Summer Low Flow Characteristics of Forest Streams in Northeast Oregon

by

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Summer low flow characteristics of six forest streams in Northeast Oregon were examined using long term streamflow records. Time series and trend analysis revealed highly significant (alpha=0.01) increasing trends in summer low flow over the period of record on four of the selected streams, and significant (alpha=0.05) year-to-year dependence on three of the selected streams. Low flow frequency curves, flow duration curves, and flow-date curves were constructed for each stream from the long term flow records. A simple method of forecasting streamflow recessions using flow records is developed resulting in improvement over the average in forecasting recession volume, but little improvement in forecasting end-of-water year flow levels.

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SUMMER LOW FLOW CHARACTERISTICS OF FOREST STREAMS IN NORTHEAST OREGON

INTRODUCTION

Recent research indicates that interest in water yield, particularly as influenced by forest management activities, is reviving (Troendle and King, 1987; Cheng, 1989). Factors capable of influencing peak flows and annual water yields such as afforestation or timber harvesting have been described by many authors (Hibbert, 1967; Bosch and Hewlett, 1982; Kattlemann, 1982). Although less attention has been given to the portion of annual water yield derived from low streamflows on forested watersheds, these flows are of increasing importance to land managers and others concerned with water yield and streamflow from forested watersheds.

Forest land managers may be concerned with low flows for a variety of reasons. Policy determination for instream flow provisions requires a realistic assessment of the amount of water available. Silvicultural activities may be planned more beneficially if effects on streamflow can be forecast (Brown, 1973). Stream habitat evaluation must be done within the context of often widely varying flow regimes, including periods of low streamflow (Meehan, 1982). Of course, holders of downstream water rights also maintain a keen interest in the nature of their water supply. Thus, knowledge of the low flow characteristics of streams is essential if the water is to be used most efficiently during the low flow period.

The vast majority of streamflow generated in the western United States originates from forested watersheds (Rosquist, 1989). This is especially true in eastern Oregon's semi-arid climate. Forest streams in eastern Oregon are an invaluable resource, providing water downstream for domestic and agricultural use as well as aquatic habitat and recreational opportunities on-site. Information on low flow characteristics of eastern Oregon streams may be incorporated into plans designed to maximize the range of benefits derived from aggregate forest land uses (Bowes et al, 1984).

OBJECTIVES

The primary purpose of this study is to provide a quantitative overview of streamflow during the summer low and base flow periods using readily available sources of data. The completion of three specific objectives will establish such an overview. First, trends and patterns, if they exist, in summer low and base flows on selected watersheds will be identified. Second, several methods of examining and comparing summer low and base flow characteristics will be described and applied to the streamflow records of the selected watersheds. Finally, a predictive model will be constructed in an attempt to forecast summer low flows.

BACKGROUND

Scientists have sought explanations for various attributes of streamflow for more than two thousand years. Both Plato and Aristotle hypothesized on the origin of summer streamflow (Linsley et al, 1982). Hall's (1968) review of base flow recession recounts modern interest in low flows back to at least 1842, when the Frenchman M. Dausse may have originated the notion that drought flows are greater and streamflow more uniform from forested rather than denuded watersheds. Early studies investigating runoff and low flows in the northeast U.S., as cited by Hall, were completed by Vermeule (1894), who examined groundwater depletion, and Horton (1903), who developed recession curves.

Low flows occupy a unique niche in the hydrologic cycle as the only manifestation of subsurface flow that is readily observable across both time and space. Low flow characteristics may be used as indicators of groundwater supply and availability (Riggs, 1963).

DEFINING AND MEASURING LOW FLOW

A disconcerting vagueness exists in the literature regarding the definitions and nomenclature of base flow. Hall (1968) notes that base flow has also been referred to as "groundwater flow, low flow, percolation flow, underrun, seepage flow, and sustained flow." Appleby (1970), in a response to Hall's paper, contends the title 'Base-flow Recession' is misleading because the paper addresses streamflow recession, rather than "that fascinating arena of fancy and speculation, the separation of baseflow." Nonetheless, when attempting to distinguish base flow from direct runoff, Appleby agrees with Hall that no satisfactory definition of base flow exists.

Contemporary nomenclature regarding low flows is equally vague. Linsley et al (1982) use the term groundwater flow, and acknowledge the terms base flow and dry-weather flow. Recent researchers have defined low or base flow according to their specific needs. McMahon et al (1982) note that low streamflow may be defined on a seasonal basis, eliminating the need for theoretical hydrograph separation. Linsley et al (1982) add that the distinction between interflow and base flow is temporal and not based on the particular route taken by runoff. Recent research by Kobayashi (1985,1986) in Japan used stream temperature and conductance to separate snowmelt hydrographs into surface and subsurface components, but made no distinction between various possible subsurface pathways.

QUANTITATIVE CHARACTERISTICS

A wide variety of techniques have been developed to quantitativley describe and compare streamflow characteristics, including low flows. Some techniques place low flows in the context of the yearly hydrologic regime, while other techniques compare low flows against each other. Several low flow characteristics, or indexes, were thought to be potentially useful to this study. Streamflow recessions, daily flow duration curves, low flow frequency curves, and flow-date curves were developed using streamflow records from each of the selected watersheds.

In streamflow recession, a watershed saturated to some degree drains under the influence of gravity much like a sponge. This runoff is typically thought of as arriving at the stream channel via one of three general paths. Overland flow travels directly over the ground surface and is thought to be relatively rare on most forest watersheds (Freeze and Cherry, 1979). Overland flow may occur when precipitation or melt rates exceed the infiltrability of the soil (Horton overland flow), or when the soil is completely saturated. Interflow is water that infiltrates the soil profile and moves laterally towards the stream. This lateral movement may be facilitated by macropores or by downward percolating water "piling up" above a soil layer of lower hydraulic conductivity. A considerable portion of the infiltrated water may become groundwater as it reaches the water table. Groundwater moves saturated flow along a gradient through a porous medium, becoming streamflow as it is discharged from the surrounding medium into the stream channel. Groundwater may have relatively short, or very long residence times before becoming streamflow.

Hydrologists have devoted considerable effort to distinguishing between these three sources of streamflow. It is generally accepted that receding streamflows are composed of progressively higher proportions of groundwater, until at some point groundwater is the sole source of discharge.

LOW FLOW STUDIES

Low flow studies in the United States have typically been undertaken to address questions of water supply for agricultural, industrial, and municipal uses, navigation, and dilution of polluted waters. These assessments generally produce information intended for use by local water consumers and land use managers making water use or allocation decisions. A good example by Singh and Stall (1973) calculates and catalogs the 7-day 10-year low flows for all gaged streams in Illinois. Campbell (1971) developed low flow probability graphs with recurrence intervals based on gaged streamflow records for 27 randomly selected watersheds across the United States.

Several studies have also associated seasonal or annual streamflow to geologic and physiographic characteristics of the watershed. McGuiness and Harold (1962) found that small watershed streamflow regimes in Ohio were regulated primarily by evapotranspiration, and that a larger watershed area did not always result in increased in high or low streamflow. Farvolden (1963) related base flow to several geologic and geomorphic variables on watersheds in the mountains of northern Nevada, noting that "basins larger than two square miles in area tended to behave hydrologically as though underlain by an isotropic, homogeneous rock medium." In Pennsylvania, Schneider (1965) found that low flows were closely related to geology in a basin where a diversity of geologic units were found. Comer and Zimmerman (1969) investigated the low flow and basin characteristics of two forest streams in Vermont, where higher summer base flow from the smaller watershed was attributed to differences in soils and basin slope. Wright (1970) developed a regression equation for the Lothians River basin in Scotland relating the mean lowest annual daily mean flows to watershed area, slope, annual runoff, and a geological index based on the characteristics of surface deposits. A study into the low flow characteristics of British rivers by Beran and Gustard (1977) discusses catchment characteristics to be used in regression analysis for low flow forecasting. Catchment area, slope, stream frequency, urbanization, lakes, soils, and parent material were all expected to correlate with low flow indices. Chang and Boyer (1977) used eight topographic and climatic variables in their regression analysis to estimate the 7-day 10-year low flow at twelve stream gaging stations in the Monongahela river basin in West Virginia. In that study, watershed perimeter was found to account for 88% of the variability in low flows, and the final regression equation resulted in R^2 of 0.999. The authors note that watershed perimeter and watershed area were highly correlated, but that watershed perimeter might be related to input and storage factors as well as area, producing the higher overall correlation with low flows. It should be noted that the final regression equation allowed only four degrees of freedom (eight variables with twelve observations). Furthermore, many of the gaging stations were tributary to each other in the Monongahela basin and consequently dependent on each other. Consequently, the results of this particular study appear somewhat questionable.

There are few papers in the literature dealing specifically with low flows in forested regions. In an early study, Johnson and Meginnis (1960) examined low flow data from watersheds in Ohio and North Carolina. Watersheds in both areas showed low flows were inversely related to changes in forest cover; after forest clearing, streamflow receded more slowly, absolute low flows increased, and fewer consecutive low flow days occurred. After clear-cut logging on Needle Branch Creek in Oregon's Coast Range, Harr and Krygier (1972) found significantly (alpha = 0.05) fewer days when flow was below an arbitrary threshold, indicating an increase in low flows. No consistent relations were found between logging and the timing or volume of the increase in low flows. No trends toward prelogging levels were apparent five years after treatment.

Information on the low flow characteristics of forest streams must often be gleaned from literature concentrating on other factors. A few studies include an analysis of low flows within a larger hydrologic investigation, such as Cheng et al's (1989) study of forested watersheds in interior British Columbia. Low flows on those watersheds were found to be highly variable and highly dependent on summer rains and the previous year's snowpack.

Frequently, studies will focus on annual water yield and peak flows, but make little or no mention of low flows.

Fowler et al (1979) summarize the baseline climatic and hydrologic relationships on the Umatilla Barometer Watershed in northeast Oregon, yet low flows and factors influencing them are not discussed. Researchers in northern California made little effort to secure complete summer flow records (Rice et al, 1979). No mention of low flows is made in either of Troendle and King's (1985, 1987) studies on the hydrologic effects of timber harvest in Colorado.

PAIRED WATERSHED STUDIES

Paired watershed studies have been used extensively to evaluate factors influencing streamflow. Most often, the factor of interest is vegetation management. These studies show, with little exception, that reductions in forest cover, whether natural or man-caused, result in increased annual streamflows (Hibbert, 1967). Water yield in the Oregon Cascades after timber harvest was analyzed by Rothacher (1970), who discovered significant increases in post-logging streamflow in all seasons. Conversely, there is evidence to show that afforestation results in decreased streamflows in the humid eastern U.S. (Trimble et al, 1987).

In many areas, relative increases in streamflow appear to be most pronounced during the low flow season. In New Hampshire, Hornbeck et al (1970) note that the largest relative increases in streamflow after clearing of hardwood forest cover occurred during the summer low flow period - from approximately 5 to as much as 50 times the untreated estimate for August flows (from 1.2 to 5.8 and 0.02 to 1.1 area-inches, respectively).

Similar results were obtained by Lynch et al (1976) in central Pennsylvania. After removing forest cover from approximately twenty percent of a 106 acre watershed, the largest relative increases occurred during the May-August period, and ranged from 0.89 to 2.89 area-inches (31.8 and 13.4 percent increases, respectively).

In North Carolina, Swank et al (1982) observed that streamflow increases associated with forest harvesting became significant (alpha = 0.05) at the onset of the growing season and remained so through late winter. While the authors do not include actual runoff data in their paper, they remark

> "it is also apparent that some of the largest increases in flow occurred during the low flow months of October through November...streamflow was increased during this period by at least 40%."

Greater relative response during the low flow period to vegetation changes does not appear to be limited to the eastern U.S. In central Arizona, Davis (1984) found that conversion of chaparral watersheds from brush to grass cover resulted in slower recession and greater baseflows. As illustrated by the graphs in Davis' paper, post treatment baseflows appear to be approximately twice those measured during the calibration period, but tabular data is not included.

After removal of woodland-riparian vegetation in southern California, Rowe (1963) also found the greatest relative gain in water yield during the season of lowest streamflow, noting that "streamflow became proportionately greater as the flow decreased during the drying period."

Rothacher (1970), on the H.J. Andrews Experimental Forest in the Pacific Northwest, notes that after clear and patch-cut logging, the largest portion of the annual increase in streamflow occurs during the first fall rains, and that "small but important increases in the August-September flow period may be much more significant for downstream use." Similar results were quantified by Rothacher's (1971) findings that average streamflow tripled during the week of lowest flow after a 96 Ha watershed on the H.J. Andrews was clearcut and broadcast burned.

Because of the difficulty in accurately measuring, monitoring, and controlling conditions on large watersheds, these hydrologic studies have been conducted on small watersheds. It is not known if increased summer flows found after timber harvest are detectable downstream. Hibbert (1967) indicates that the longevity of any increase in flows is limited to a few years for most watershed studies if vegetation is allowed to reestablish on the harvest sites.

Even less predictable at the present time is the magnitude of change in summer streamflow associated with forest management (Bosch and Hewlett, 1982). Increases in low flow may vary from imperceptible to substantial between watersheds. These differences are commonly attributed to contrasting geology, vegetation, and climate.

RECENT RESEARCH IN THE PACIFIC NORTHWEST

Several studies addressing yields from forested watersheds in the Pacific Northwest have been conducted on watersheds representing a variety of climates and timber types.

Helvey and Tiedemann (1978) tested streamflow data from three watersheds in the Blue Mountains, two of which experienced extensive defoliation by Douglas-fir Tussock moth in 1972 and 1973. The Umatilla River watershed was roughly 25% defoliated and displayed a 13.2 cm (approximately 14%) increases in annual runoff in 1974 only. While runoff during the summer (July-September) months unchanged, runoff during the autumn (September-October) months was 32.6% greater than expected. The North and South Forks of the Walla Walla River were defoliated to a lesser degree and exhibited no significant change in annual runoff. Mill Creek, untouched by the epidemic, was used as a control during the study period.

No significant increases in annual water yield were found by Fowler et al (1987) after various degrees of timber harvest on the Umatilla Barometer Watershed in the Blue Mountains. Increased wind velocities and wind run are given as possible explanations for the lack of expected increase in yield. The primary interest of Fowler et al's (1988) study central Washington was water quality and climate after timber harvest. Despite the inadequacy of streamflow records for testing changes in water yield, the authors are convinced that increases in yield were small and inconsequential.

Harr (1980) examined streamflow after patch-cut logging of small drainages in the northern Oregon Cascades. Annual water yields and peak flows were not affected, but low flow were found to decrease between 15 and 20 percent on one of two watersheds, presumably because of less fog-drip in the patch cuts.

The effects of wildfire on runoff from forested watersheds in north central Washington were observed by Helvey (1980). Following large, intense wildfires, annual water yield and average daily streamflow were increased, and to date no significant trend toward pre-fire flow regimes was identified over a nine year period. Comparison of pre- and post-burn flow duration curves showed discharges more than doubled at all flow percentages following the fires.

The hydrologic effect of clear-cut logging of a pine beetle infested watershed in southern British Columbia was investigated by Cheng (1989), who reported 48.9 and 38.4 percent average increases in July and August flows for a six year period. The direction and magnitude of changes in streamflow were found to be "clear and consistent," with increases in annual and monthly water yields and earlier peak flow dates.

A survey of the literature reveals there has been no regional analysis of the low flow characteristics of streams in the Blue-Wallowa area of northeastern Oregon.

METHODS

The procedures leading to the completion of the stated objectives begin with the selection of a study area. Next, it is necessary to ascertain what data is available and appropriate for analysis. Time series and trend analysis are then used to determine whether flows have increased or decreased over the period of record Several different low flow indices are then applied to each selected watershed and compared. Finally, a simple method for predicting summer streamflow recessions is derived and evaluated. All calculations and data manipulation were performed on a personal computer with commercial spreadsheet and statistical software package.

