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Hydrologic effects of logging in western Washington, United States

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Abstract. Possible changes in streamflow associated with logging were analyzed for 23 western Washington catchments with drainage areas from 14 to 1600 km^2. Statistically significant trends in annual streamflow minima, uncorrected for climatic influences, are all decreasing and are apparently dominated by a regional climate signal associated with the Pacific Decadal Oscillation, rather than land cover change. Using paired catchment analysis, the number of statistically significant trends detected for the peak flow series is largely within the range of statistical noise. Only in the case of the annual minima were more trends detected than could be attributed to chance, owing in part to the lower relative variability, hence greater detectability of trends in low flows. Investigation of the effect of return period on peak flow changes shows an apparent increase in flood peaks for treatment relative to control catchments, the mean magnitude of which decreases with increasing return interval up to about the 10-year return period. In large part, owing to the small number of catchment pairs available, this analysis cannot be considered conclusive. An alternative approach to evaluating trends in peak flows based on time series residuals of observed flows from hydrology model predictions detected increasing trends in peak flow series, which were largely absent in the paired catchment analysis. This is attributed both to the ability of the model, which acts as the control, to filter out natural variability and to a larger trend "signal" in the residuals analysis resulting from the ability of the method to fix the vegetation condition in the model control.

1. Introduction

In the mountainous areas of the northwestern United States, what amounts to a large-scale land use experiment has taken place in the last half-century. The "experiment" has been to remove much of the old growth, primarily coniferous, forest by clear-cut logging and to replace it with younger stands of more uniform age and reduced species diversity. There is a perception that this land cover change has resulted in increased frequency and severity of flooding in the watersheds of the western Cascades, especially during rain-on-snow events, which occur when warm fronts follow periods of cool, wet weather, usually in late fall and early winter. *Anderson and Hobba* [1959] argued that the size of peak flows in western Oregon had been increased by logging, but the issue was not addressed in much detail until the work of Harr in the 1980s [see, e.g., *Christner and Harr*, 1982; *Harr*, 1981, 1986; *Berris and Harr*, 1987]. Plot-scale work has demonstrated that removal of the forest canopy can cause substantial increases in both snow accumulation before rain-on-snow events and snowmelt during these events [*Beaudry and Golding*, 1983; *Berris and Harr*, 1987; *Coffin and Harr*, 1992; *Storck et al.*, 1999]. Greater accumulations of snow in cleared areas prior to rain-on-snow events are a consequence of the absence of ablation of snow that otherwise would have been intercepted by the canopy and removed prior to onset of the melt event. Increased snowmelt rates during rain-on-snow events are expected owing to enhanced latent and sensible heat transfer in harvested areas, which results from increased surface wind [*Berris and Harr*, 1987; *Harr*, 1981, 1986; *Kattelman*, 1990; *Storck et al.*, 1999].

While these mechanisms have been demonstrated conclusively at the plot scale, retrospective evaluations at the catchment scale have produced conflicting results. The most consistently detected response to forest harvest has been an increase in summer and annual water yield due to a decrease in evapotranspiration [*Keppeler and Ziemer*, 1990; *Rothacher*, 1965, 1970; *Harr et al.*, 1982; *Harris*, 1977]. Retrospective studies have found the effect of logging on peak flows to be less pervasive. Several studies [*Harr et al.*, 1975; *Harris*, 1977; *Jones and Grant*, 1996; *Wright et al.*, 1990] have found increases in total storm runoff volumes attributable to logging. However, increases in peak flows are often only detected for storms with intermediate intensity and volume, especially early in the fall [*Harr et al.*, 1975; *Ziemer*, 1981]. In a reanalysis of western Oregon streams, *Harr* [1986] found an increase in peak flows associated with snowmelt following logging, with the greatest changes in moderate-sized flows. No significant changes were detected in flows resulting from rainfall alone [*Harr and McCorison*, 1979]. In western Oregon paired catchments, *Jones and Grant* [1996] observed increased average peak discharges of up to 46% following 100% clear cutting in small catchments (0.6–1.0 km^2) [*Jones and Grant*, 2000]. In large catchments (60–600 km^2), they found increases in the 1-year return interval flow of the order of 10–30% per 5% difference in basin area cut. However, *Thomas and Megahan* [1998] have argued that these results overstate the percent increase for small catchments due to the inclusion of small peak flows with return intervals as low as 0.4 years. In a reanalysis of the Jones and Grant data, *Thomas and Megahan* [1998] found increases in peak flows between 5 and 25% for return intervals greater than 2 years in the small basins. Their reanalysis of the Jones and Grant data did corroborate the significance of differences in

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harvested area as a predictor variable for two of the three large-basin pairs. However, they concluded that the statistical model has insufficient predictive power to estimate the effects of timber harvesting on peak discharges [*Thomas and Megahan*, 1998, 2000].

