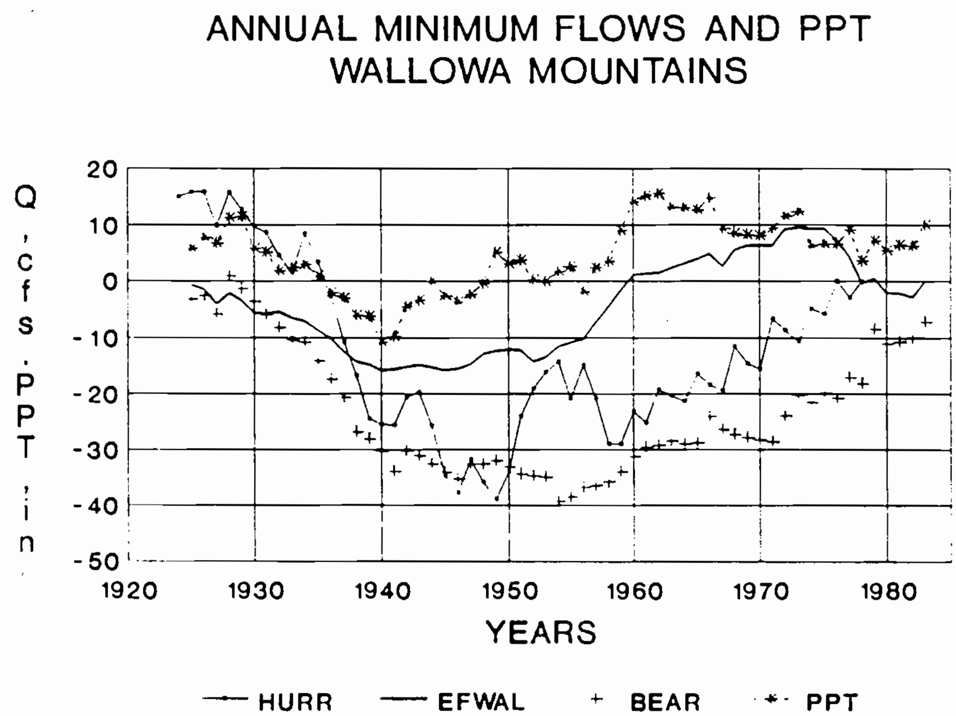

Figure 167. Cumulative departures from means for annual minimum flows and annual precipitation in the Wallowa Mountain region.

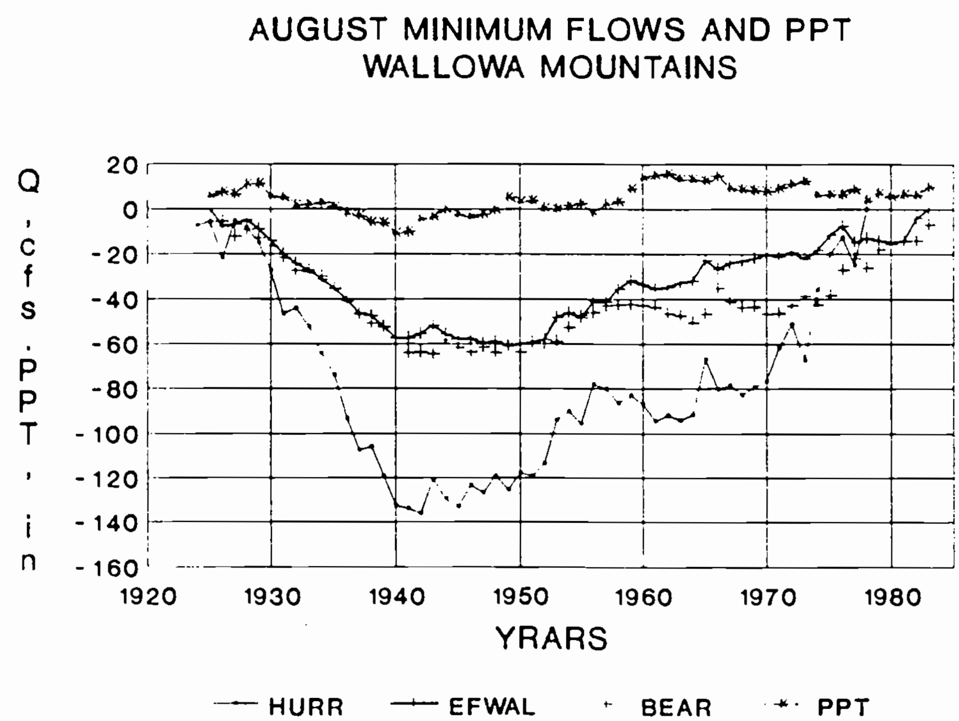

Figure 168. Cumulative departures from means for August minimum flows and annual precipitation in the Wallowa Mountain region.