STUDY AREA

The geographic area for this study includes the forested mountainous region of northeast Oregon and southeast Washington. Unlike ranges such as the Sierra Nevada in California, or the mountains on Washington's Olympic peninsula, the mountainous areas of northeast Oregon and southwest Washington do not lie on a single, easily identifiable massif or cordillera. Rather, the area is comprised of many sub-ranges, each with a different shape, orientation, and geology. Some sub-ranges, such as the Wallowas, are essentially isolated from other ranges by broad intermontane valleys. The set of sub-ranges collectively referred to as the Blue mountains extends east through the Ochoco, Aldrich, and Strawberry mountains, then northeast through the Elkhorn sub-range and the amorphous Blue mountain massif into the southeast corner of Washington. Figure 1 shows the general location of the study area and selected watersheds. The study area includes major portions of the Umatilla and Wallowa-Whitman National Forests

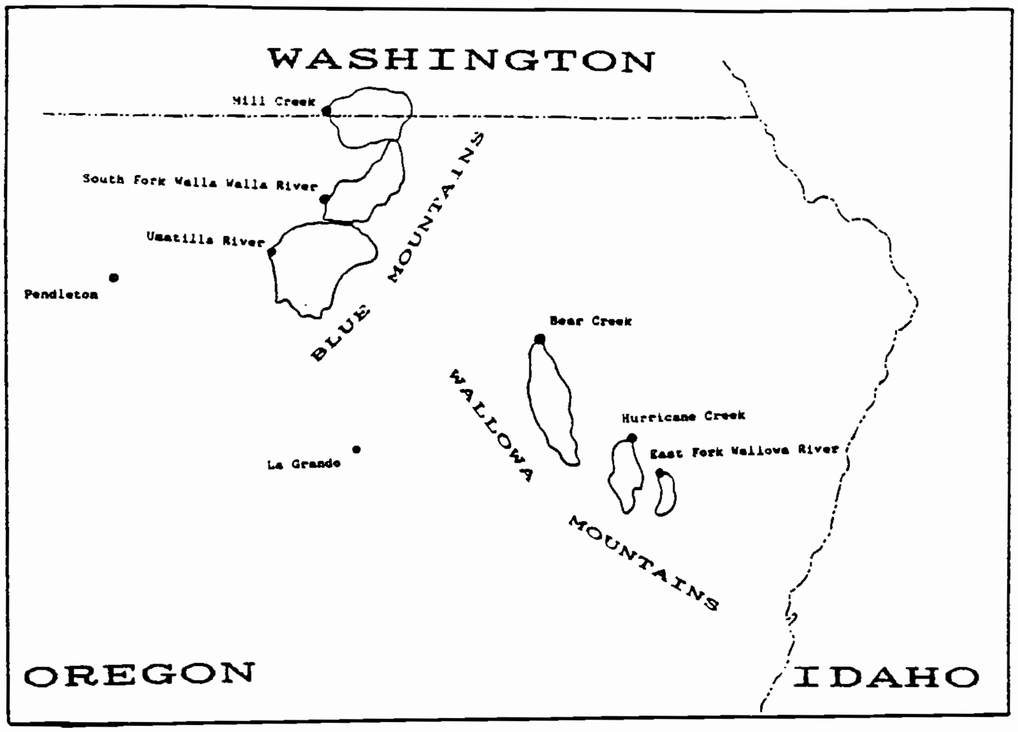


Figure 1 General study area and location of selected watersheds.

DATA ACQUISITION AND SELECTION

Daily streamflow records for selected streams in the Blue-Wallowa area were acquired from the Oregon State Water Resources Department, and the United States Geological Survey. Several criteria are used to determine a particular streamflow record's suitability for inclusion in the study. Completion of the first objective required the longest uninterupted data sets available. This markedly limited the choices as many stations have been established only recently.

An additional constraint is imposed by streamflow regulation and irrigation diversions. Obviously, if water is being impounded or diverted upstream of the gaging station, one cannot expect to make accurate quantitative judgements about the stream's discharge regime. This is especially true for low flow analysis; irrigation withdrawals may be expected to have their greatest impact on streamflows when discharge is at a minimum and withdrawals are at a maximum. This condition severely limited the choice of usable streamflow data sets. Because of this situation, the majority of USGS stream gaging station records in northeast Oregon and southwest Washington are useless for almost any type of low flow analysis. In most cases, there is simply no way to ascertain from the record how much the streamflows at the gaging station are influenced by irrigation withdrawals and/or return flows. As a result, on most gaged watersheds in the study area, there is little basis to conclude that the published streamflows accurately represent the amount of water yielded during the summer months. However, there are a few stations in the study area that, according to the USGS Water-Data Reports for several years, are either unaffected by diversions or withdrawals, or provide some quantitative basis for adjusting the data to natural discharge conditions. These stations are listed in Table 1.

For the time series analysis and low flow index selection, it was determined that the included streamflow records would meet the following criteria:

1.) Entire gaged watershed is within forested mountainous Blue-Wallowa area.
2.) At least 40 years of continuous record are available.
3.) Diversion or control of flow on gaged watershed is either nonexistent, inconsequential, or some basis is given for adjustment.

Table 1 Selected Watersheds

Watershed	Years of Record
Bear Creek	1925-1985 (61)
East Fork Wallowa River	1925-1983 (59)
Hurricane Creek	1925-1978 (54)
Mill Creek	1940-1988 (46)
South Fork Walla Walla River	1932-1986 (55)
Umatilla River	1934-1986 (53)

TREND AND TIME SERIES ANALYSIS

Trend and time series analysis is included for two reasons. First, it is desirable to know if the streamflow records presents any long term trends of increase or decrease in summer low flows. Current popular opinion often holds that "things were better in the good old days," and the concern has been expressed recently that summer flows on forest streams in the study area have diminished. Trend analysis allows quantitative and objective evaluation of these perceived changes over time.

Second, time series analysis includes methods of testing low flow indices for dependence from year to year. In some regions, low flows are known to be supplied at least in part by aquifers that don't recharge and discharge on a regular yearly basis. Low flows on these watersheds may exhibit a considerable degree of dependence from year to year. The probability interpretation of low flow frequency curves, discussed in the next section, is only strictly valid if annual low flows are independent of each other (Riggs, 1982).

Simply plotting the time series of low flows is the first step in identifying any trend. However, the high degree of year to year variability becomes immediately apparent and makes identification of long term trends difficult. Moving averages of increasing length progressively smooth the data. Long term trends become apparent at the expense of yearly detail. Linear regression of the time series and moving averages may be used to determine quantitatively the magnitude and direction of a trend over a given time period. Regression of a random time series, stationary with respect to the mean, will result in a line with a slope not significantly different than zero. Increasing trends appear as positive slopes, and decreasing trends appear as negative slopes.

Year-to-year dependence in the annual, August, and September low flow time series was investigated by caluculating the lag 1 correlation coefficients for each of the selected streams. A T-test is then used to determine whether the dependence in the sample is significant at alpha levels of 0.05 and 0.01.

LOW FLOW DESCRIPTORS

Low flow characteristics of forest streams may be compared using several techniques. Particular techniques employed here include:

1. Recession curves and coefficients.
2. Flow duration curves
3. Low flow frequency curves
4. Flow-date curves

Each of these techniques quantitatively illustrates different qualities of a stream's flow regime, as determined from streamflow records.

Recession Curves

Average annual hydrographs of the selected streams reveal the streamflow regimes for an average year. The streams all showed spring peaks, with flows declining through summer and the end of the water year. Figure 2 shows the annual average hydrographs for each of the selected streams in discharge per unit area (where CSM = cubic feet per second per square mile of watershed area), and total discharge (where CFS = cubic feet per second). Recession curves (sometimes called depletion curves) depict the declining discharge of a stream after a peak is past, and, in the absence of precipitation, the declining amount of water stored in the watershed. Streamflow recession curves are often extracted from annual hydrographs. However, average annual hydrographs were used here because average streamflow recessions were desired. Streamflow recession curves will give some indication of the rate of streamflow decline, the level and persistency of flow attained at the end of the recession, and the volume of water released over an average recession period. Figure 3 is an example recession curve extracted from the streamflow

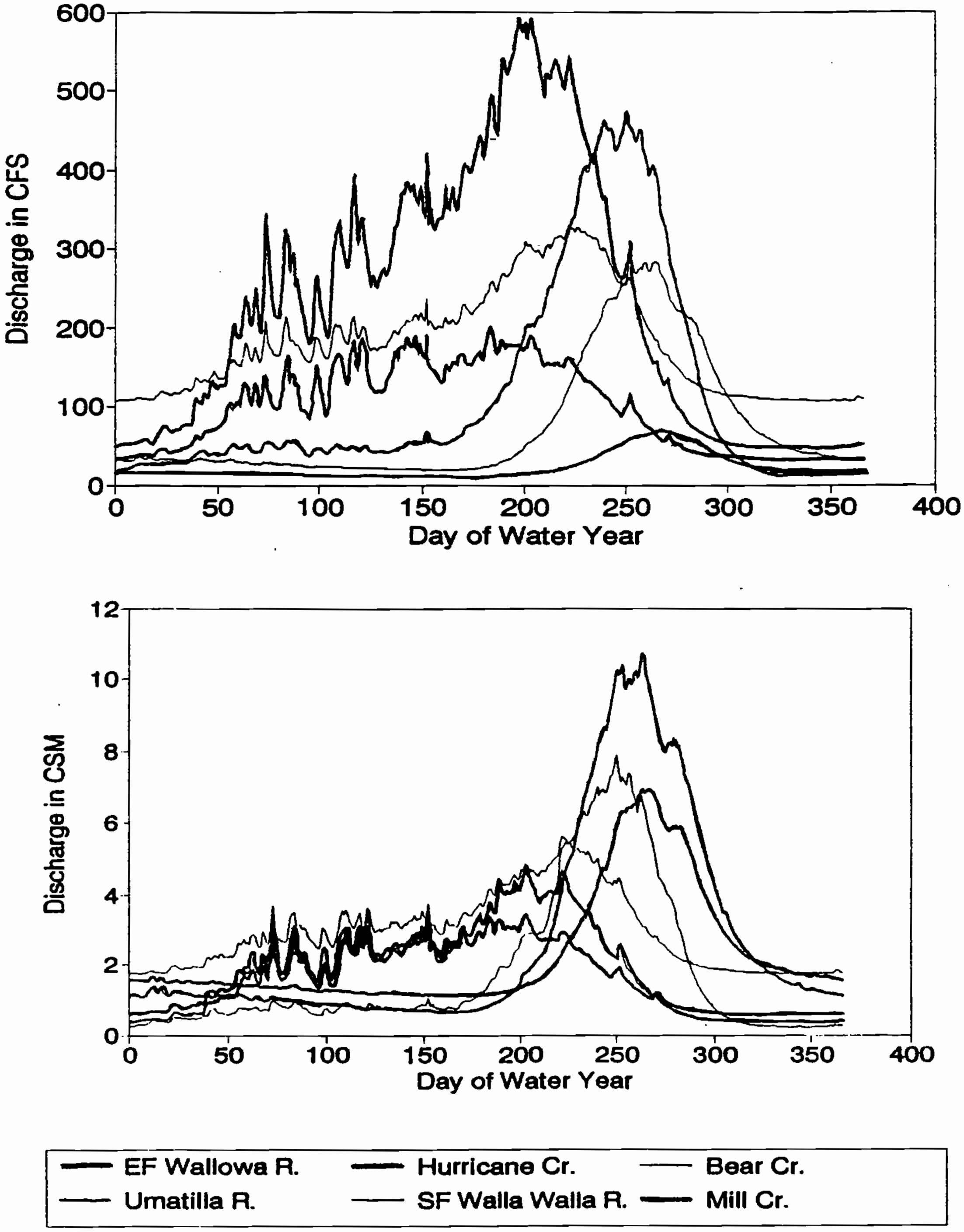


Figure 2 Average annual hydrographs of selected streams.

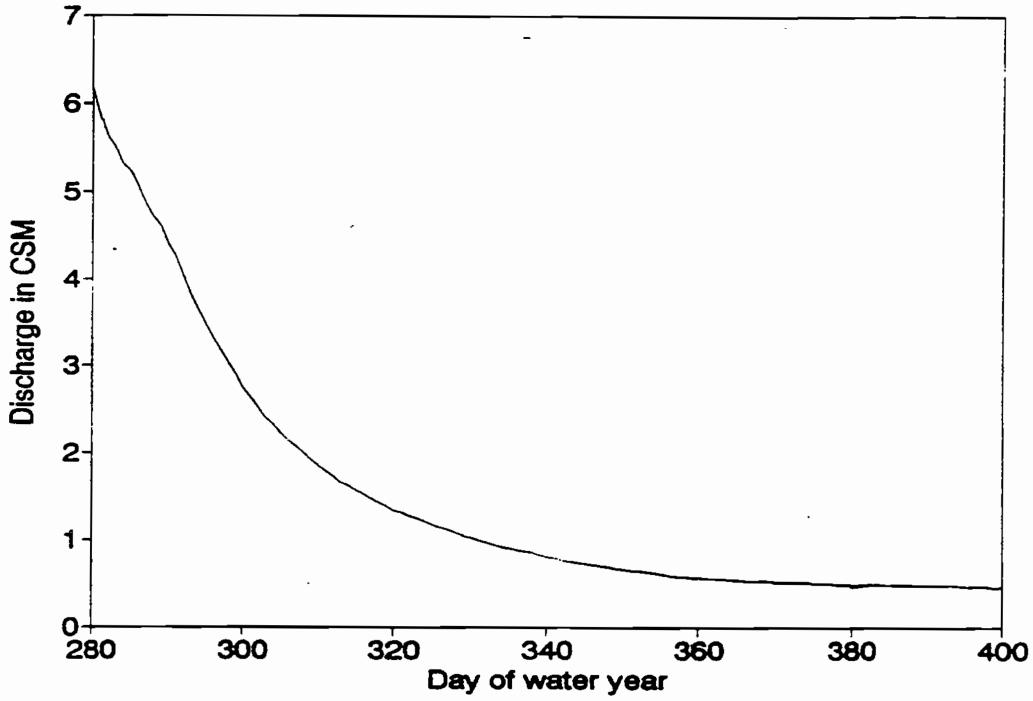
data for Strawberry Creek, a stream not used in this analysis because of its lack of proximity to other streams with flow records deemed suitable for this analysis.

Streamflow recessions are reviewed comprehensively by Hall (1968). McMahon et al (1982), in agreement with Hall and others, note that recession curves are most often described by equations of the simple exponential form:

$$Q_{t+dt} = Q_t K^{dt}$$

where Q_t is initial discharge, Q_{t+dt} is discharge at time t+dt, and K is the recession constant as determined from streamflow data.

Several similar methods have been used to obtain recession constants from streamflow data. Generally, streamflow at some point in the recession is compared with streamflow at some later point (Hall, 1968; Linsley et al, 1982; McMahon and Arenas, 1982). This is repeated through the recession and a scatterplot is produced with the resulting data (Riggs, 1985). Usually, an envelope line enclosing the points comprising the steepest possible recession is drawn. The slope of this line is then taken as the recession constant for the hydrograph of interest. Recession constants are smaller for depletion curves that decline rapidly and continuously, and verge on unity as unvarying base flow levels are approached.



Average annual hydrograph of Strawberry Creek

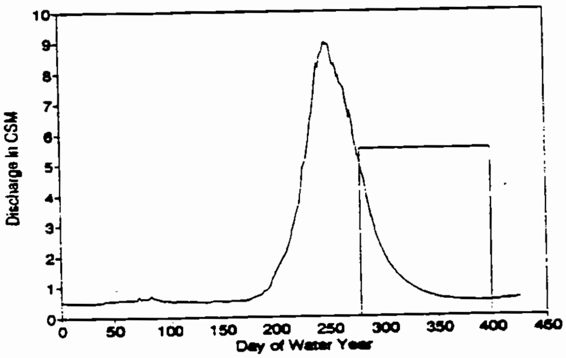


Figure 3 Streamflow recession for Strawberry Creek extracted from average annual hydrograph.

Flow Duration Curves

Flow duration curves show the percent of time a given discharge is equalled or exceeded. Duration curves are cumulative frequency curves that compare discharges without regard to their sequence of occurrence. Figure 4 shows a duration curve constructed from daily flows (where CFS = cubic feet per second) over the period of record from Strawberry Creek. Duration curves are typically used to illustrate a stream's low flow potential. The low flow end of the duration curve may be used as an index of groundwater contributions to streamflow (McMahon and Arenas, 1982). The 90% flow duration value is recommended as an indicator of groundwater flow (Cross, 1949). Flow duration curves are useful because they show the amount of time that different flow levels are attained. Because they use daily or sometimes monthly values, flow duration curves give no information on year to year variability. Because values are taken out of order, the flow duration curve contains no information on the sequence of flows.