Other studies have found no trend in peak flows following clear cut or patch cut logging [*Rothacher*, 1965; *Harr et al.*, 1982]. The conflicting results are understandable at the catchment scale because changes in storm response are dependent on antecedent soil moisture and snowpack, precipitation, and temperature during specific storms and their spatial variations within a catchment. For instance, at the onset of some storms, there is little or no snow at low elevations, so changes in land cover only minimally affect the response of the low-elevation part of the basin. Likewise, little contribution to storm runoff is expected from high elevations above the snow line. For these reasons, the signature of land cover change is thought to be most evident within the so-called transient snow zone, usually taken to range from 300 to 900 m elevation in western Washington, within which snow cover is ephemeral throughout the winter.

Detection of peak flow increases due to vegetation removal is further complicated by the effects of forest roads, which can effectively short circuit the natural drainage network. It is difficult to segregate the effect of forest roads in catchment-scale studies because road construction often accompanies logging. Some studies have found statistically significant increases in peak flows associated with forest roads [*Harr et al.*, 1975; *Jones and Grant*, 1996; *King and Tennyson*, 1984]. *Bowling and Lettenmaier* [2000] and *LaMarche and Lettenmaier* [1998] have found that forest roads and vegetation removal effects on peak flows are of similar magnitude. Several studies have suggested that forest roads interact with logging to increase runoff through increased soil water (i.e., increase in the water table following logging) which is then available for interception by road cuts [*Megahan*, 1983; *Jones and Grant*, 1996; *Wemple*, 1998; *Wright et al.*, 1990; *Keppeler and Ziemer*, 1990; *Ziemer*, 1981]. However, peak flow decreases have also been found, depending on road position with respect to drainage and harvest areas [*King and Tennyson*, 1984].

From a statistical standpoint, retrospective assessment of the effects of logging and road construction on streamflow is a classical trend detection problem. The "noise" from which the signal must be extracted results from variability in storm characteristics and antecedent conditions, both spatially, in the case of paired catchments, and temporally, over the period of analysis. Temporal variability in storm characteristics may include errors in measurement, as well as the influence of long-term climate variability. One approach to filtering out the resulting noise associated with climate variability is to perform paired catchment analyses. That is, if hydrologically similar catchments can be identified that have had different logging histories, then analysis of the difference series should filter out the common effects of climate variations. An alternative is to analyze the residuals of observed flood peaks from those predicted using a continuous model simulation of streamflow in which the vegetation condition is fixed. The rationale is that both the model and the natural system are driven by a similar sequence of meteorological events, hence the residual series should filter out any systematic effects, as does the paired catchment approach. The model residuals approach also should avoid the effects of spatial variability between paired catchments. However, it introduces a new source of variability in the model error. If model error is small enough, we will show that this approach offers the potential for greater trend detectability than does the paired catchment approach.

The objective of this study, then, is to determine (1) the extent to which changes in streamflow have occurred in western Washington forested catchments over the last 66 years and (2) the extent to which the changes can be explained by forest harvest and road construction. Three approaches are employed: analysis of individual catchments, paired catchments, and model residuals analysis.