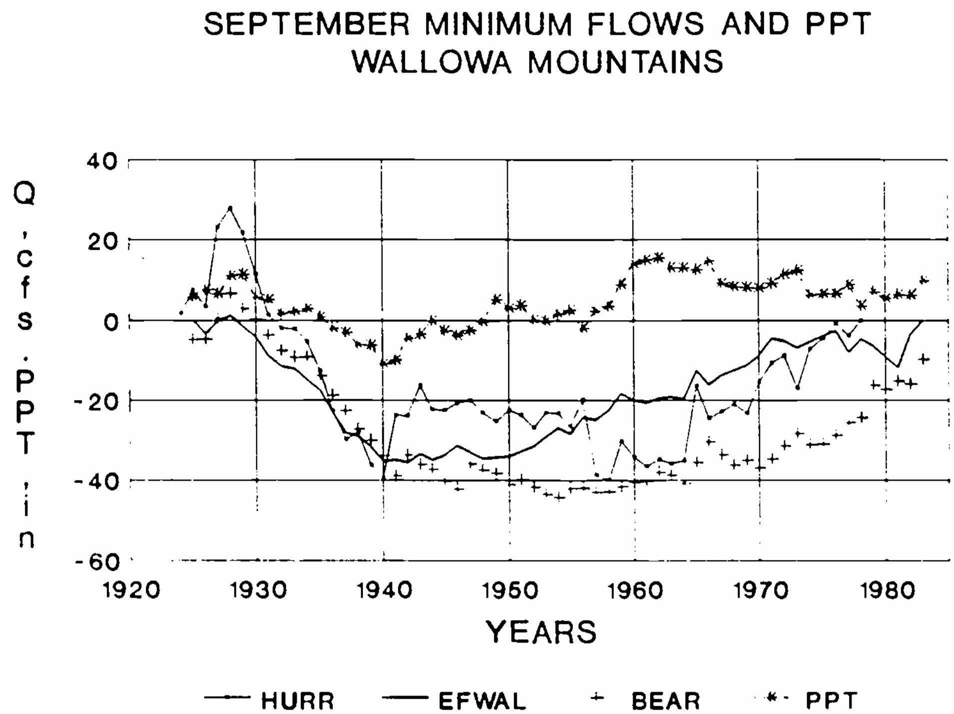

Figure 169. Cumulative departures from means for September minimum flows and annual precipitation in the Wallowa Mountain region.

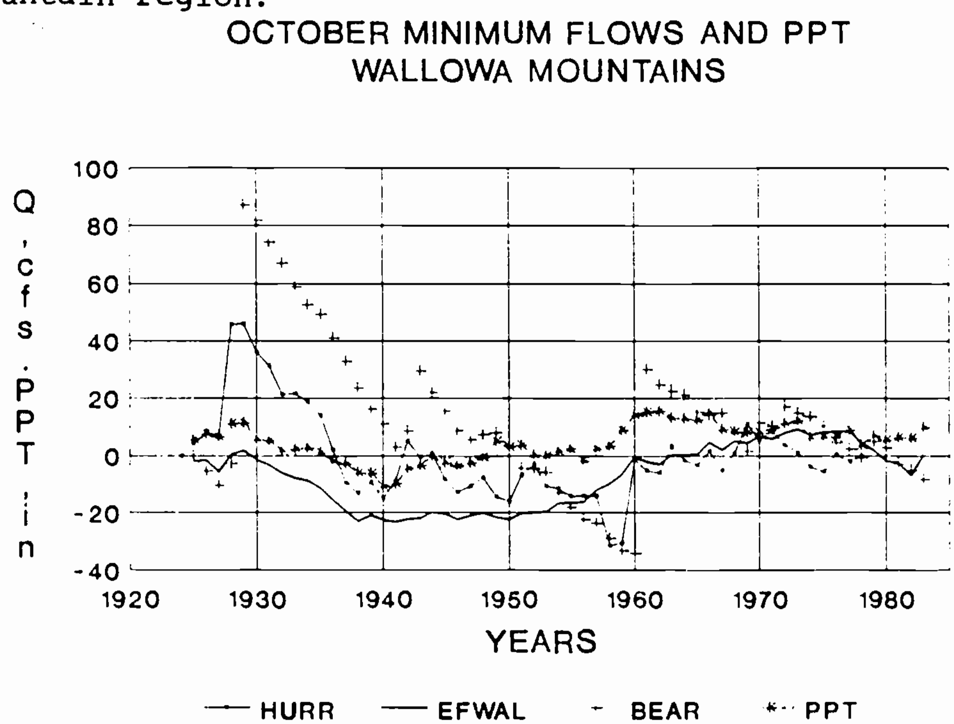

Figure 170. Cumulative departures from mean for October minimum flows and annual precipitation in the Wallowa Mountain region.

departures, all three streams in the region showed trends with similarities to the annual precipitation cumulative departures throughout the period. Year-to-year variations increased from August to September minimum flows. The fluctuations in the cumulative departures for annual precipitation are equally above and below mean value. However for the majority of the time, streams showed negative cumulative departures.

Trends in the cumulative departures for October minimum flows for Bear Creek and Hurricane Creek are different from those of the East Fork Wallowa river. Trend similarities between October minimum flow cumulative departures and annual precipitation cumulative departures are moderate and vary with the streams (Fig. 168, 169 & 170).

BLUE MOUNTAIN REGION:

Trends in the cumulative departures for annual precipitation and annual minimum flows for all three streams in the region showed moderate similarities throughout the record, except during the 1960's. Mill Creek and the South Fork Walla Walla River showed cumulative departures trends opposite to the annual precipitation cumulative departure trends during the 1960's. Trend similarities between the annual minimum flow cumulative departures for the Umatilla River and annual precipitation were better than for the other two streams throughout the period. The cumulative departures for August, September and October minimum flows showed similar trends similarities to annual precipitation cumulative departures, as are shown by annual minimum flows (Fig. 171 to 174).