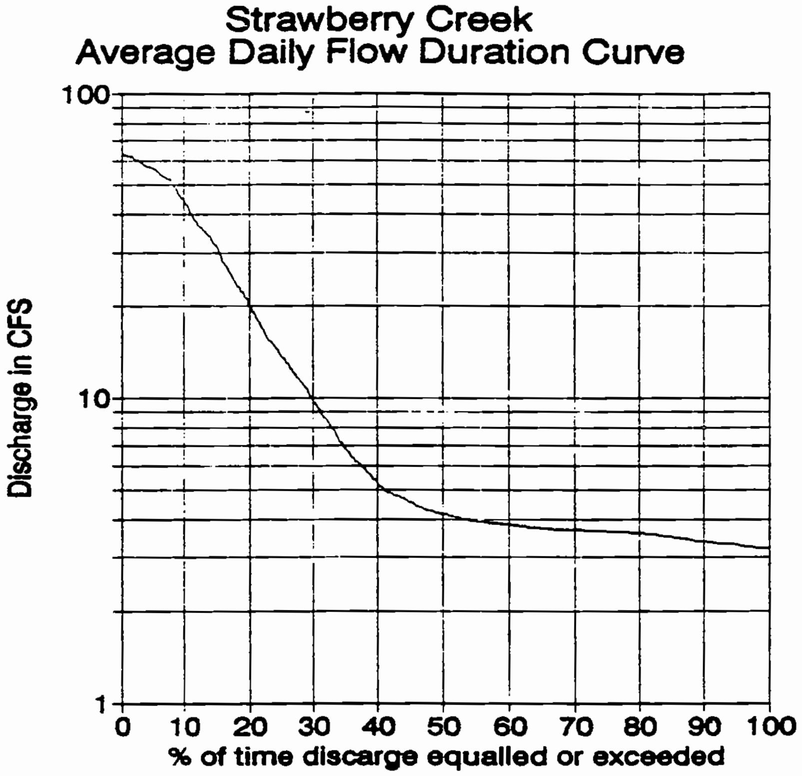


Figure 4 Sample flow duration curve for Strawberry Creek

Low Flow Frequency Curves

Low flow frequency characteristics may be illustrated using low flow frequency curves, which assign a return interval (or probability) to events of varying magnitude. Low flow frequency curves help convey the dependability of low flows from a particular watershed. Generally, longer records produce better frequency curves by allowing consideration of more extreme probabilities. Low flow frequency curves are usually concave upwards, but abrupt breaks in slope may indicate different sources of streamflow, especially during dry periods. Changes in slope may also aid in determining what constitutes base flow at a particular gaging station.

Frequency curves may be constructed using annual or seasonal minimum flows. Frequency curves plot magnitude of flow on the Y-axis against probability or return interval on the X-axis. Low flow frequency curves for the selected streams were plotted using the Weibull formula (Linsley et al, 1982) on a log-log scale, and are typically concave upward. Annual low flow frequency curves are typically constructed from the average flow over some number of consecutive days. 1,3,7,14,30, 60, 90, 120, or 183 days are common. The 7-day low flow is widely used as a low flow index. Ostensibly, the 7-day average is less likely to be affected by short term variations in streamflow than the minimum daily flow. Annual low flows of any length do not discern the season or timing of low flow. If low flows during a particular time of the year are of interest, frequency curves should be constructed from seasonal or monthly data. Figure 6 shows the 7 and 30-day low flow frequency curves constructed from annual flow records for the Strawberry Creek watershed in northeast Oregon.

Monthly minimum flow frequency curves show what minimum daily flow may be expected for a particular month of interest, and are also associated with various probabilities or return intervals. This type of frequency curve better illustrates the flow frequency characteristics during the summer low flow period by using only flows that occur during the summer low flow period. Annual, 7, and 30 day low flow frequency curves may include data from winter low flow periods when low flows are due to the watershed and/or stream freezing. Figure 7 illustrates monthly minimum flow frequency curves for the months of July, August, September, and October for the Strawberry Creek data.

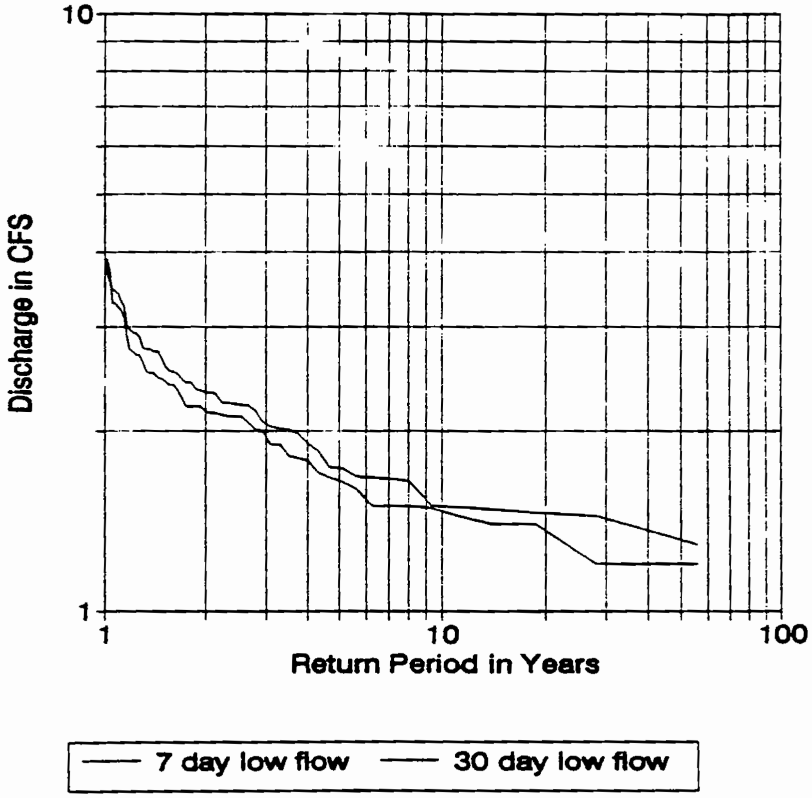


Figure 6 Seven and 30 day low flow frequencies for Strawberry Creek

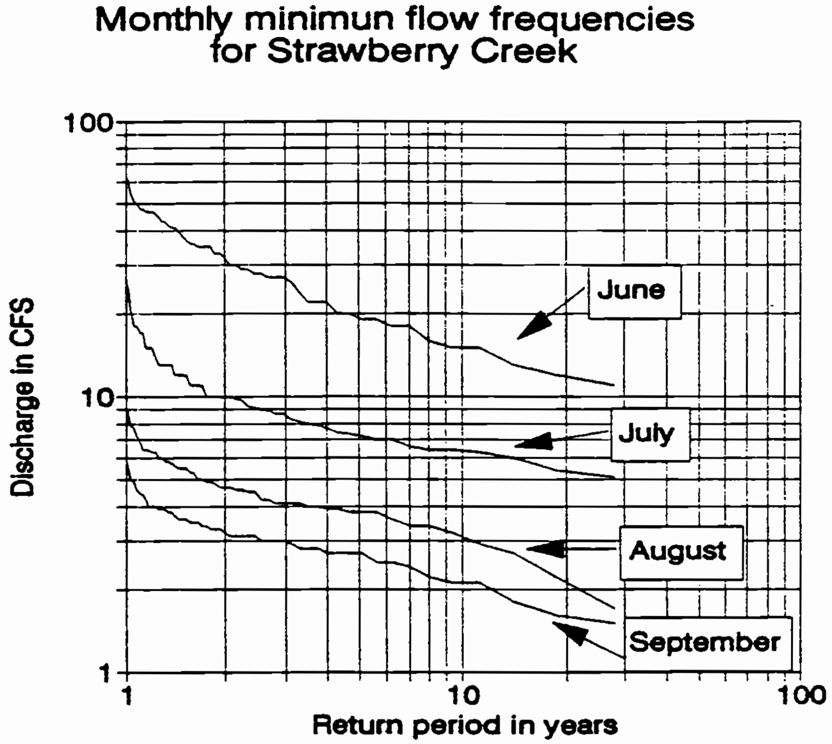


Figure 7 Monthly minimum flow frequencies for Strawberry Creek

Flow Date Curves

Flow-date curves show the proportion of annual water yield past the gaging station by a given date. The concept of the flow-date curve originates in Court's (1962) measures of streamflow timing, where half-flow date was defined as the date "on which half of the year's total streamflow has passed." Baker (1982) expanded on Court's idea by examining the one tenth and nine tenths flow dates as indicators of snowmelt runoff timing. It was thought that a curve could be constructed encompassing all possible runoff fractions and dates that would illustrate the temporal characterisics of runoff more completely than any single date or fraction. Figure 8 is an example of such a curve.

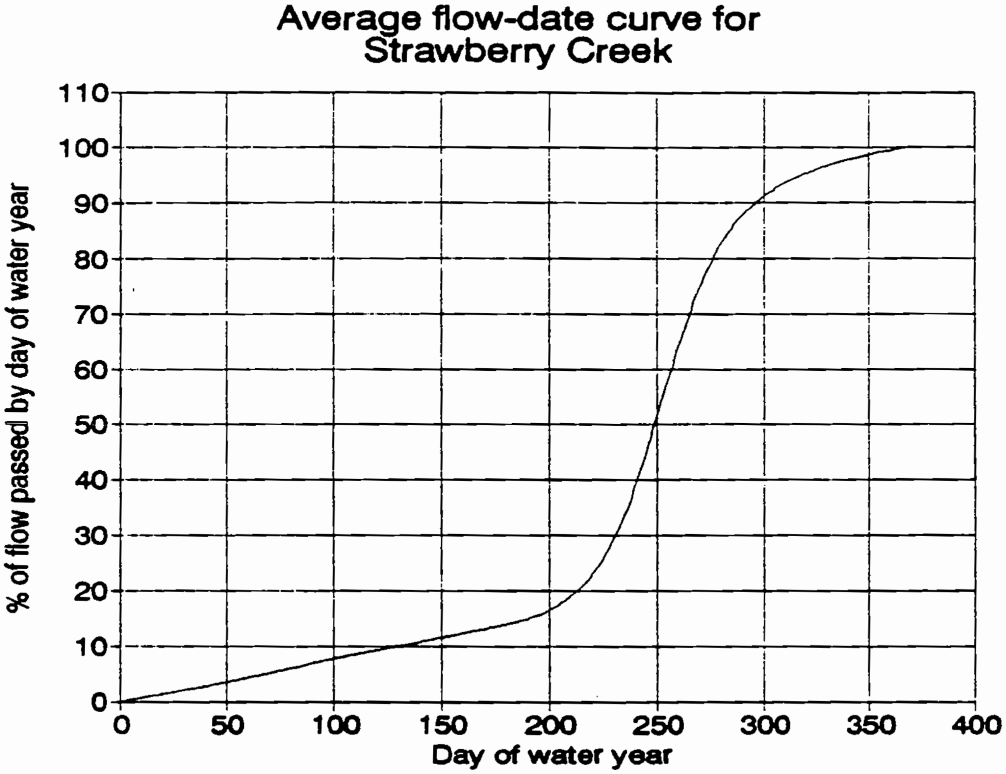


Figure 8 Sample flow-date curve for Strawberry Creek.

FORECASTING

It was considered desirable to be able to predict in advance the magnitude of summer low flows from the study watersheds. Several alternative approaches to this goal were considered.

Initially, it was thought that the factors influencing low flows could be adequately identified using multiple regression in a manner similar to many of the paired watershed studies or to other deterministic streamflow models found in the literature (Campbell, 1971;). Predictor variables were to include one or more climatic indexes (from weather records) and one or more geomorphic indexes (derived from topographic maps), and the dependent variable was to be a low flow index. Several problems prevented this approach from being effectively applied to watersheds in the study area. First, a small number of data sets were available, limiting the degrees of freedom available for analysis.

Second, the watersheds which were determined to have suitable records were highly varied in terms of watershed characteristics such as area, elevation, geology, etc. Low flows were found to correlate poorly with drainage area on these watersheds. Figure 9 reflects the wide range of low flows and watershed areas. Also, the climatic data available was not considered to adequatley represent

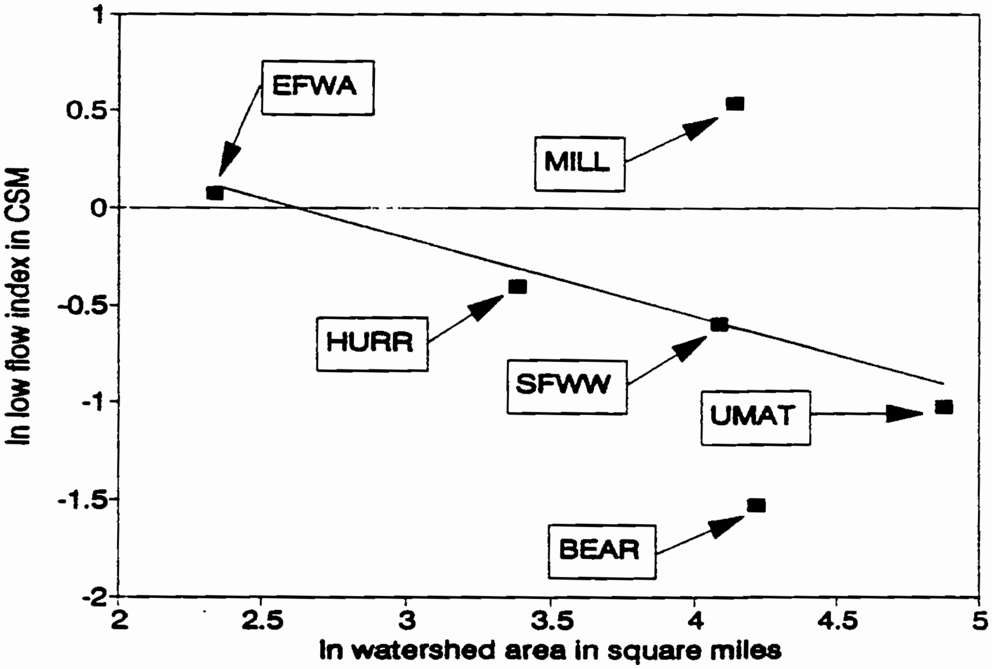


Figure 9 Discharge per unit area and drainage area of selected watersheds.

conditions on the study watersheds. Long term weather records in the region were typically from stations at lower elevations and some distance from the study watersheds.

The paired watershed method appears to lend itself best to detecting the effects of some sort of change, usually vegetative, on the watershed of interest. To successfully implement the paired watershed approach, at least two watersheds with similar physical characteristics and several years of concurrent streamflow record are required. Equations are developed prior to treatment during a calibration period to establish relationships between watersheds. One or more watersheds are then treated. After treatment, streamflows are again monitored and analyzed. If flows from the treated watershed(s) are found to lie significantly outside the relationship established during the calibration period, it is concluded streamflows on the treated watershed were altered.

The watersheds in the study area were not suited to this approach. Although long term flow records were available for concurrent time periods, no accurate information was readily available on treatments to the study watersheds. Furthermore, the study watersheds encompass a very wide range of physical characteristics. Perhaps most importantly, this technique did not appear to be adaptable to predicting streamflows; its chief utility lies in detecting changes in streamflow or water yield as a result of treatment, usually vegetative manipulation, to a watershed.

Given similar meteorological inputs, variations in streamflow regimes between watersheds have been explained by differences in the geometry and subsurface hydraulics of different drainage basins (Kraijenhoff and Moll, 1986). Most studies use multiple regression with this approach (see Mustonen, 1967; Wright, 1970; Beran and Gustard, 1977; Chang and Boyer, 1977), where the dependent variable is some streamflow index, and the independent or predictor variables describe the drainage basin and meteorological inputs.

Several factors prevented the development of this type of deterministic model for the study watersheds. Conditions or assumptions must be addressed prior to employing regression analysis in model building. Most statistical references recommend a minimum number of cases or observations for each predictor variable included in regression analysis. Neter et al (1989) give as a rule of thumb at least 6 to 10 observations for each independent variable included in the regression. Consequently, a much larger number of watersheds with concurrent streamflow data were needed to utilize this technique than were available.

Difficulties were encountered in acquiring or measuring predictor variables. None of the selected watersheds were found to have adequate meteorological data;

those available were discontinuous or short term, and most often located some distance from the watershed of interest. Coverage of the study area on isohyetal maps required use of maps from several sources and time periods. Isohyets on adjacent edges of adjoining maps were typically not in agreement, casting a high degree of uncertainty on their suitability for this study.

While documentation and evaluation of many drainage basin characteristics likely to influence low flows are evident in the literature, and objective methods for selecting those characteristics which most strongly influence low flows have been discussed, values for each characteristic must be measured from topographic maps in the absence of extensive field surveys. The value of a particular drainage basin characteristic as measured on a map of the watershed is heavily dependent upon several factors unrelated to the mechanisms governing low flow, not the least of which is the measurement precision possible on a map of a given scale.

An act of faith is required prior to measuring any drainage basin characteristics from a topographic map. As a map is a simplified representation of the actual watershed, at some degree of detail, the errors in measurements of watershed characteristics from the topographic map will be excessive. While some watershed characteristics, such as area, are routinely measured from topographic maps, measurement of other characteristics may be of questionable validity. For example, some authors have used length of perennial stream channel as a surrogate for the size of the contributing aquifer (Zecharias and Brutsaert, 1988), and measured this length from a map. While there may be plausible mechanistic reasons for this substitution, it is unclear how well the length of the blue line on the map actually represents the length of the perennial stream channel.