2. Basin Selection

2.1. Approach

A population of 23 forested catchments in western Washington was identified for analysis by screening U.S. Geological Survey (USGS) stream gauge records for completeness, length of record, and the absence of upstream regulation and diversions (Figure 1). The USGS gauge identification numbers and basin names are listed in Table 3. The gauges can be considered accurate to within 10%. The basins were segregated based on record length into three categories: 1930–1996 (8), 1945–1996 (7), and 1960–1996 (8). Statistical trend analysis using the nonparametric Mann-Kendall test was performed on five data series (where possible) for each of the 23 basins. The historical annual maximum series (AMS) and the instantaneous peaks-over-threshold (POT) series were constructed by the USGS. The AMS is composed of the largest instantaneous discharge recorded per year. The instantaneous POT series is composed of the maximum instantaneous discharge for each storm that exceeds an established base discharge. The base discharge is determined by the USGS for each gauge location. However, the USGS base discharge frequently is changed over time, so the instantaneous POT series was filtered, through the use of a standard baseline for each gauge, to create a series that contained, on average, three to four storms per year for the period of analysis. The mean annual flow (MAF) and annual minimum and daily POT series were constructed from the mean daily discharge time series published by the USGS. The daily POT series was created by selecting all daily flows that exceeded a baseline chosen to yield three to four storms per year, on average. To avoid including multiple peaks for the same flood event, only peaks separated by more than 2 days were included. The annual minimum series was calculated as the minimum daily flow for each water year (October 1 through September 30).

Following the preliminary Mann-Kendall analysis, two techniques were used to account for the influence of climate trends: paired catchment analysis and analysis of model residuals. Initially, 62 catchment pairs were selected for trend analysis from the 23 basins, based primarily on basin location. A complication occurs in creating the difference series because not all of the specific flood events that are included in the AMS and POT series will be the same for both basins, and differencing of floods not caused by the same storm makes little sense. As shown in Figure 2, the distance between catchment centroids is one of the primary factors controlling the coincidence of peak flows. Peak flows that did not occur in both catchments within a specified difference in time of occurrence were excluded from the series for analysis. The threshold time of occurrence differences were 2 days for the daily POT series, 1 day for the instantaneous POT series, and 7 days for the AMS. Only catchment pairs with greater than 60% of peak flows occurring in both catchments within these time limits, for