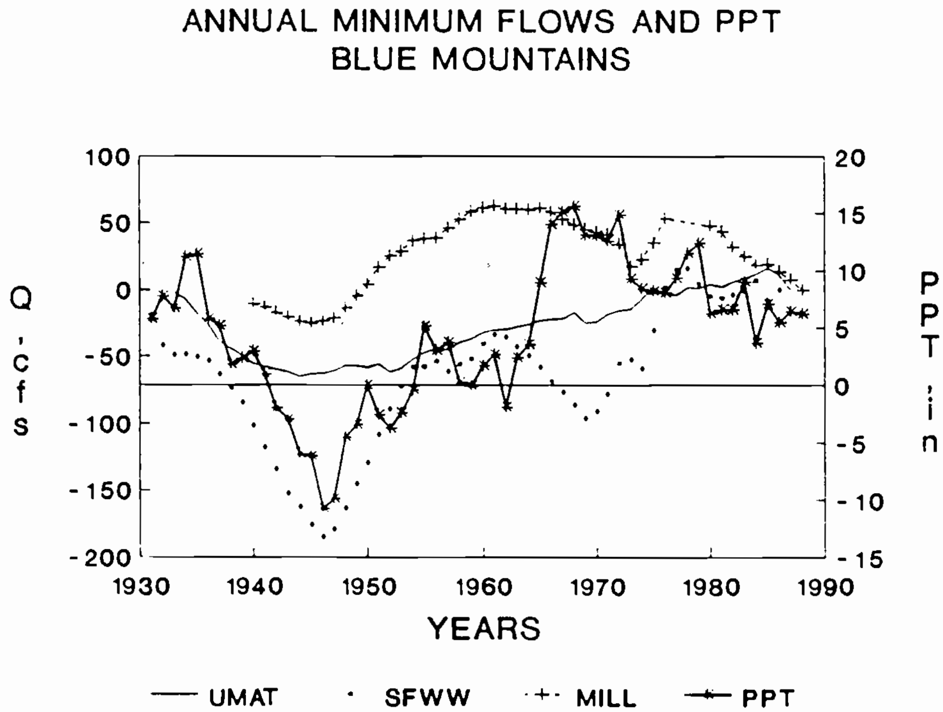

Figure 171. Cumulative departures from means for annual minimum flows and annual precipitation in the Blue Mountain region.

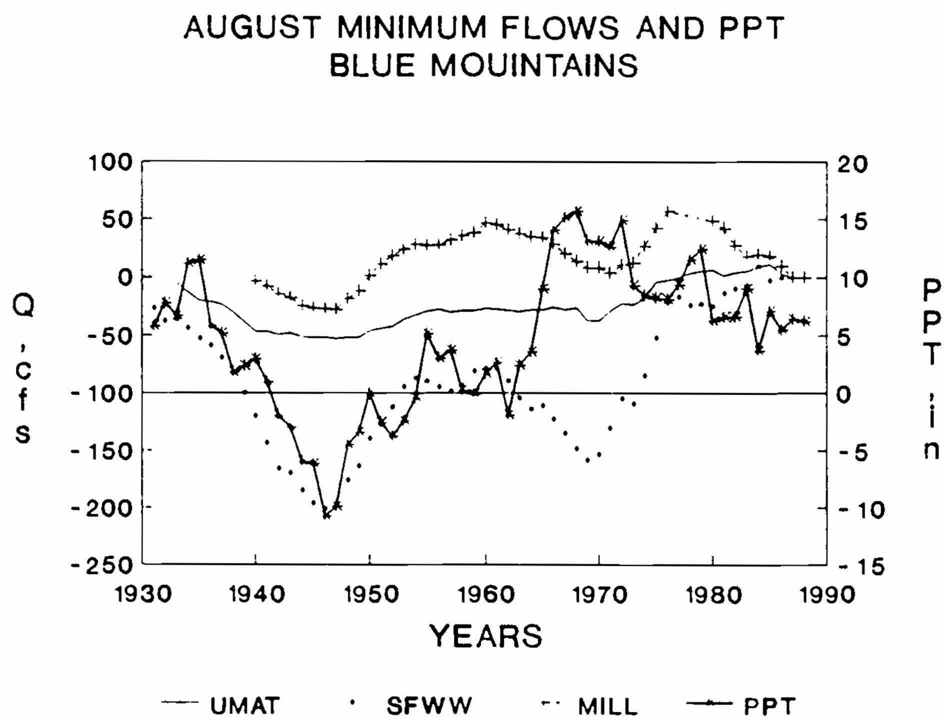

Figure 172. Cumulative departures from means for August minimum flows and annual precipitation in the Blue Mountain region.

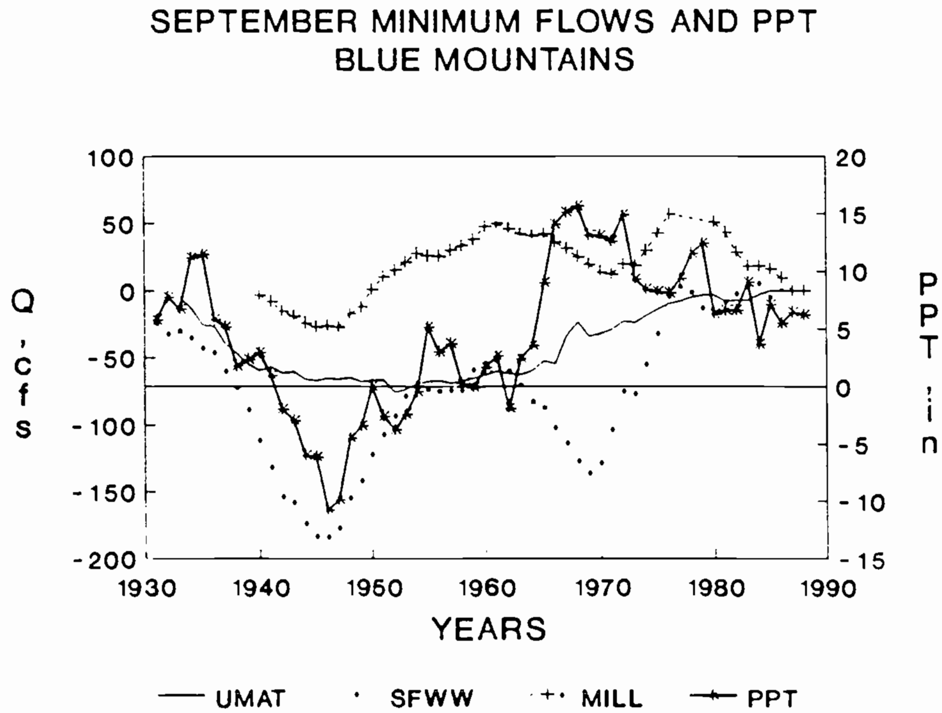

Figure 173. Cumulative departures from means for September minimum flows and annual precipitation in the Blue Mountain region.