Map scale proved to be a problem with the selected watersheds, which ranged in size from 10.3 to 131 square miles. A small scale map is required to examine the large watersheds entirely so that measurements may be taken, yet the small scale map renders smaller watersheds obscure. Using different scale maps for different size watersheds introduces an undesireable source of inconsistency. For example, the length of perennial stream as measured by the length of the blue line on the map representing the stream may vary considerably between map scales.

The wide range of measured values combined with the small number of samples resulted in little promise of a good predictive model. Given the high degree of variability of low flows among the study watersheds, and the small number of watersheds in the study area with streamflow records suitable for analysis, it was concluded that a deterministic regression model based on climatic and drainage basin characteristics was infeasible.

The techniques used in recession analysis appeared encouraging towards forecasting of low flows. McMahon et al (1982) note that recession analysis is commonly used as a forecasting tool during periods of prolonged drought using the simple exponential equation previously mentioned. However, the simple exponential equation has distinct limitations with regard to predicting streamflow. Linsley et al (1982) show that the simple exponential equation plots as a straight line on semilog paper, but that the plot of a streamflow recession on semilog paper typically produces another line with gradually decreasing slope. In effect, the value of K in the streamflow recession increases as the recession progresses. Explanations for this vary, but most reflect a real world system more complex than the description provided by the relationship. Linsley et al (1982) attribute the change to remaining components of interflow and surface runoff in the streamflow hydrograph. Riggs (1985) points out that natural aquifers do not meet the assumptions of the theoretical aquifers in the equations, and that there may be more than one aquifer contributing to streamflow in a basin. Riggs also notes that while the simple exponential equation will often adequately predict part of the recession, it does poorly when the recession includes components in addition to base flow.

The method described by Riggs (1985) for synthesizing hydrograph recessions appeared adaptable to forecasting streamflow recessions on the selected watersheds. For each selected watershed, the mean flow for each day of the water year was calculated for the entire length of record to produce an average yearly hydrograph. The average annual recession was extracted from the average yearly hydrograph at some arbitrary point past the spring peak to the end of the water year. This point is picked by eye from the average annual hydrograph where the recession appears to have clearly begun and flows generally continue to decline at a decreasing rate through the end of the water year.

The average discharge values for the recession are plotted against the average discharge values for the following day. Simple linear regression is used to derive the best fit line through the resulting scatterplot as in Figure 10. The slope and intercept of the best fit line are noted.

A forecast is made initially for the average recession to see if the synthetic recession is at all reasonable. The daily flow value from the first day of the actual average annual recession (Q_n) is entered into the following equation:

$$Q_{n+1}=(Q_n*M)+B$$

where M and B are the slope and intercept of the best fit line from the regression equation (as shown in figure 10), and Q_{n+1} is the first synthesized recession flow value. This process is repeated using Q_{n+1} instead of Q_n, resulting in a second synthesized flow value. This continues until the synthesized recession is complete through the end of the water year. Riggs method is similar, but uses components of several actual recessions rather than the average recession, and the coefficients M and B are determined graphically rather than using regression.

The synthesized and actual average annual recessions are plotted together to see how well the synthetic recession emulates the actual recession. If the synthesized and actual average recessions are quite similar, the coefficients from the regression equation are accepted and "forecasts" are made for each summer recession over the period of record. If the synthetic average recession matches the actual average recession poorly, the average annual hydrograph is again examined to determine if other starting points might result in a better match. Usually, a later starting date (and consequently a shorter forecast) resulted in a better match between the synthesized and actual recessions. Figure 11 shows the actual and synthesized average recessions developed for the example stream, Strawberry Creek.

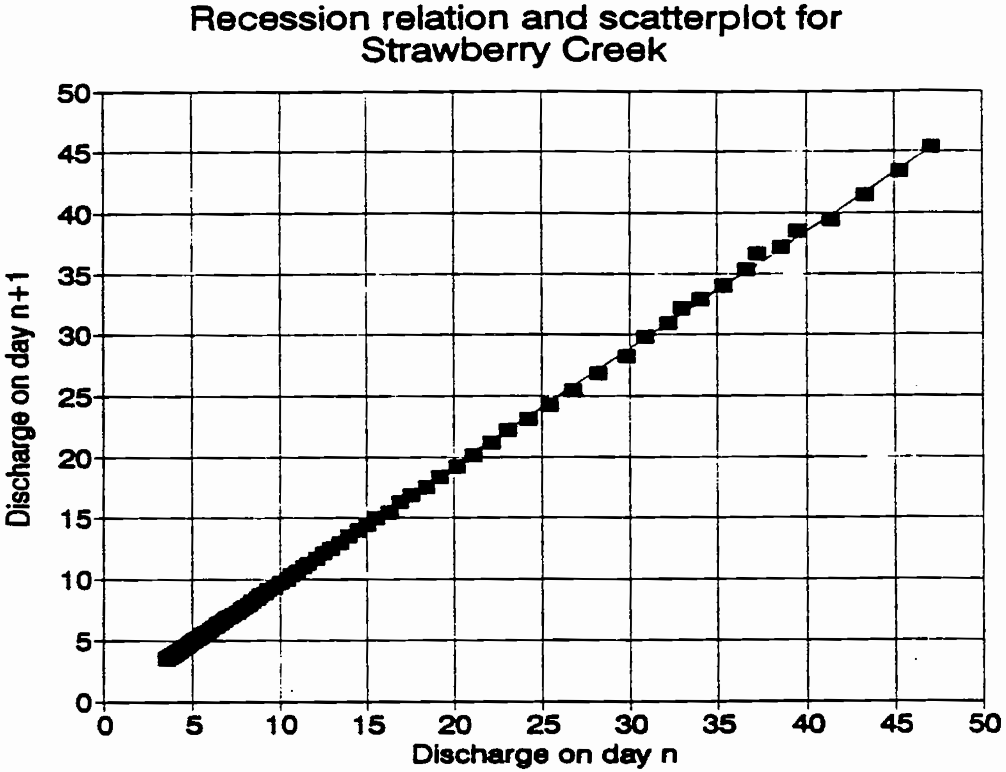


Figure 10. Recession relation and scatterplot for Strawberry Creek

The slopes for each recession synthesis control the rate at which the recession declines initially, while the intercepts control the attenuation of this decline. The product Qn*M dominates the equation at larger Qn's. Because M is always less than one if streamflow is declining, the product Qn*M will always be less than Qn. The amount by which subsequent Qn's are attenuated also decreases as the progression continues, and eventually the amount of attenuation for each subsequent Qn is offset by the addition of the constant, B. From this point, each new calculated Qn is equal to the previous Qn, and a constant baseflow discharge is emulated.

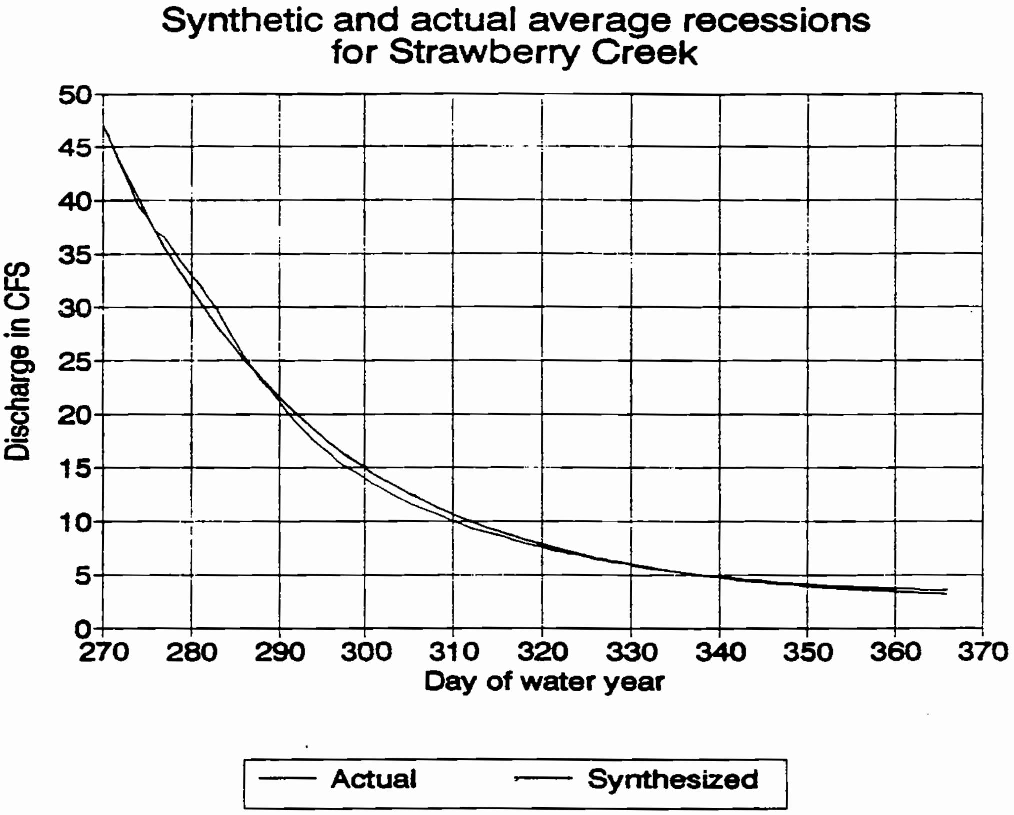


Figure 11 Synthesized and actual recession curves for Strawberry Creek

RESULTS AND DISCUSSION

TIME SERIES AND TREND ANALYSIS

Annual and monthly low flows were plotted as time series to provide an initial view of the data. From these, it appeared on several of the study streams that overall trends or year-to-year dependence were distinct possibilities.

For each stream, the raw time series for August, September, and annual low flows were plotted with their 5-year moving averages. These graphs are included in figure 12. Simple linear regression was used to determine the best fit line through each time series and moving average. The slope of the resulting regression equations and their significance levels were noted. Low significance levels and high T-values indicate a high probability of slopes not equal to zero, and that a trend exists in the data over the period of record. Positive slopes indicate a trend of increasing flows, while negative slopes indicate a trend of decreasing flows. Steeper slopes indicate a more rapid change, while slopes near zero indicate little or no change in the average over the period of record and the absence of a trend. The effect of the moving averages is generally to clarify the existence of a trend in the raw time series.

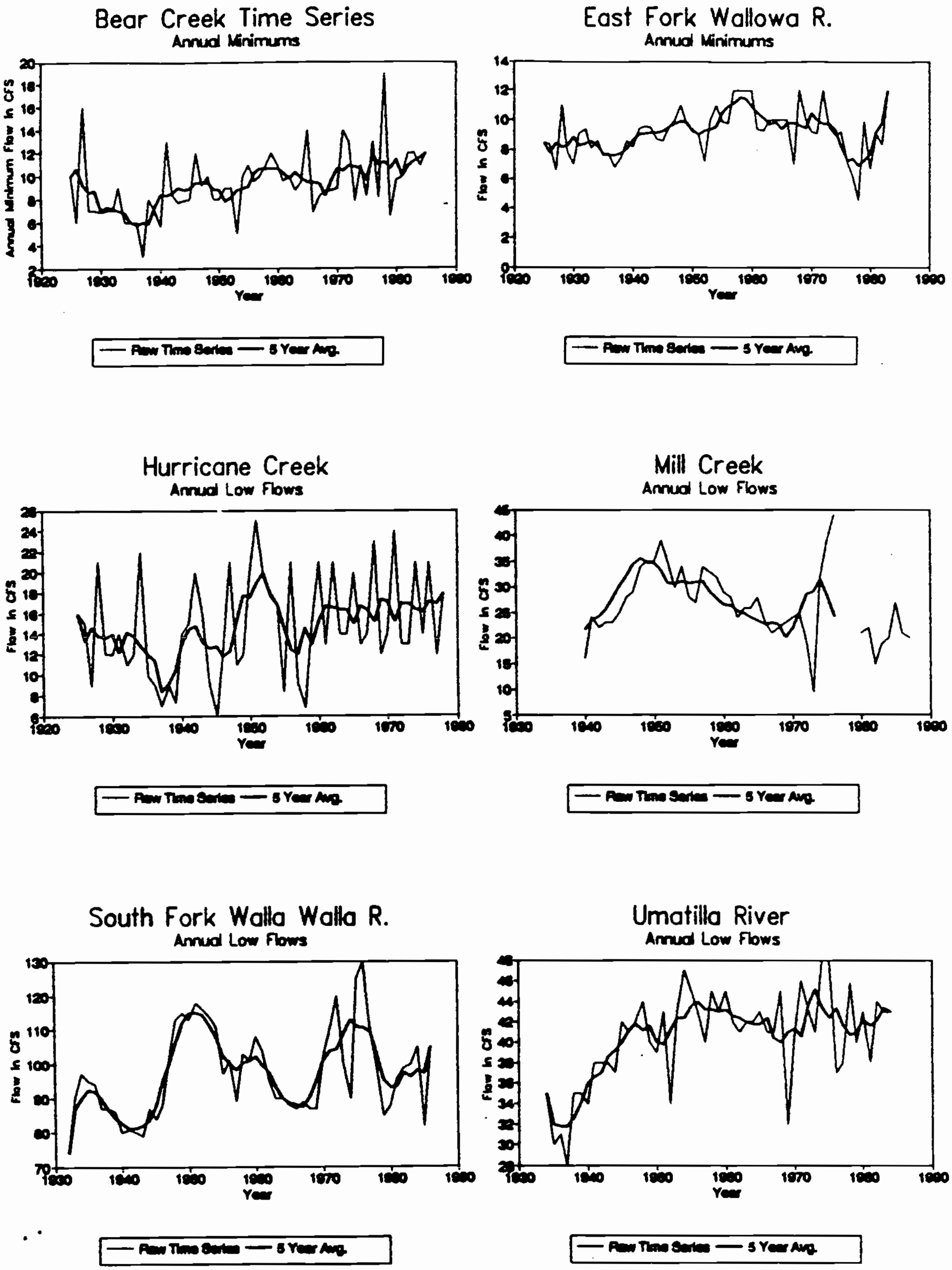


Figure 12a Time series plots of annual low flows on selected streams.

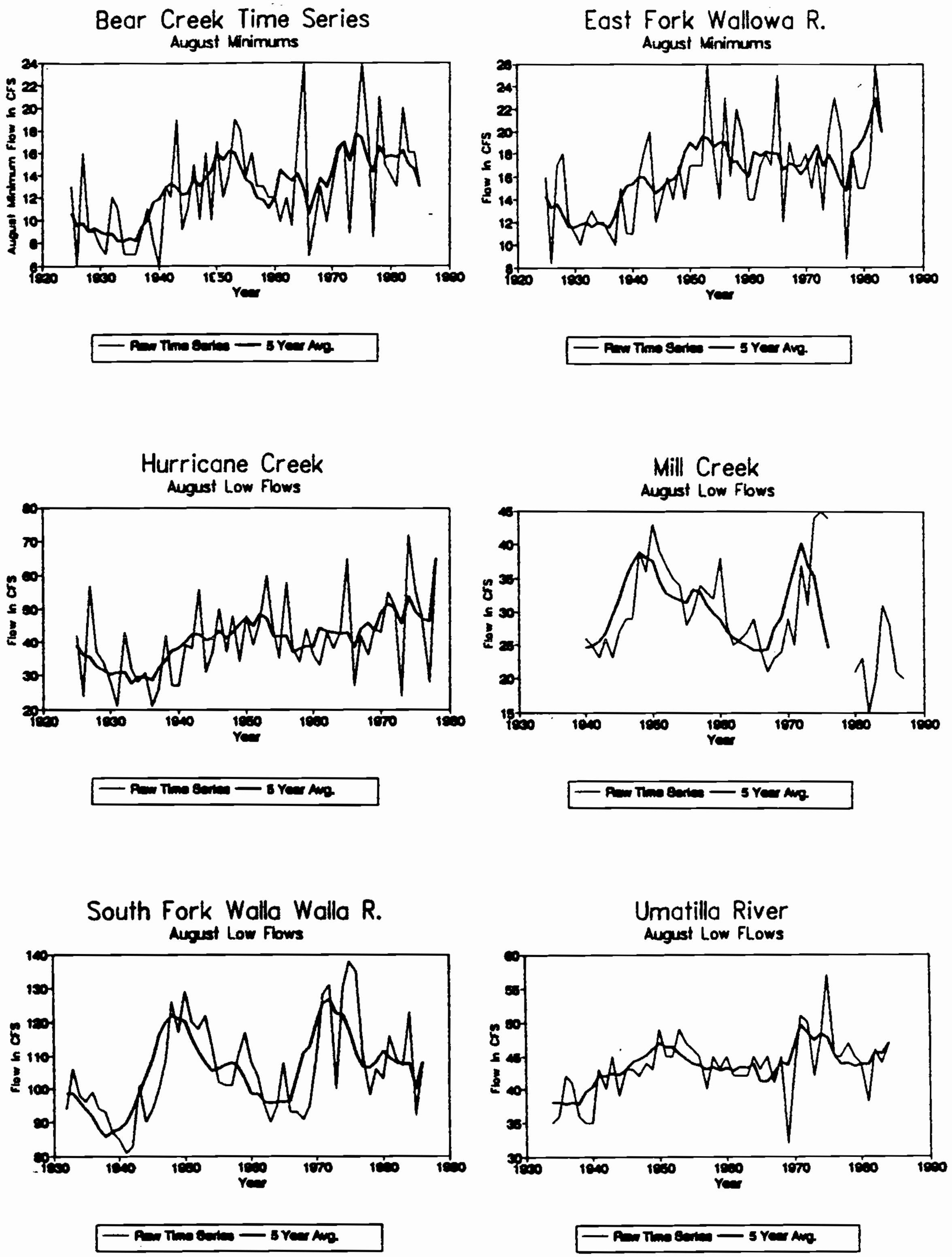


Figure 12b Time series plots of August low flows on selected streams.