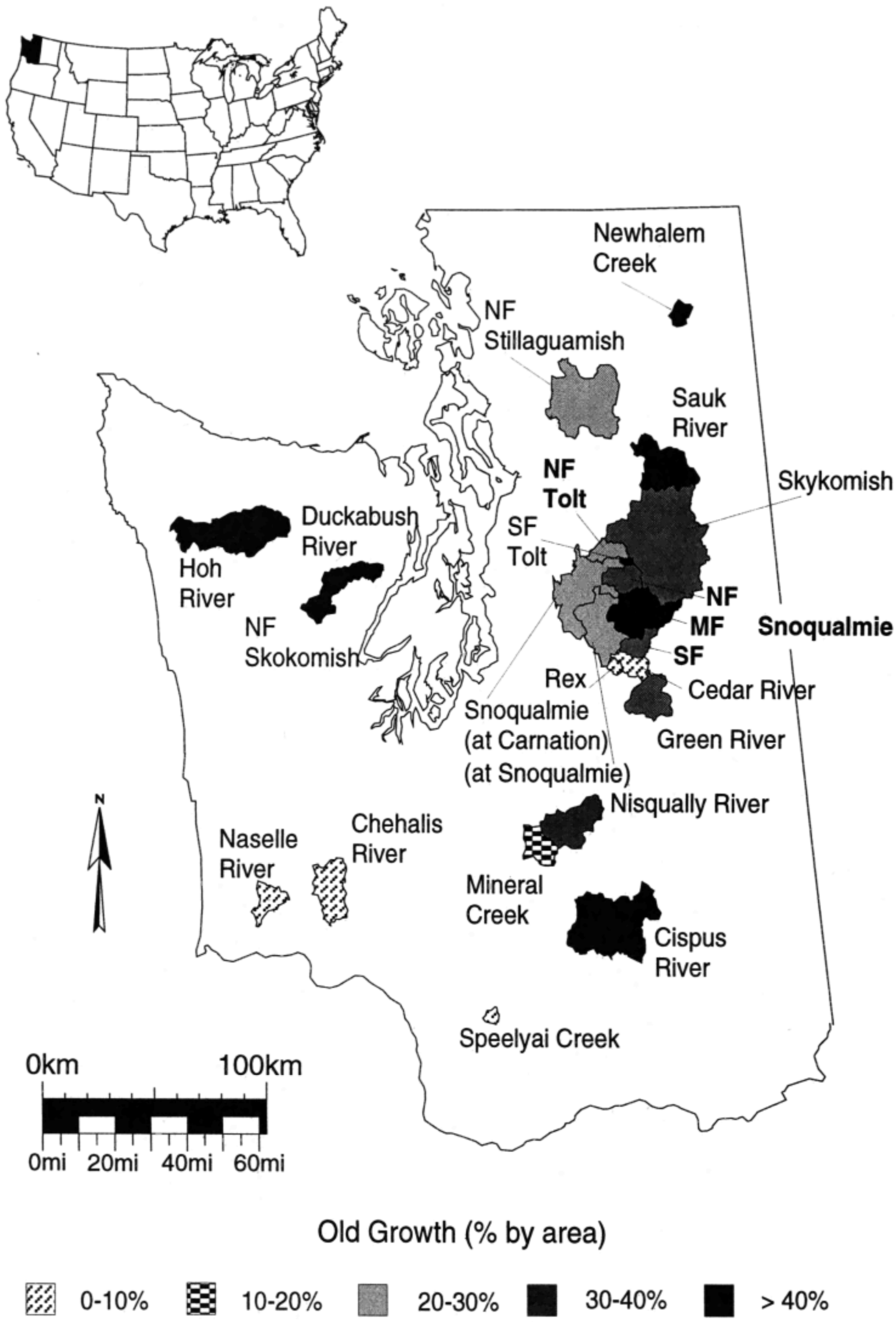

Figure 1. Location of the 23 forested catchments in western Washington analyzed for trend. Shading represents the percent of basin area with old growth forests (greater than 100 years old). Basin names in bold font correspond with basins in Figure 3.

all three peak flow series, were included in the paired catchment analysis. Twenty-two of the identified basin pairs were discarded for this reason. The average percentage of events occurring within the threshold time range for the remaining 40 basin pairs was 70.6 for the AMS, 75.0 for the instantaneous POT, and 75.2 for the daily POT. The annual minimum and MAF series were matched by water year, and no time of occurrence criterion was applied.

Analysis of model residuals was limited to three catchments for which detailed topographic, soil, and vegetation data were readily available along with representative high-elevation me-

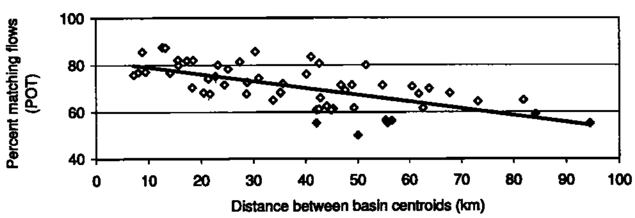

Figure 2. The percentage of paired basin instantaneous POT which occur within one day of each other versus the distance between basin centroids. Filled points represent basin pairs that were excluded from further analysis.

Table 1. GAP 1991 Classified Landsat TM Land Cover Data Set

Primary Attributes	Secondary Attributes	Tertiary Attributes
Bare ground	General type	Form
Developed	Level of development	Type of development
Agriculture	Irrigation status	Crop type
Open Water	Level of salinity	Water body type
Wetlands, riparian	Water flow type	Vegetation physiognomy
Nonforested	Seral stage or disturbance status	Vegetation physiognomy
Hardwood forest	Seral stage	Canopy closure
Mixed hardwood/conifer	Seral stage	Canopy closure
Conifer forest	Seral stage	Canopy closure

teorological data necessary to drive the physically based hydrologic simulation model. These included the Snoqualmie River at Carnation, Washington (1561 km^2; see Figure 1), and two of its headwater tributaries.

2.2. Forest Harvest History

The development of simple, objective procedures to classify harvest history differences is important for identification of discharge trends related to forest harvest. The land ownership for the 23 catchments in this analysis includes federal and state forests, as well as privately held and tribal lands. Even if detailed records of forest stands could be obtained from all of the owners, differences in record keeping might well render them incompatible. To avoid these problems a satellite-derived land use classification was used. The relative maturity of each of the identified basins was estimated using classified Landsat thematic mapper (TM) land cover data sets from the national Gap Analysis Program (GAP) [*Scott et al.*, 1993]. GAP analysis is a method of identifying conservation "gaps" in the existing network of conservation lands through mapping of natural vegetation and native species. GAP data are produced as state-level projects coordinated by the U.S. Geological Survey. As part of the GAP analysis, Washington State land cover was classified into 1 of 9 primary, 28 secondary, and 35 tertiary attributes using spectral cluster analysis of Landsat TM images from 1991. In the product produced by *Scott et al.* [1993], clusters with a minimum area of 100 ha were manually delineated, and the final product includes classification codes for the major (greatest surface area) and minor (second greatest surface area) land cover within each polygon, although relative percentages are not provided. The GAP attributes are listed in Table 1.