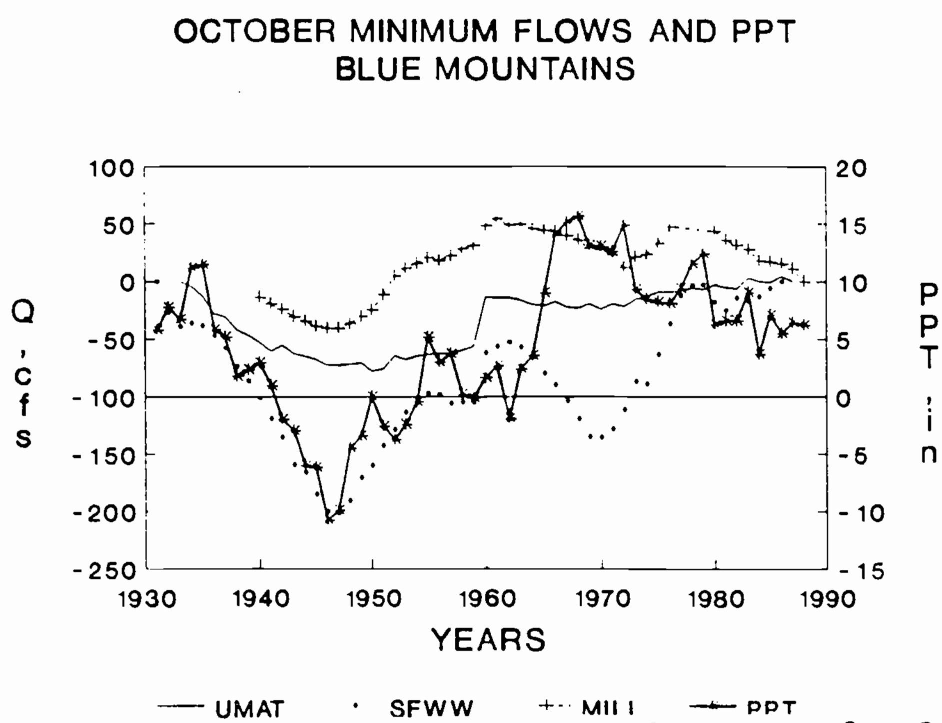

Figure 174. Cumulative departures from mean for October minimum flows and annual precipitation in the Blue Mountain region.

SOUTH EASTERN OREGON REGION

The cumulative departures for annual minimum flows for Bridge Creek maintained good similarities to the annual precipitation cumulative departures trends. For the Silvies River and the Donner Und Blitzen River, similarities are poor between the annual minimum flow cumulative departures and annual precipitation cumulative departures. The cumulative departures for August, September and October minimum flows showed similar trends similarities to annual precipitation cumulative departures, as are shown by annual minimum flows (Fig. 175 to 178).

CORRELATION BETWEEN LOW STREAMFLOWS AND PRECIPITATION

REGIONAL PRECIPITATION AND REGIONAL LOW FLOWS

Regression analyses were conducted to find the correlation between regional annual precipitation and regional annual, August, September and October minimum stream flow variables. All the correlations are positive. Results showed that August and September minimum flows for the Wallowa Mountain region and the southeastern Oregon region have highly significant relationship with annual precipitation (Table 11). For all the regions, October minimum flows have minimum correlation with the regional precipitation. Minimum flows for streams in the Blue Mountain region showed very poor correlations with the regional precipitation.

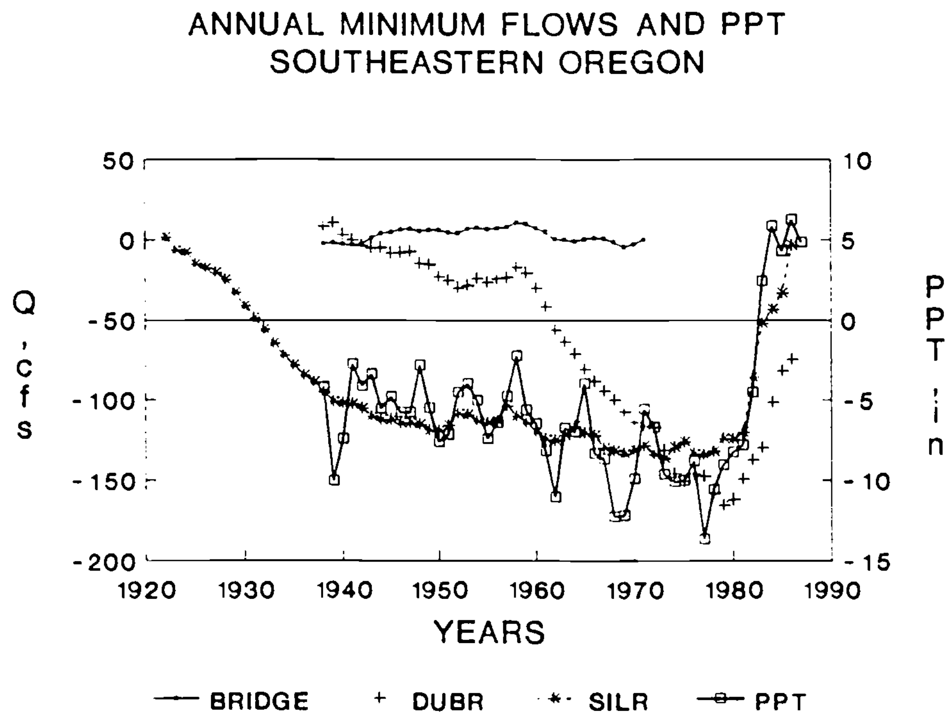

Figure 175. Cumulative departures from means for annual minimum flows and annual precipitation in the southeastern Oregon region.