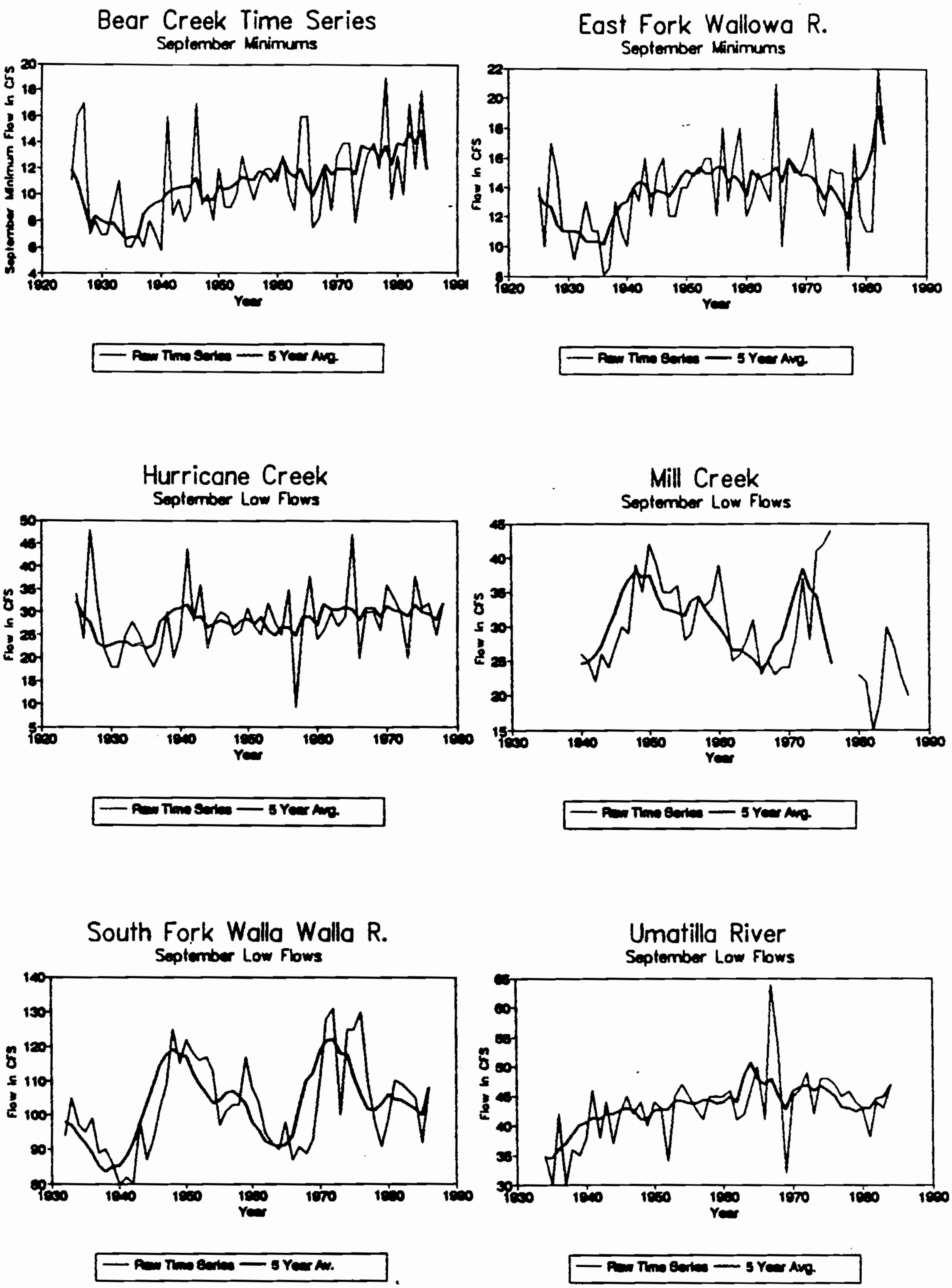


Figure 12c Time series plots of September low flows on selected streams.

Significant trends tend to get stronger with longer moving averages, while insignificant (or nonexistent) trends disappear. Note that these results should not be extrapolated outside the range of the original time series. Furthermore, the occurance of a "significant" trend does not necessarily provide insight as to causality.

Trend analysis of time series constructed from the entire period of record revealed that on five of the six study streams, summer low flows have tended to increase over the period of record. Figure 13 summarizes the slopes of the regressions. Only one stream, Mill Creek, showed a decrease in low flows. As is, the streamflow records from Mill Creek begin in 1940, and data was not collected for years 1977-1979. Considering that the South Fork Walla Walla and Umatilla Rivers experienced their lowest flows on record prior to 1940, it is quite possible Mill Creek would show no or an increasing trend if the record were complete.

Most of the increases indicated by positive slopes are highly significant. Figure 14 summarizes the significance levels of the slopes. Of the 18 time series examined, 14 have slopes not equal to zero at significance levels greater than 90%. Ten of the time series are, for all practical purposes, significant at the 100% level. Of the four time series with significance levels less than 90%, two are from Mill Creek (decreasing) and one corresponds to a slope of 0.01.

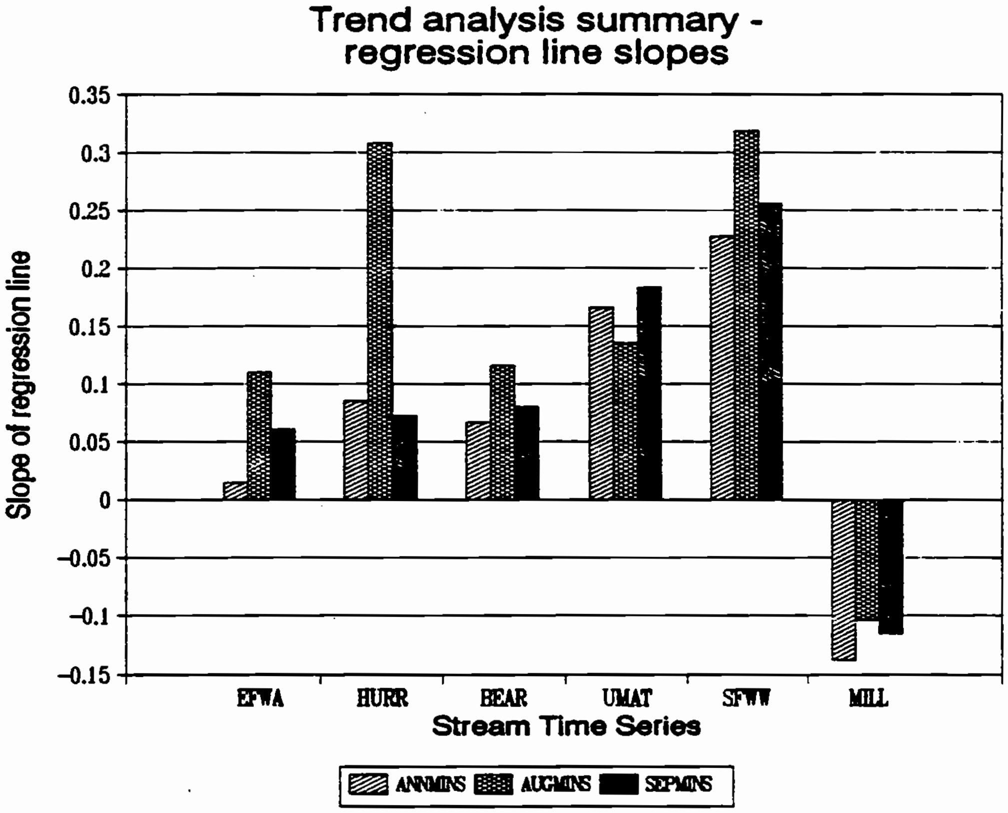


Figure 13 Regression line slope summary

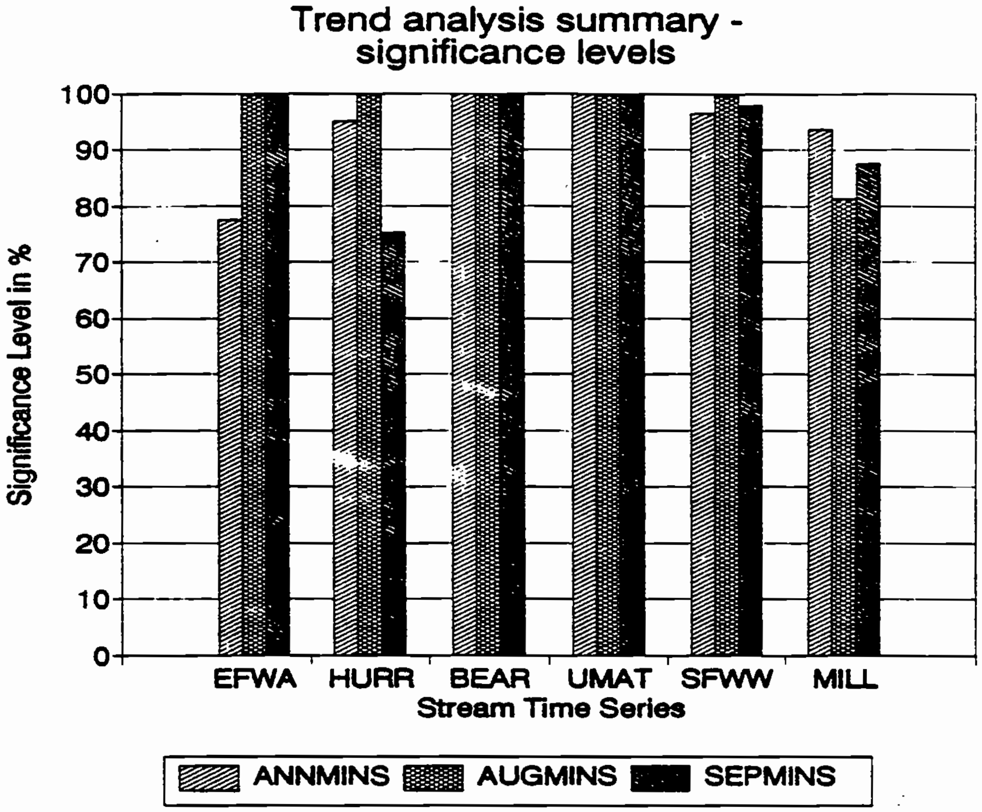


Figure 14 Regression line significance level summary

The high year-to year variability in each of the low flow series is evident in the time series plots included in figure 12. The magnitude and direction of trends indicated in figures 13 and 14 may be visualized in the 5-year moving averages included with the raw time series plots. Additional analysis would likely reveal that the magnitude and direction of the trends identified depends heavily on the particular period of record used. The best example of this is on the Umatilla, where annual low flows appear to increase sharply from about 1935 and 1950, then appear essentially stationary from about 1950 to the end of the record in 1985. Many of the lowest flows occur prior to this period. Interestingly, all the annual low flow time series appear to exhibit stationary or decreasing means in the time period 1950-1970, yet the highest low flows are almost always found near the end of the record in the late 1970's and early 1980's. So despite intervals of decreasing streamflows, annual low flows appear to have increased in general over the period of record.

August and September minimums (the lowest daily flows of the specified month for each year of record) give a better picture of summer low flows on the Wallowa watersheds than annual low flows. Low flows on these watersheds typically continue to decline slowly until the onset of snowmelt in spring. Also, ice buildup in the vicinity of the stage recorder may result in erroneous readings corresponding to substantial streamflows, when in fact flows are very low. Consequently, stage levels on Wallowa watersheds during the coldest months were not considered indicative of actual streamflow.

Annual low flows from the selected watersheds in the northern Blue Mountains more closely coincide with the summer low flow season because here, streamflow tends to increase in autumn in response to significant rainfall. This is evident from the autumn "noise" in the yearly and average annual hydrographs.

August and September low flow time series for each stream are in most cases quite similar to the annual low low series. Increasing trends throughout the period of record generally exist regardless of the month of low flow. One clear exception is Hurricane Creek, where August low flows appear to have increased much more sharply than either annual or September minimums. On Bear Creek and the East Fork of the Wallowa River, August and September minimums show greater inherent year-to-year variability than in annual low flows. The sharp increase in annual low flows early in the Umatilla River's streamflow record is less pronounced in the August and September low flow series. On the South Fork of the Walla Walla and Mill Creek, all three time series are remarkably similar.

DEPENDENCE

The existence of year-to-year dependence in low flows was explored using correlation analysis as described by DeVore and Peck (1986). For each of the selected streams, the annual, August, and September low flow levels were correlated with the corresponding flow from the previous year. The resulting correlation coefficients were used to calculate T statistics, and compared with T critical values at alpha levels of 0.01 and 0.05 with n-2 degrees of freedom.

Table 3 summarizes the results of the T tests for each time series. In no case did changing the alpha level affect the outcome of the test, although some of the calculated T statistics were only slightly larger than the critical T statistics at an alpha level of 0.01. Generally, low flows from the Wallowa streams (East Fork Wallowa River, and Hurricane and Bear Creeks) appear to be independent from year-to-year, while low flows from the Blue Mountain streams (South Fork Walla Walla and Umatilla Rivers, and Mill Creek) appear to exhibit varying degrees of year-to-year dependence. There are two exceptions to this generalization. Annual low flows on the East Fork of the Wallowa River exhibit considerable ($r=0.34$) year-to-year dependence, while August and September low flows do not. The reasons for this are not clear, but factors involving the PP&E generating station are possible. Also, September low flows on the Umatilla River do not exhibit significant year-to-year dependence, while all other time series from the selected Blue Mountain streams exhibit significant dependence. One plausible explanation for this includes the increased streamflows usually experienced in autumn on the Blue Mountain watersheds.

Table 3 Dependence Inference Summary

Stream	Variable	Correlation	T-calc	T-crit 0.05	T-crit 0.01	Depend?
EFWA	annmin	0.34	2.74	2	2.67	y
EFWA	augmin	0.23	1.78	2	2.67	n
EFWA	sepmin	0.09	0.65	2	2.67	n
BEAR	annmin	0.03	0.26	2	2.66	n
BEAR	augmin	0.22	1.72	2	2.66	n
BEAR	sepmin	0.21	1.66	2	2.66	n
HURR	annmin	0.05	0.36	2.01	2.67	n
HURR	augmin	-0.03	-0.19	2.01	2.67	n
HURR	sepmin	-0.06	-0.46	2.01	2.67	n
MILL	annmin	0.56	4.45	2.02	2.69	y
MILL	augmin	0.62	5.17	2.02	2.69	y
MILL	sepmin	0.6	4.97	2.02	2.69	y
SFWW	annmin	0.65	6.19	2.01	2.67	y
SFWW	augmin	0.64	5.98	2.01	2.67	y
SFWW	sepmin	0.69	6.94	2.01	2.67	y
UMAT	annmin	0.48	3.95	2.01	2.68	y
UMAT	augmin	0.35	2.7	2.01	2.68	y
UMAT	sepmin	0.23	1.7	2.01	2.68	n

LOW FLOW INDEX COMPARISON

Several methods were employed to portray the low flow characteristics of the selected streams. Some of these methods appear to be useful for comparing and distinguishing low flow characteristics between streams, while others seem better suited to analysis of individual streams. Streamflow recessions, flow duration curves, low flow frequency curves, and flow-date curves were developed for each of the selected streams.