The qualitative GAP classifications were associated with forest stand ages using year of origin data for four subcatchments of the Snoqualmie River watershed. Dates of stand origin for the North Fork Snoqualmie, the Middle Fork Snoqualmie, the South Fork Snoqualmie, and the North Fork Tolt were provided by the Weyerhaeuser Co., the Washington Department of Natural Resources, and the U.S. Forest Service and were originally compiled by B. A. Connelly et al. (unpublished data, 1993). For two of the subcatchments, the Middle Fork Snoqualmie and the North Fork Tolt, histograms were created of the years of origin coinciding with each GAP classification code. In this manner, a range of years of harvest could be associated with each GAP code. The relationship was evaluated by comparing total land areas in various age ranges from the GAP analysis with the year of origin data for all four subcatchments (Table 2; see Figure 3 for a spatial comparison). Examination of the histograms suggested that the GAP major and minor land types cover ~60 and 40% of the individual polygons, on average, although the relationship varies for each polygon. The 60/40 distribution was found to result in the best match of age inferences, from the GAP and year of origin data, as reported in Table 2.

Table 2 and Figure 3 confirm that this approach is able to identify forests in the late and midseral stages (3.5 and 4.5% average absolute difference in identified area). However, the classification error increases with decreasing stand age. This is partially a reflection of the large fraction of land area that falls into the "other" category for the year of origin data. The other category for the GAP data includes areas classified as water, wetlands, and bare ground, as well as a nonforested classification determined to be high-altitude meadows. Unclassified year of origin data represent land areas that cannot be commercially planted such as water, bare rock, and meadows, as well as areas of mixed or unknown ownership. Therefore the unclassified category fraction tends to be much higher for the year of origin data, and an exact match is not possible. Both classification schemes show that the Middle Fork Snoqualmie

Table 2. Comparison of Vegetation Indices for the Snoqualmie River Watershed

Catchment Name	GAP data <1900, %	1900–1950, %	1950–1970, %	1970–1990, %	Other/Unclassified[1]
North Fork Tolt	22.1	18.8	24.7	29.1	5.4
North Fork Snoq.	38.8	13.4	22.7	19.2	6.0
Middle Fork Snoq.	49.9	10.1	11.2	5.5	23.3
South Fork Snoq.	38.5	10.5	12.7	19.0	19.3
			Year of Origin Data		
North Fork Tolt	22.7	22.5	32.5	13.7	8.6
North Fork Snoq.	41.3	5.0	20.6	7.7	25.5
Middle Fork Snoq.	41.8	15.3	2.7	3.3	36.8
South Fork Snoq.	35.6	11.2	8.0	14.0	31.2
Average Absolute Difference	3.5	4.5	5.8	8.5	12.0

[1]No year of origin provided in the B. A. Connelly et al. (unpublished data, 1993) data; from visual examination this category includes areas of private land ownership and areas not available for commercial harvest such as riparian and high-altitude meadows. This category may also include some recent clear cuts which have not been replanted.