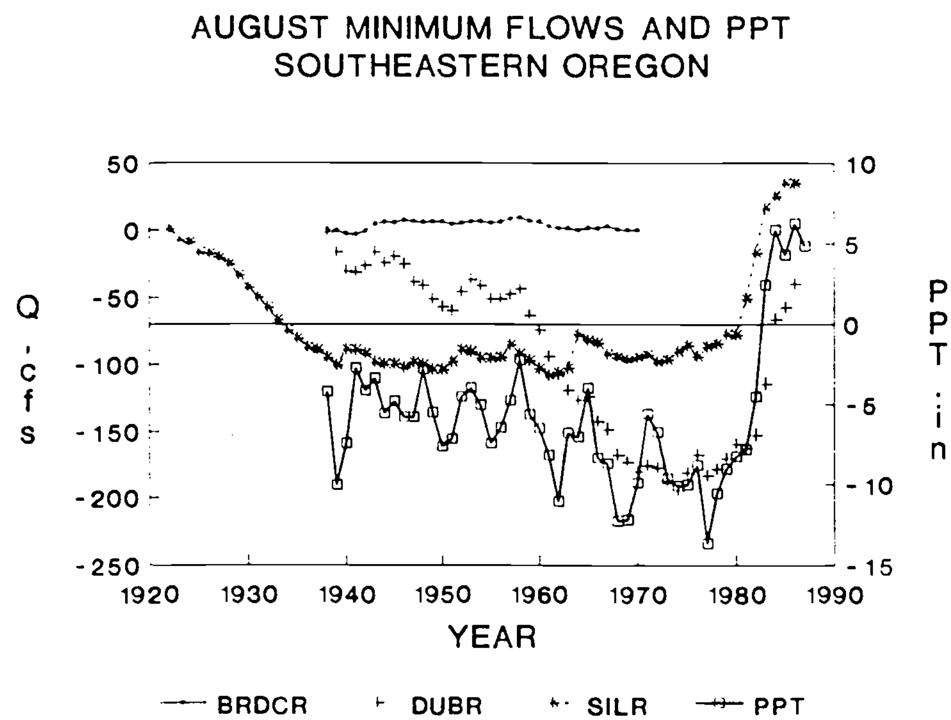

Figure 176. Cumulative departures from means for August minimum flows and annual precipitation in the southeastern Oregon region.

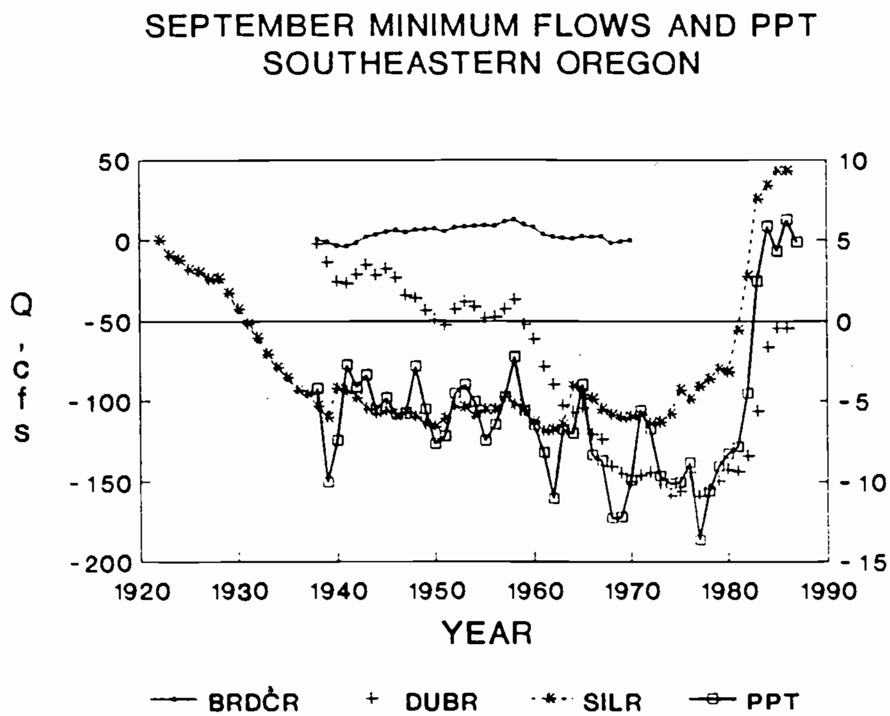

Figure 177. Cumulative departures from means for September minimum flows and annual precipitation in the southeastern Oregon region.