Recessions

Average streamflow recessions are easily constructed from the streamflow data. Average recessions reveal several aspects of a given stream's flow characteristics. Figure 15 contains average recessions from each of the selected streams in CSM (CFS per square mile of drainage area), whereby each stream's recession is illustrated from day 200 (April 18) through the end of the water year (Sept 30). The Wallowa streams' (EFWA, HURR, BEAR) average recessions clearly do not begin until the month of June (DWY 244-275), while the streams from the northern Blue mountains (UMAT, SFWW, MILL) begin to recede much earlier. From the recessions, each stream appears to attain a unique base flow level at its own rate, and at different times near the end of the water year.

Notably, even within either of the geographic subregions, stream recessions' relationships to each other are not fixed. That is, despite similarities, recessions from both the Blue and Wallowa mountain streams maintain unique characteristics. It was not possible with these watersheds to discern the cause of these differences. However, large differences in watershed area alone may be largely responsible.

Figure 16 shows the streamflow recessions from the northern Blue mountain watersheds. While the Umatilla River consistently has the highest peaks and greatest discharge volume, the South Fork of the Walla Walla River consistently has the highest low flow levels. The Umatilla River eventually attains a low flow level only slightly greater than that of Mill Creek, which drains a much smaller (131.0 vs 59.6 square miles, respectively) watershed. The Blue mountain streams, on average, also begin to rise again near the end of the water year, indicating that these recessions do not generally continue through autumn and into winter.

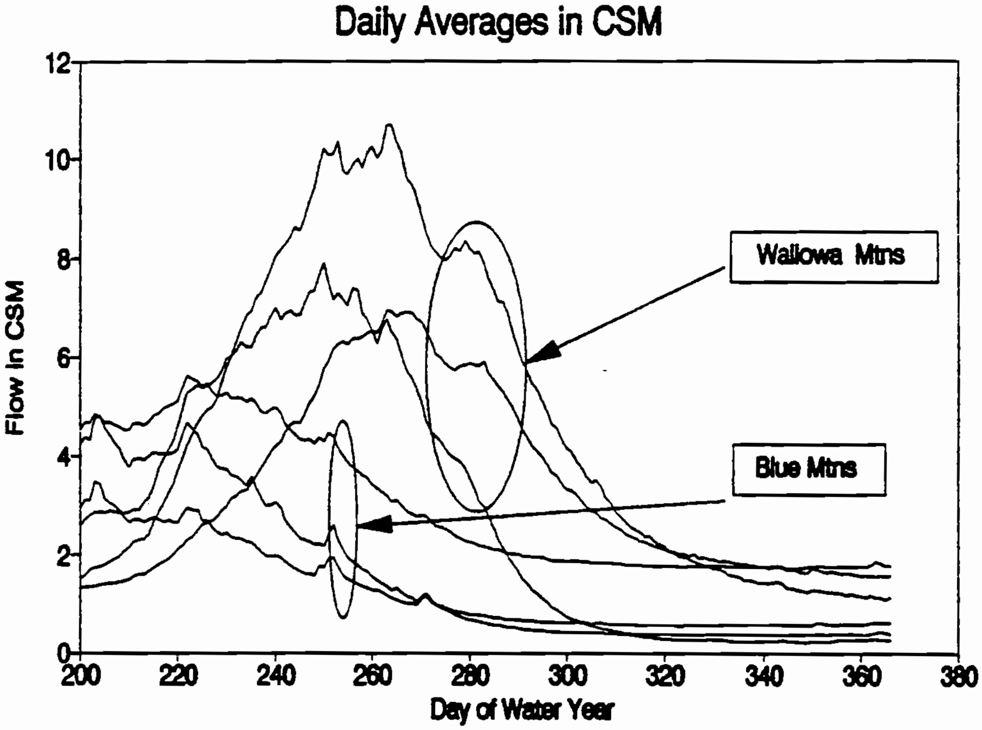


Figure 15 Average recessions of selected streams in CSM

Streamflow recessions from the Wallowa watersheds, shown in Figure 17, present several clear differences from the Blue mountain recessions. Wallowa recessions begin at a later date, usually sometime in June. The Wallowa recessions also appear to be steeper than those from the Blue mountains, with the possible exception of the East Fork of the Wallowa River, and continue to decline well past the end of the water year.

Again, the low flow discharges attained near the end of the water year do not necessarily depend in the size of the peak or volume of the hydrograph. Bear Creek has the highest average peak and greatest volume, but streamflow declines much more rapidly and slightly earlier than Hurricane Creek. Bear Creek eventually attains a low flow level only slightly greater than that of the much smaller East Fork of the Wallowa, whose hydrograph is muted by the much larger absolute values of the Bear and Hurricane Creek runoff peaks.

Plausible reasons for the differences in these recessions are easy to hypothesize, but difficult to test with the data available to this study. Bear Creek is substantially larger than Hurricane Creek and almost six times the size of the East Fork, so it might be expected to have the largest runoff volume. But it also has the lowest gage datum, and a greater proportion of its area at low elevations. Watershed characteristics may be such that the aquifers contributing to low flows are actually larger on the smaller watersheds in this study. Further studies with better information on watershed characteristics and a larger number of streams are needed to explore this possibility. The streamflow recessions' chief utility in this study was found in forecasting, which is discussed later.

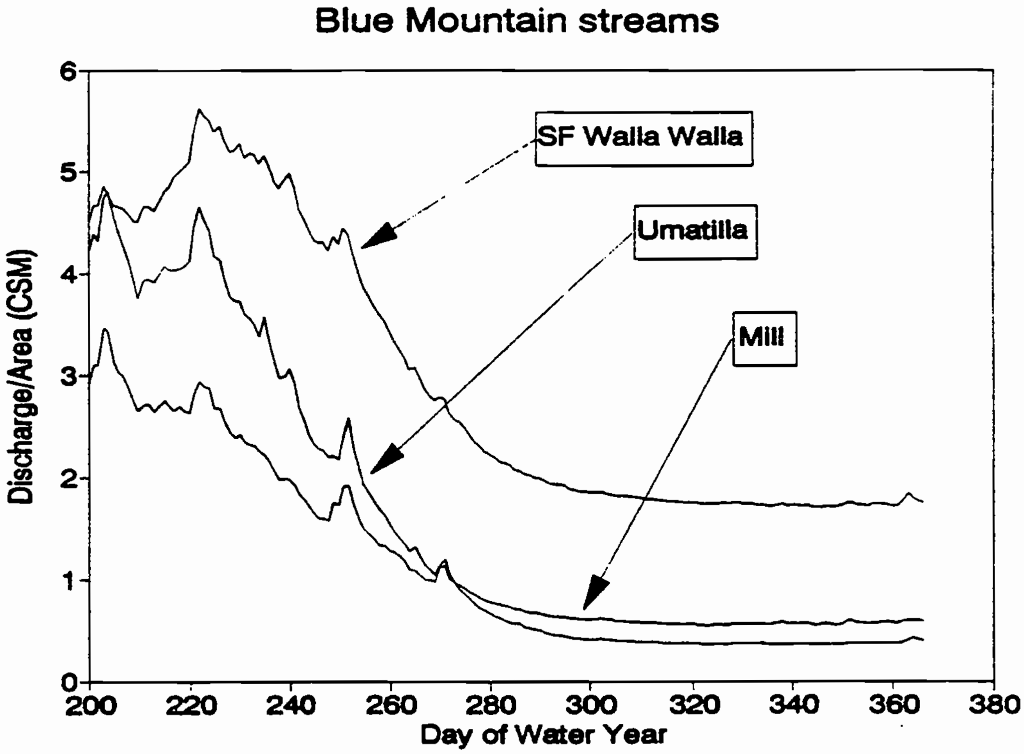


Figure 16 Blue Mountains streamflow recessions

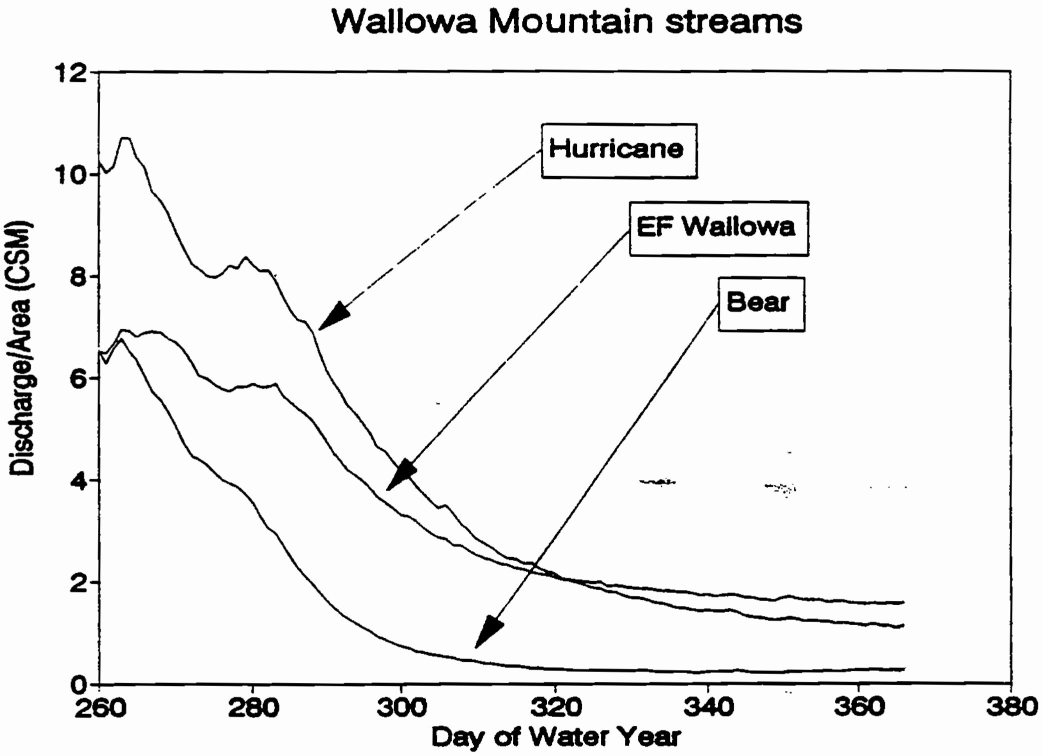


Figure 17 Wallowa Mountains streamflow recessions

Flow Duration Curves

Flow duration curves are a useful method for graphically comparing the variability of flows. The flow duration curves presented in this analysis are cumulative frequency curves of daily streamflows based on the entire period of record. The upper left portion of the curves represent high flows (the extreme peaks are not included in the graphs), while the lower right portion of the curve represents the low flows during the periods of record.

One shortcoming of the flow duration curve is its unsuitability as a probability curve. Because daily flow values show high serial correlation, the probability of a given discharge exceeding some specified level depends on both the time of year and on the prior flow levels. However, the flow duration curve may be used to determine the relative amount of time discharges exceed or fall below a certain level over the period of record.

Figure 18 displays the duration curves constructed for each of the selected streams. Absolute minimum flows from a particular stream may be read as the discharge equalled or exceeded 100% of the time. Variability of flows may be interpreted by the range of flows shown in the duration curve. Bear Creek and the South Fork of the Walla Walla provide contrasting examples of streams with high and low variability in low flows.

Figure 19 shows the 95% and 50% flows for each of the selected streams. The 95% flow may be thought of as representing low flows, and the 50% value as representing the median flow. The relative difference between these two flow values provides an index of low streamflow as compared with the median discharge, enabling comparisons between streams with different magnitudes of flow. Figure 20 illustrates these differences as the ratio of the two flows. The highest ratios, found on the East Fork of the Wallowa and the South Fork of the Walla Walla, indicate relatively high and reliable low flows that are closer to the 50% flow value. The smallest ratio, found with the Bear Creek data, reflects low flow discharges that are consistently small compared with the stream's medium discharge. This may indicate relatively small amounts of groundwater storage capacity on the watershed and meager low flow potential. Hurricane Creek, the Umatilla River, and Mill Creek all have flow duration curve characteristics lying between the high and low extremes.

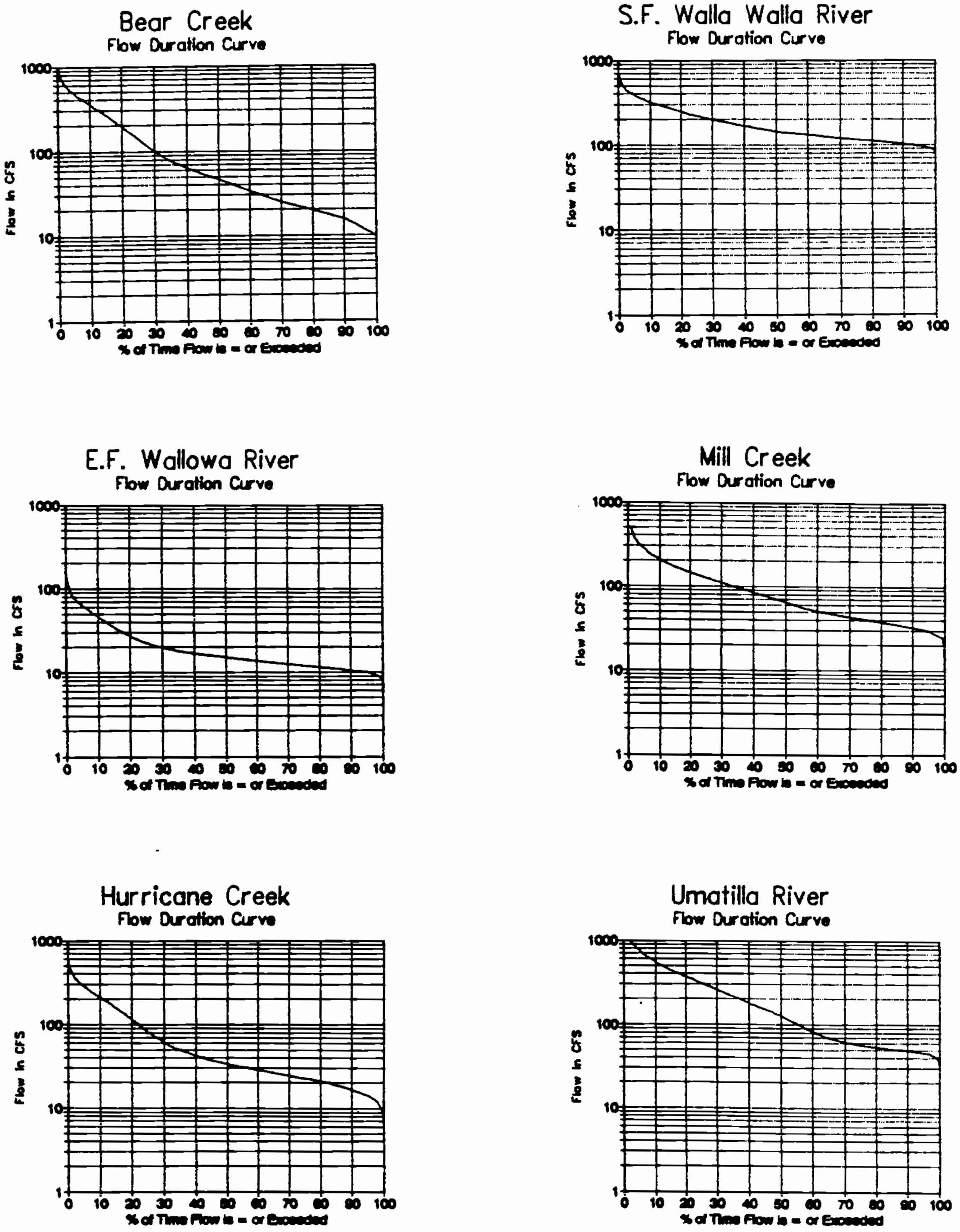


Figure 18 Duration curves for selected streams.