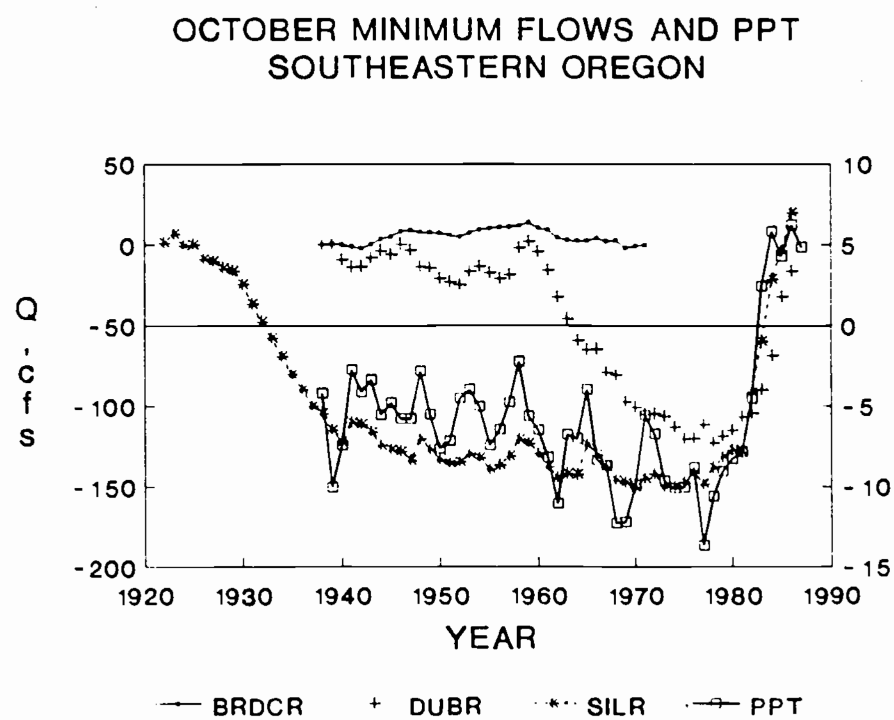

Figure 178. Cumulative departures from mean for October minimum flows and annual precipitation in the southeastern Oregon region.

Table 11. Correlations between regional precipitation and regional annual (ANN), august (AUG), September (SEP) and October (OCT) minimum flows (r=correlation coefficient, p= p-value).

		ANN	AUG	SEP	OCT
Wallowa	r	0.299	0.540	0.600	0.060
Mountain region	p	0.022	0.000	0.000	0.622
Blue	r	0.105	0.074	0.130	-0.040
Mountain region	p	0.434	0.585	0.347	0.794
Southeastern	r	0.350	0.620	0.590	0.090
Oregon region	p	0.012	0.000	0.000	0.549

CORRELATION OF INDIVIDUAL STREAM MINIMUM FLOWS WITH REGIONAL AND LOCAL PRECIPITATION

Correlation between individual stream low flows and annual precipitation varies with the streams and low flow variables (Table 12). Streams in the Wallowa Mountain region showed almost the same correlations with the local and regional precipitation. Correlations are comparatively better with the regional precipitation than the local precipitation for streams in the Blue Mountain region except for Mill Creek. Whereas, local precipitation explained the variabilities in low flows better for streams in the southeastern Oregon region except the Silvies River. The Donner Und Blitzen River showed the largest correlations between low flows and precipitation of all the streams analyzed. Mill Creek has the poorest correlations between precipitation and low flows. For annual minimum flows, Bear Creek has the highest correlation with precipitation. October minimum flows for the majority of streams are very poorly correlated with precipitation. Snowmelt ceases by the end of summer. Soil moisture is depleted during summer due to

Table 12. Correlation between annual (ANN), August (AUG), September (SEP) and October (OCT) minimum flows and local and regional precipitation (r=correlation coefficient, p=p-value).

		ANN	AUG	SEP	OCT
Wallowa Mountain region					
EF Wallowa River					
Local ppt	r	0.2	0.60	0.59	-0.09
	p	0.25	0.000	0.000	0.48
Region.ppt	r	0.22	0.61	0.60	-0.03
	p	0.09	0.000	0.000	0.83
Hurricane Creek					
Local ppt	r	0.17	0.54	0.58	-0.01
	p	0.67	0.000	0.000	0.95
Region. ppt	r	0.10	0.58	0.58	0.04
	p	0.46	0.000	0.000	0.77
Bear Creek					
Local ppt	r	0.61	0.51	0.54	0.09
	p	0.000	0.000	0.000	0.50
Region.ppt	r	0.55	0.56	0.55	0.12
	p	0.000	0.000	0.000	0.35
Blue Mountain region					
SF Walla wall River					
Local ppt	r	0.09	0.24	0.24	-0.14
	p	0.52	0.08	0.08	0.31
Region.ppt	r	0.14	0.29	0.30	-0.10
	p	0.32	0.03	0.25	0.46
Mill Creek					
Local ppt	r	0.34	0.26	0.31	0.05
	p	0.01	0.15	0.09	0.77
Region.ppt	r	0.22	0.13	0.17	-0.07
	p	0.8	0.39	0.30	0.62
Umatilla River					
Local ppt	r	0.26	0.22	0.19	0.17
	p	0.055	0.11	0.17	0.80
Region. ppt	r	0.36	0.25	0.29	0.36
	p	0.01	0.01	0.03	0.79
Southeastern Oregon region					
Silvies River					
Local ppt	r	0.37	0.64	0.58	-0.02
	p	0.009	0.000	0.000	0.91
Region. ppt	r	0.50	0.69	0.65	0.08
	p	0.000	0.000	0.000	0.58
Donner Und blitzen					
R. Local ppt	r	0.34	0.75	0.70	0.15
	p	0.02	0.000	0.000	0.33
Region.ppt	r	0.16	0.62	0.60	0.03
	p	0.28	0.000	0.000	0.85
Bridge Creek					
Local ppt	r	0.37	0.31	0.47	-0.002
	p	0.05	0.10	0.01	0.99
Region.ppt	r	0.27	0.24	0.33	-0.14
	p	0.13	0.18	0.06	0.44

high evapotranspirational demands and low precipitation. As a result, there is little correlation between October streamflows and annual precipitation.

Higher year-to-year dependence of minimum flows is expected to reduce the correlation between low flows and precipitation. However, each wet and dry cycle for annual precipitation occurred over at least a couple of years in eastern Oregon. Unless the carryovers are for larger periods, relationship between minimum flows and precipitation in the Blue Mountain region should follow the general trend with other two regions. Year-to-year dependence of low flows for the southeastern Oregon region is also high but they showed highly significant correlation with precipitation. This may be a result of different topographic, geologic, vegetational characteristics and evapotranspiration demands in the two regions. However, the most important aspect is the validity of precipitation as representative of the region. Three precipitation stations selected in the northeastern Oregon are closer to the Wallowa Mountain region than the Blue Mountain region. Increasing the number of precipitation stations from within the Blue Mountain region may improve the relationship between low flows and precipitation.