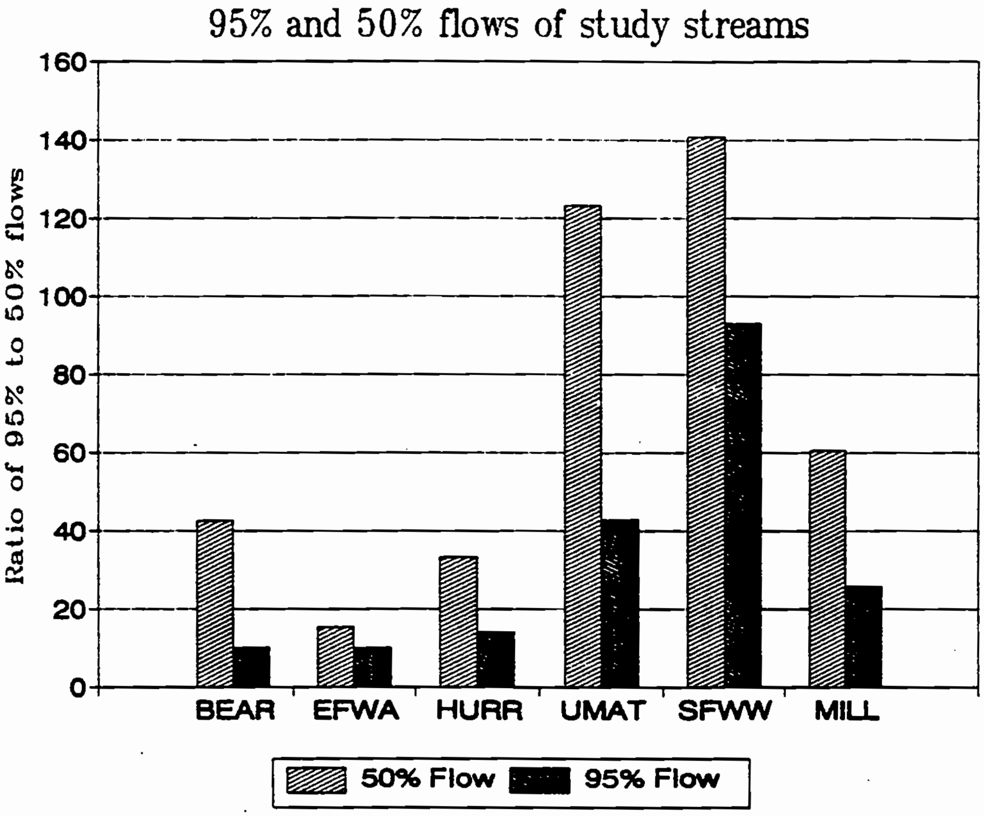


Figure 19 95% and 50% flow durations for selected streams.

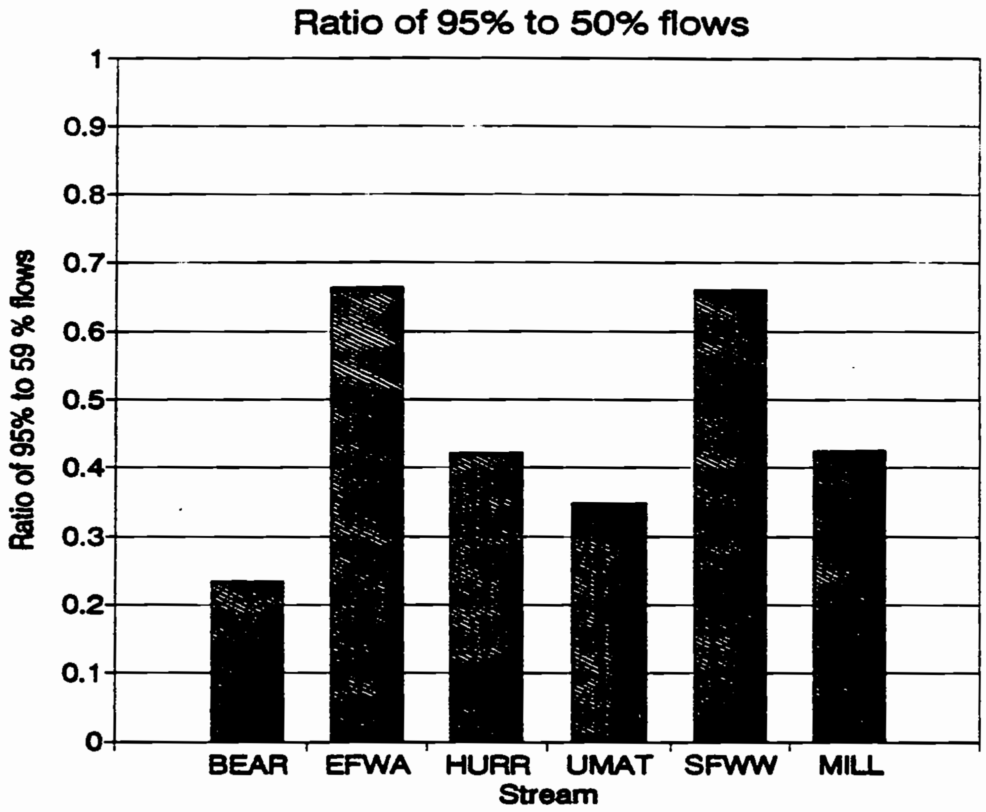


Figure 20 Duration curve ratios for selected streams.

Low Flow Frequency Curves

Two separate sets of frequency curves were prepared for each watershed. Figure 21 illustrates the lowest mean 7- and 30-day flows on each of the selected streams. As might be expected on streams with established low flow seasons, the 7- and 30- day flow values are quite close to one another. Low flow levels, once attained, tend not to drop abruptly over short periods of time under natural conditions. As illustrated, the range of flows between different return intervals is far larger than the difference between the 7- and 30-day low flows. The Wallowa streams in this study typically continue to decline until the onset of snowmelt in late winter or early spring. As such, the 7- and 30-day low flow curves give no information on flow frequencies during the seasonal streamflow recession and summer low flows.

For the East Fork of the Wallowa, and the South Fork of the Walla Walla, the 7- and 30-day low flow frequency curves are almost superimposed on one another. This indicates that throughout their range, low flow levels on these streams are consistent and sustained. This is supported by the high duration curve ratios for each of these streams noted in the previous section.

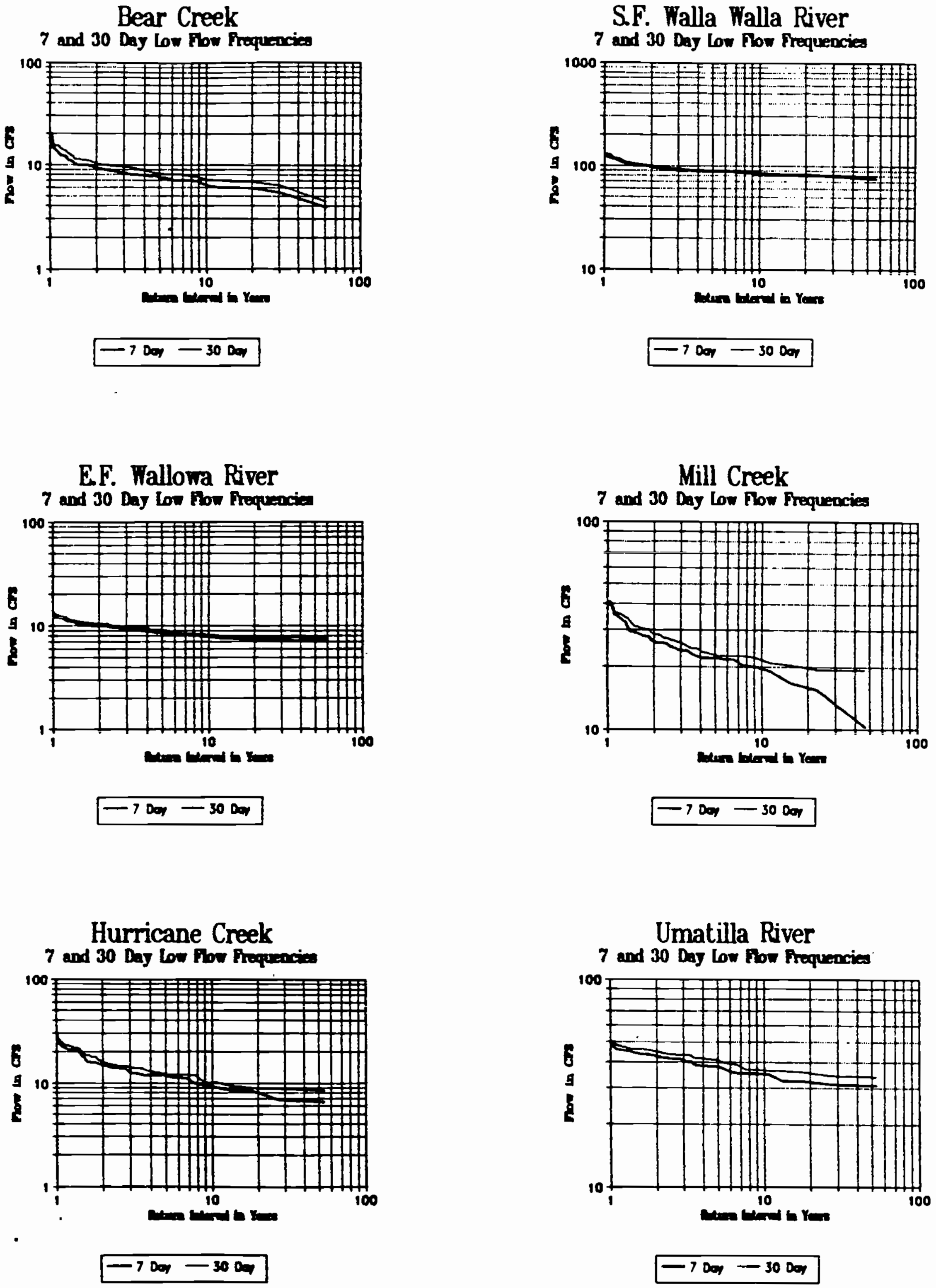


Figure 21 Seven and 30 day low flow frequency curves for selected streams

These two streams also have flatter frequency curves, indicating low year-to-year variability of 7- and 30-day low flows compared with the other streams in the study. Bear Creek, Hurricane Creek, Mill Creek, and the Umatilla River all show similar and consistent variability between 7- and 30-day low flows throughout most of their range.

Frequency curves for summer low flows may be constructed using monthly low flow values. Figure 22 shows monthly low flow values for July, August, September, and October from each of the study streams. These curves exhibit the same concave upwards shape as the 7- and 30-day low flows, yet the summer recession is evident in the spacing between the curves. July low flows on the Wallowa streams, typically in the steep part of the seasonal recession, are substantially larger than either August or September low flows. During August, September, and into October, streamflow is expected to continue to decline, but at a decreasing rate. This is supported by the relatively small differences between flows of a given return interval in these two months. It should be noted, however, that over the period of record, nominal low flows in July encroach well into the range of common August and even September low flows. Monthly low flow frequency curves for the Blue mountain streams appear similar to the 7- and 30-day low flow frequency curves. This is consistent with the occurence of annual low flows on these streams during the summer months.

Flow Date Curves

The flow date curve is really a cumulative relative average hydrograph and conveys much of the same information, but in a different way. By revealing the percentage of flow passed by a certain date, runoff timing is emphasized. Figure 23 shows flow the flow date curves for each of the selected watersheds.

Each stream starts with 0% of annual flow past on day of water year (DWY) 0, and concludes with 100% of flow passed on DWY 365. Every flow date curve is S-shaped to some extent. The flow date curves typically start gradually with relatively low slopes, then curve sharply upwards as high proportions of annual runoff are concentrated in a short period of time. As the spring peak is past and recession begins, the curves again flatten out, representing low discharges relative to the rest of the year. The curves for each stream clearly fall into one of two groups, one from the Wallowas (the uppermost group) and one from the northern Blue Mountains (the lowermost group). Flow date curves from the Wallowa streams show much more pronounced S-shapes, with flatter tails and steeper midsections.

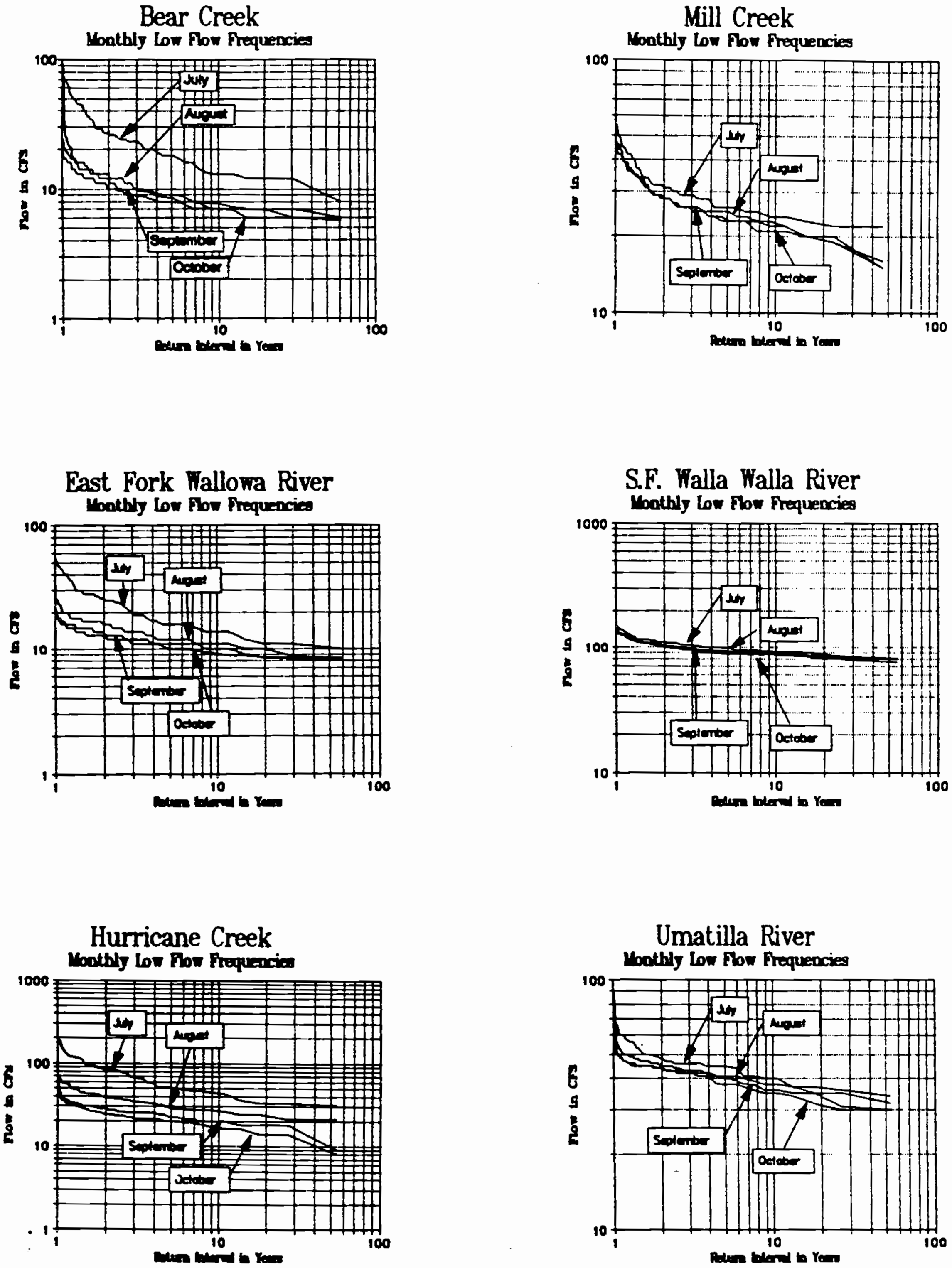


Figure 22 Monthly low flow frequency curves for selected streams.

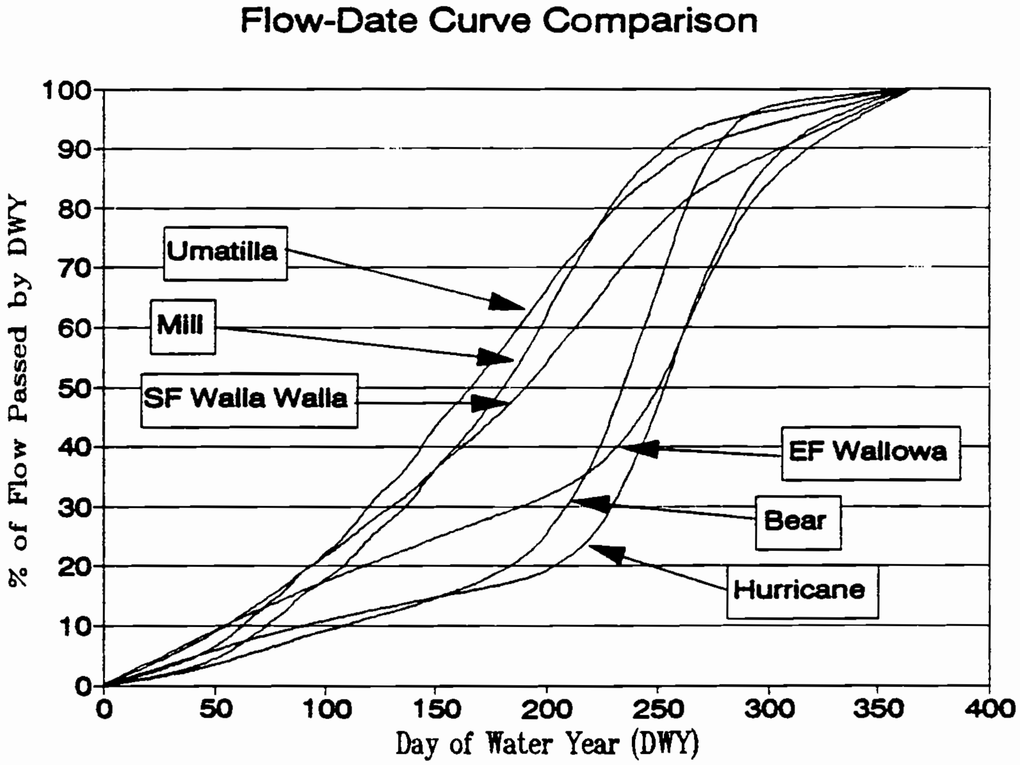


Figure 23 Flow date curves for selected streams.