CORRELATION OF WATERSHED PARAMETERS AND AVERAGE ANNUAL PRECIPITATION WITH LOW FLOWS

All the minimum flow variables (annual, August, September and October minimum flows) for streams in eastern Oregon are negatively correlated with the watershed parameters, though the correlations are statistically not significant (Table 13). Catchment area, area under flood plain, length of perimeter, length of the

Table 13. Correlation coefficients between watershed parameters and precipitation and annual (ANN), August (AUG), September (SEP) and October minimum flows.

Parameter		ANN	AUG	SEP	OCT
Watershed area	r	-0.20	-0.27	-0.23	-0.18
	p	0.61	0.48	0.55	0.64
Watershed perimeter	r	-0.17	-0.24	-0.20	-0.15
	p	0.67	0.53	0.61	0.71
Stream length	r	-0.14	-0.21	-0.17	-0.11
	p	0.73	0.59	0.67	0.78
Watershed relief	r	-0.11	-0.04	-0.06	-0.06
	p	0.78	0.92	0.88	0.88
Watershed length	r	-0.18	-0.25	-0.21	-0.15
	p	0.64	0.51	0.59	0.70
Circulatory ratio	r	-0.25	-0.35	-0.32	-0.27
	p	0.52	0.36	0.41	0.48
Watershed shape factor	r	-0.18	-0.25	-0.21	-0.15
	p	0.64	0.51	0.59	0.71
Channel slope	r	-0.22	-0.17	-0.20	-0.25
	p	0.58	0.67	0.60	0.52
Watershed slope	r	-0.14	-0.10	-0.13	-0.17
	p	0.72	0.81	0.75	0.66
Flood plain area	r	-0.21	-0.30	-0.26	-0.21
	p	0.58	0.43	0.49	0.58
Average annual precipitation	r	0.33	0.35	0.31	0.30
	p	0.38	0.36	0.42	0.44
Average winter precipitation	r	0.57	0.53	0.52	0.52
	p	0.12	0.14	0.15	0.16

main channel, watershed relief, watershed length, circulatory ratio, shape factor, channel and watershed slopes all showed negative correlations with minimum flows. Circulatory ratio and catchment area are marginally more negatively correlated with minimum flows than the rest of the watershed parameters. Correlations of minimum flows were found positive with average annual precipitation with larger absolute values than watershed parameters, however, the correlations are statistically insignificant.

As the annual precipitation showed comparatively larger correlations with minimum flows as an independent parameter, it was split into seasonal precipitation. Regional and local precipitation were segregated into winter and summer precipitation, respectively. Annual, August, September and October minimum flows were regressed against regional winter, regional summer, local winter and local summer precipitation. It was found that local winter precipitation is comparatively better correlated with all minimum flows. The winter average precipitation improved the correlation coefficients over the annual precipitation.

SUMMARY AND CONCLUSION

This study was conducted in order to gain a better understanding of the hydrologic characteristics of summer low streamflows in eastern Oregon. Three streams each in the Wallowa Mountain, the Blue Mountain and the southeastern Oregon regions having continuous daily streamflow record of more than 30 years were selected for study. Five precipitation stations with long-term records, three in northeastern Oregon and two in southeastern Oregon, were selected. Year-to-year dependence of low streamflows and their trends over the period of record were determined. Flow duration curves, flow date curves and low flow frequency curves were constructed for each stream to examine their low flow characteristics. Forecast equations for summer low flows for each stream were constructed. Trend similarities between summer low flows and precipitation are traced. The relationships between stream low flows and watershed parameters and precipitation are explored.

Year-to-year dependence is significant for most of the variables analyzed. Dependencies are higher for the Blue Mountain and the southeastern Oregon regions than the Wallowa Mountain region showing higher carryovers of climatic effects year-to-year. Low streamflows increased over the period of record for the majority of streams, except for Mill Creek and Bridge Creek whose flows decreased. Increase in October minimum flows is small. Comparatively, increase in different low streamflow variables over time is largest for the southeastern Oregon region and lowest for the Wallowa Mountain region. The increase of the trend of low flow in northeastern Oregon may be a function of the drought in the mid 1930's. The higher increase of the trend of low flow in southeastern Oregon may be partly a function of the wettest period of record during the early to mid 1980's in that region. Availability of the streamflow records for the 1930's, the most severe drought in southeastern Oregon, would have further increased the low flow trends for streams in the southeastern Oregon region. Year-to-year dependence and trends over time for low streamflows are insignificant for Bridge Creek, showing a long-term source of water supply which is least affected by small changes in the climate. For the majority of streams, year-to-year dependence and trends are greater for August and September minimum flows.

A flow duration curve, which is a cumulative frequency curve of a continuous time series, was prepared for each stream. Flow duration curves are quite similar for all the streams showing similar relative flow regimes. Low flows, represented by the flatter portions of the curves, occurred during at least 70% of the time for each stream showing existence of long periods of sustained low flow for streams in eastern Oregon. This also suggests a shorter duration for peak flows, as well as relatively large ground water capacities, in eastern Oregon.

Flow date curves are helpful in understanding the flow regimes throughout the year and the availability of a particular flow level during critical periods. Flow date curves showed similar annual flow regimes for the Wallowa Mountain region and the southeastern Oregon region except for Bridge Creek. More than 70% of the total annual flow occurs during late April to late June in these two regions. These streams showed higher variabilities in streamflows over a water year than streams in the Blue Mountain region. Bridge Creek showed the minimum variabilities in streamflow for a water year. It is possible that flow for Bridge Creek is supplied by a stable aquifer which is least affected by smaller seasonal and periodical changes. It is speculated that rain-on-snow events in the Blue Mountains keep the streamflows at higher levels during winter, however, the extreme peak flows occur during April and May.

A low flow frequency curve illustrates the risk of occurrence of various magnitudes of low flows for different return periods for a given stream. Flatter low flow frequency curves for the majority of the streams showed less year-to-year variability in low flow levels. Variabilities in probability of occurrence of low flows with increasing return intervals are low for the majority of the streams except for Mill Creek and Bridge Creek. Low flow frequency curves for different selected streams provided us with a level of confidence with which we can plan our future strategies in eastern Oregon regarding irrigation, fish habitat management, etc. Annual and seasonal low flow frequency curves provided additional information about summer low flows and variations in low flows from month to month during summer. Annual low flows coincide with summer low flows at lower altitudes where snow accumulation is less and snowmelt starts earlier. Annual low flows in the Wallowa Mountains and the Steens Mountains in southeastern Oregon occur during winter, probably when surface and part of sub-surface water supply ceases due to freezing.

Average annual hydrographs per unit area provided the relative flow regime in each stream throughout the year. Throughout the year, flow per unit area during peakflows is higher for streams in the Wallowa Mountain region than streams in the southeastern Oregon region. Rain-on-snow events in the Blue Mountain region may have resulted in "noisy" rising limb of the annual hydrograph. Also, peak flows occur earlier in the Blue Mountain region than in the other two regions.

Recession analyses were conducted to develop model equations from the first half of the data set to forecast summer low flows for each stream and are evaluated against the second half of the data. Forecasts made for recession volume are highly accurate for all the streams except for Mill Creek and Bridge Creek. However, forecast accuracy decreased with the increase in the prediction period. Forecasts for August average low flows are fairly accurate, whereas forecasts for September average low flows and last week of water year are poor. Forecasts are better for streams in the Wallowa Mountain region than forecasts for streams in the other two regions. Forecast and average errors are compared graphically and percent improvements in prediction by forecast over the simple average were calculated. Percent improvements are better for recession volume and August average flows and poor for September and last week of water year' average flows. Accumulation of the error term with the length of the prediction period limited the utility of the model equations for longer periods. Accuracy of the forecast equation improves if forecasts are made for individual parameters using only observed flow just prior to that period.

Five-year moving average trends for annual, August, September and October minimum flows were compared for streams in each region. Similarities of low flow trends within streams are better in the Wallowa Mountain region than in the other two regions. August and September minimum flows showed higher trend similarities than annual and October minimum flows for all three regions. The cumulative departures from long-term mean for each variable helped understand the streamflow trends better.

Annual precipitation is fairly well-distributed over the whole year in eastern Oregon. July and August are the driest months. Annual precipitation increases from the southeastern Oregon region to the northeastern Oregon region. Five-year moving average precipitation trends for selected stations showed high similarities in each region. The Wallowa Mountain region and the Blue Mountain region experienced the most severe drought of records during the 1930's. Records are not complete for the southeastern Oregon region for this period. A lesser drought during the 1960's was experienced in the Blue Mountain and southeastern Oregon regions but not in the Wallowa Mountain region. Cycles of wet and dry periods of shorter duration and smaller magnitudes occurred throughout the record in eastern Oregon. Southeastern Oregon experienced the wettest period of the record during the early to mid 1980's.

Trend similarities between low streamflows and regional annual precipitation are fairly good for all the regions except during a few years. August and September minimum flows showed higher similarities with the regional annual precipitation. Streams in the Wallowa Mountain and southeastern Oregon regions showed higher trend similarities between summer low flows and annual precipitation than streams in the Blue Mountain region. The most prominent differences are shown during the 1960's and the early 1970's for the Blue Mountain region and during the 1950's and the early 1960's for the Wallowa Mountain region. For all the regions, similarities between low flows and precipitation are better for the first half of the records.

Regression analyses were conducted for low flows and regional, as well as local, precipitation for each stream. Correlations between summer low flows and precipitation are highly significant for the Wallowa and the southeastern Oregon regions. August and September minimum flows showed higher correlations with precipitation than annual and October minimum flows. Streams in the Blue Mountain region showed poor relationship between low flows and precipitation. Lower similarities between low flows and precipitation in the Blue Mountain region cannot be attributed solely to high year-to-year dependence of minimum flows in that region. Year-to-year dependence of low flows for streams in the southeastern Oregon region is also significant, however, they showed good similarities between low streamflows and precipitation trends. Selection of additional precipitation stations from within the Blue Mountain region could possibly have improved the correlation between low streamflows and precipitation.

An attempt was made to develop a model to forecast summer low flows in eastern Oregon. Watershed parameters and average annual, as well as, winter precipitation were used as independent variables. However, the regression analyses resulted in lack of significant correlations between low flows and selected independent variables.

All the objectives of this study were achieved with varying degrees of success. Low flow dependence and trends are identified. Characteristics of low flow for each stream are determined with the help of various low flow indices. Model equations to forecast summer low flows for each stream are developed and evaluated. Trends in summer low flows and precipitation in eastern Oregon are identified. Similarities between summer low flows and precipitation are recognized. An unsuccessful attempt was made to develop a model to forecast summer low flows for the gaged and ungaged watersheds in eastern Oregon using watershed parameters and precipitation. The information collected through this study can help utilize the summer low flows more efficiently for agricultural needs, as well as for fish habitat management. It is hoped that future planning for water use during summer low flows in the three study areas can be done with more reliability by using these results. Further research is needed to explore the affects of vegetation management activities, vegetation condition and sub-surface geology on low streamflows in the three regions of eastern Oregon.

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