In contrast, curves from the northern Blue mountains have relatively subdued S-shapes. This implies that greater proportions of the yearly total flow are passed in the spring runoff from the Wallowa streams that in the Blues. The flow date curves from the Blue mountain streams reflect rising autumn hydrographs not only by showing greater proportions of flow passed in autumn and winter, but also with lower proportions of flow passed during the melt peak in spring.

Flow date curves may be useful for determining precisely what proportion of flow has occurred by a given date as compared with the average from the period of record, but the same may be accomplished by comparing flows from a specific year with the average hydrograph. There is no way to tell what proportion of a given year's flow has passed by a specific date without knowledge of stream flow for the remainder of the year. Consequently, flow date curves appear to offer limited new utility in streamflow characteristic analysis other than to emphasize differences in runoff timing already evident in the average annual hydrograph.

FORECASTING/MODELING

Average annual streamflow recessions were extracted from the average annual hydrographs of each selected stream. The daily streamflow values for each recession were then plotted against streamflow on the following day, and simple linear regression was used to determine the best fit line through the resulting scatterplot. Synthetic average recessions (constructed as described in the Methods section) were then compared to the actual average recessions. Starting dates were adjusted on some of the recessions where the initial fit seemed poor. Table 2 summarizes the starting date, the slope and intercept of the regression relationships, and the disparity between the actual and synthetic recessions. The column headed "Last 7" shows the synthesized flow for the last week of the water year as a percent of the flows actually occurring during this period, while the column headed "R Vol" lists total recession volumes in the same manner.

Table 2 Recession relation summary.

Stream	Start	Slope	Intcpt	Last 7	R Vol
BEAR	275	0.943	0.359	45.5	103.6
EFWA	275	0.972	0.274	90.1	102.5
HURR	284	0.956	1.126	96.6	100.6
MILL	252	0.917	3.359	103.3	100.0
SFWW	251	0.950	6.008	96.7	100.4
UMAT	252	0.918	4.599	100.9	100.1

Later recession forecast starting dates for the Wallowa Mountains reflect the later peak flows from these high mountain watersheds. Earlier forecasts were possible on the Blue Mountain streams. Slopes appear similar; a T-test of equal means indicates that the slopes for the Wallowa and blue Mountain streams are not different at the 99% level. In contrast, the intercepts from the Blue mountain streams were found to be greater than those from the Wallowas, again at a significance level of 99%.

To determine how adequately the synthesized recessions emulate the actual average recessions, the synthesized values were tabulated as a percentage of the actual values. This was done for both the average flow during the last 7 days of the water year, and for the entire recession volume. Although several values are quite close to the ideal of 100%, there may be compensating errors as a recession is underestimated then overestimated at different points. Estimates of recession volume appeared to be more accurate than estimates of average flow for the last week of the water year. The synthesis was least accurate on Bear Creek in the Wallowas. Changing the date of application had little effect on the forecast error.

Despite the large error on the Bear Creek recession, the coefficients in Table 2 were accepted and recessions were synthesized for every year of record on each of the study watersheds. To maintain repeatability, each recession was synthesized on the same starting day as was determined for the average recession of a given stream. To evaluate how well the synthetic recessions emulated the actual recession, error was evaluated as the percent change in prediction accuracy from the average. The average flow for the last week of the water year and the average recession volume were considered as rudimentary forecasts, and the departure from the actual discharge was considered as error. Error in the synthesized recessions was also calculated as the difference from the actual discharge. These error terms were then combined to express the forecast's accuracy as the percentage in error reduction over using the average discharge values.

The synthesized recessions resulted in greatly improved forecasts of recession volumes on five of the study streams, and nominal improvement on SFWW. Forecasts of average discharge during the last week of the water year were improved nominally on three of the study streams (EFWA, HURR, and SFWW), and were actually worse than predicting the average on the other three. Table 3 summarizes the percent increase in prediction accuracy over the average for the mean flows during the last week of the water year and recession volumes on each of the selected watersheds.

Table 3
Percent increase in forecast accuracy over average

Stream	Last 7	R Vol
BEAR	-9.16	61.31
EFWA	4.66	46.76
HURR	14.58	66.17
MILL	-0.26	13.43
SFWW	2.95	44.19
UMAT	-51.49	33.23

Yearly forecast results over the period of record are displayed graphically in figure 24. Immediately obvious is the high degree of year-to-year variability in forecast accuracy in both the last week of the water year and in recession volumes. Improvement over the average is found in those years where the forecast error level is closer to zero. Clearly, this is not the case for most forecasts of the last week of the water year. Improvement over the average may be seen in the recession volume forecasts most clearly on Bear and Hurricane Creeks, where forecast deviations from the actual flow appear to be consistently less than for the average.

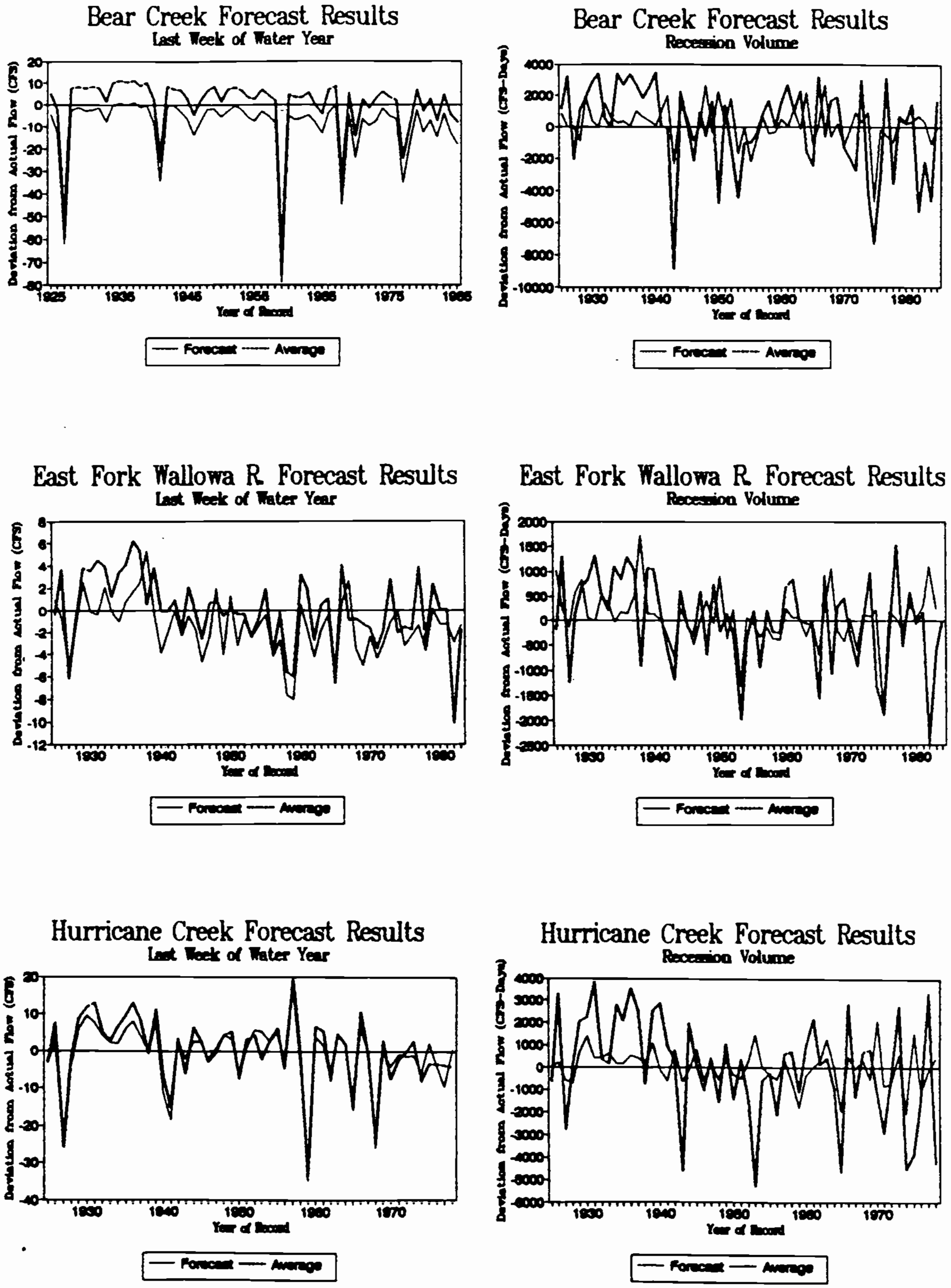


Figure 24a Forecast results for Wallowa Mountain streams.

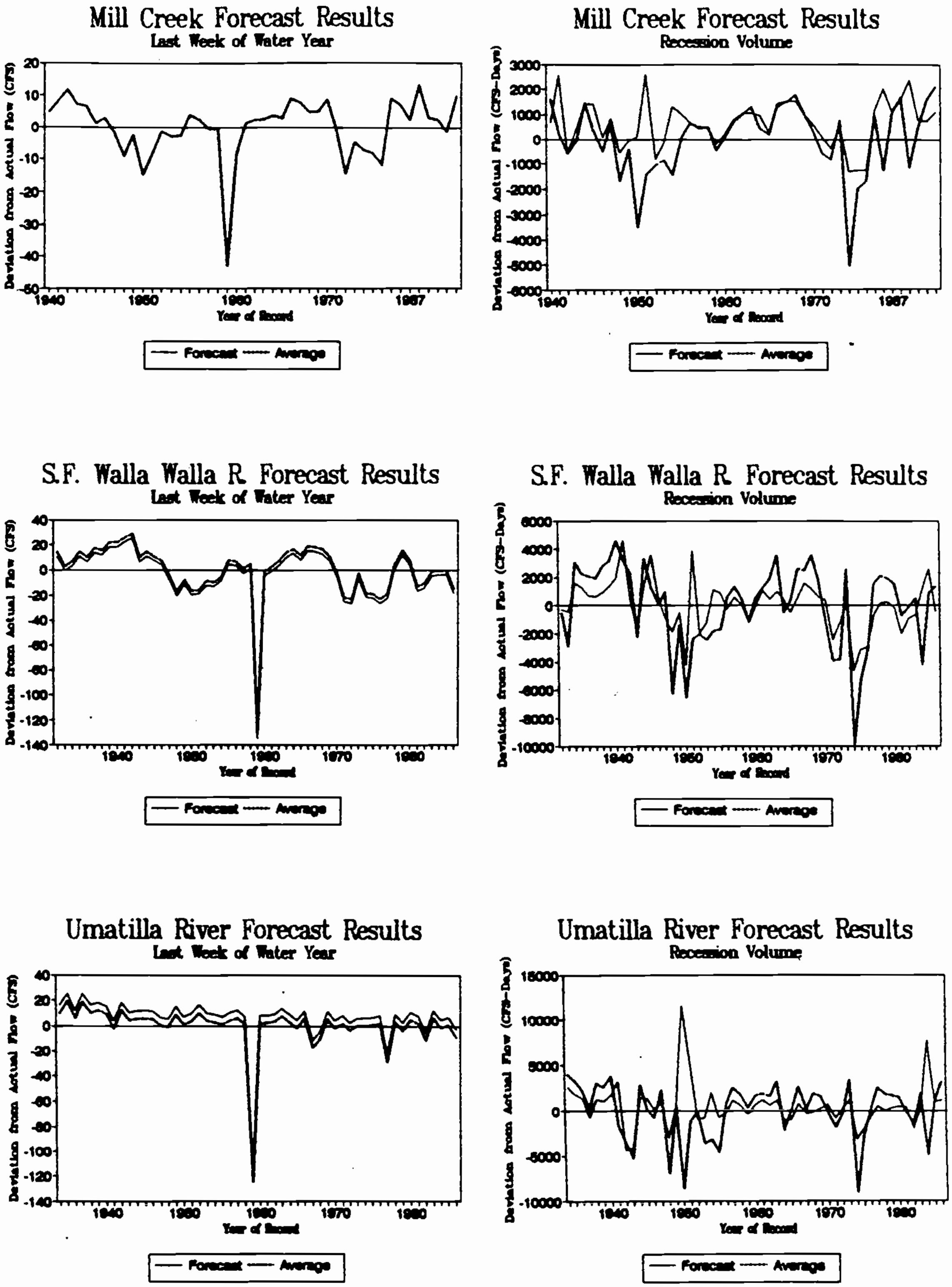


Figure 24b Forecast results for Blue Mountain streams.

SUMMARY AND CONCLUSIONS

This study has provided a general quantitative overview of the summer low and base flow characteristics of six forest streams in northeast Oregon using published streamflow data. Despite the influence of irrigation withdrawals on most daily gaged watersheds in the region, three streams from the Wallowa Mountains and three streams in the northern Blue Mountains were determined to have records adequate for analysis.

Trends and dependence in time series of low flow data were investigated. Trends of increasing low flows over the period of record were found on five of the six watersheds examined. Annual and summer low flows from the Wallowa streams were most often found to be independent from year-to-year, while flows from the northern Blue Mountain watersheds exhibited a high degree of year-to-year dependence.

Several indices of low flow were employed on each set of streamflow data for comparison purposes. Recession curves, duration curves, and frequency curves were constructed as per techniques found in the literature. Flow date curves were constructed by expanding on techniques also found in the literature.

Recession curves constructed from streamflow data found their chief utility in developing coefficients used in forecasting. Average recession curves also show the rate at which a given stream typically declines, and the level it attains after the steep portion of the recession.

Duration curves are useful for comparing the variability of low flows between streams. The ratio of flows exceeded 95% and 50% of the time provided an index of low flow potential. Bear Creek had the lowest ratio (0.23) and the lowest potential for sustained high levels of low flow compared with the 50% flows. The East Fork of the Wallowa and South Fork of the Walla Walla had the highest duration curve ratios (0.66 each) and highest relative low flow potential.

Frequency curves constructed with monthly and 7- and 30-day low flow values were found to be of limited utility on the Blue Mountain watersheds because the probabilistic interpretation of low flow frequency curves is only strictly valid when low flows are independent of one another. Also, it is difficult to compare low flows of a given frequency between watersheds because low flows may correspond poorly to watershed area. Low flow frequency curves may provide information useful for estimating return intervals on individual watersheds with adequate streamflow records. Monthly low flow frequency curves may be used when annual low flows (represented by the 7- and 30-day frequencies) do not coincide with the period of interest.

Flow date curves were developed as an expansion of Court's (1962) concept of half flow date. Flow date curves show the proportion of water passed by a given date in the water year, and show clearly the differences in runoff timing generally found between the Wallowa and Blue Mountain streams.

A simple method of forecasting seasonal streamflow recessions was developed by modifying a method described by Rigg's (1985), albeit with limited success. Forecasts of streamflow levels for the last week of the water year typically had greater error than simply predicting the average flow, although a 14.6% decrease in error was found on Hurricane Creek. Forecasts of streamflow levels for the last week of the water year were least accurate on the Umatilla River, increasing error over the average by 51.5%. Forecasts of recession volume using the prediction equations were substantially better, resulting in improvements in accuracy over predicting the average volume ranging from 13.4% on Mill Creek to 66.5% percent on Hurricane Creek.

It is not clear whether the recession equations developed for each of the selected streams are applicable to other streams. Likewise, because the coefficients were not found to be significantly different from each other, it is impossible at this time to specify regional coefficients for a recession equation applicable to the Blue or Wallowa

Mountains. However, the constants in the recession equations from the Blue and Wallowa Mountains were found to be significantly different. This probably represents a regional distinction in recession characteristics. Analysis of a larger number of streams (with shorter records) might show that regional relationships could be developed.

All of the objectives stated in the introduction have been attained, to varying degrees of success. Trends and year-to-year dependence were identified where they existed in the published streamflow data. Low flow characteristics for each of the selected streams were described quantitatively with various flows indices. For each year of record on the selected watersheds, forecasts of recession volume and flow level at the end of the water year were made using the streamflow records. These forecasts may be used as a first approximation of streamflow recessions in the absence of additional information.

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