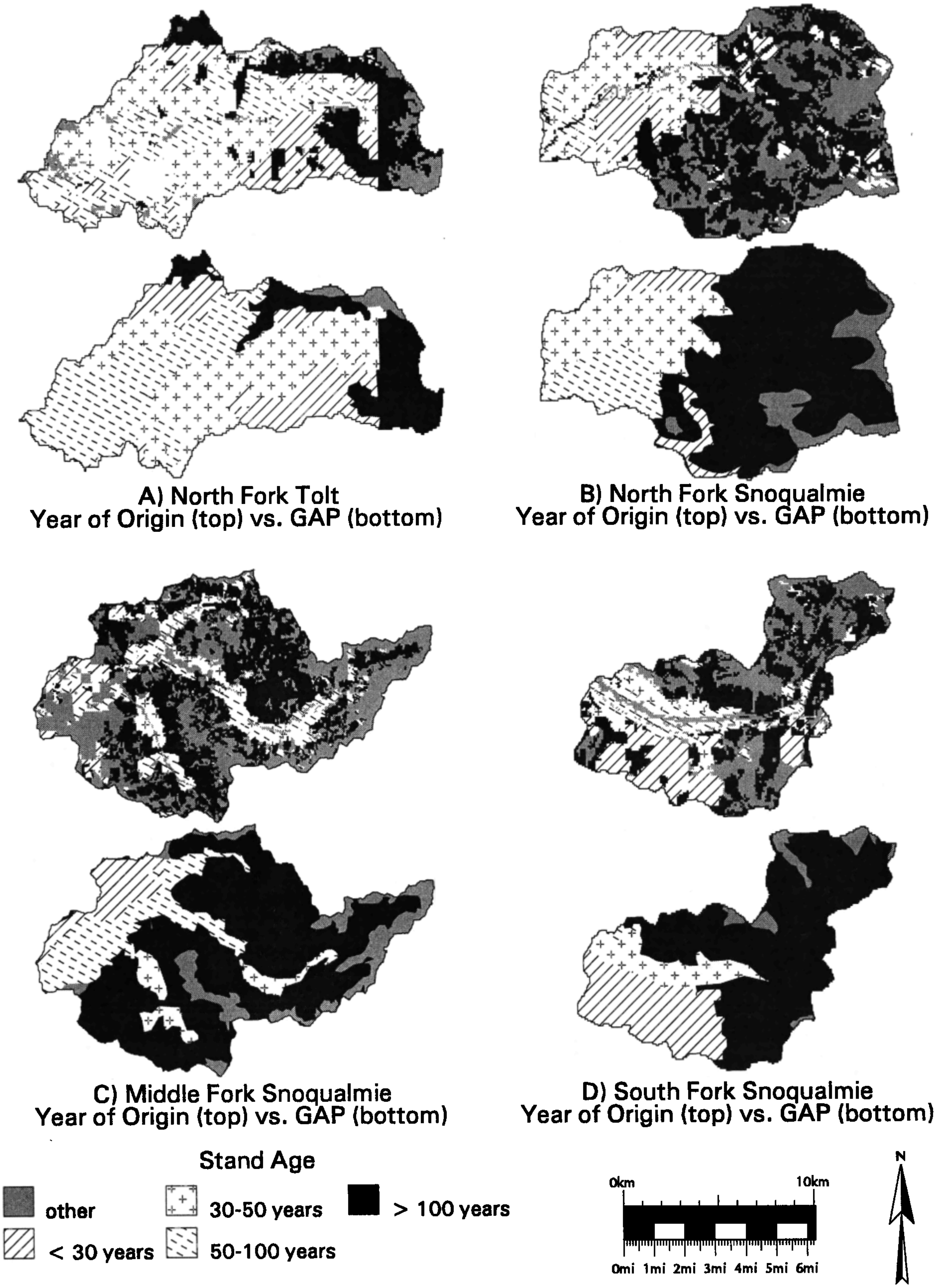

Figure 3. Spatial comparison of forest age classification via (bottom) GAP 1991 classified Landsat TM landcover data set and (top) year of origin of data. (a) North Fork Tolt, (b) North Fork Snoqualmie, (c) Middle Fork Snoqualmie, and (d) South Fork Snoqualmie. Basin names in bold in Figure 1 correspond with basins here.

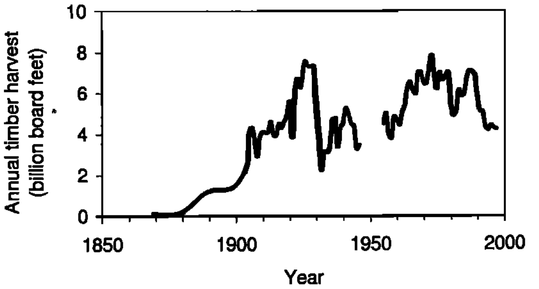

Figure 4. Annual timber harvest (lumber production) in Washington State (1869–1997). Sources are as follows: *Austin* [1970], *Hamilton* [1965], *Ruderman* [1980], *Steer* [1948], and *Warren* [1990, 1998].

has both the most mature and the least immature vegetation. The reverse is true for the North Fork Tolt. Therefore we concluded that the 1991 GAP land cover classification could serve as a coarse diagnostic tool for explanation of potential discharge trends.

Time histories of harvest since 1900 were constructed for each of the catchments using the relationship between GAP classifications and the year of origin data. Where GAP codes had been assigned years of origin spanning more than one decade, the rate of harvest was assumed to mirror the rate of harvest in all of Washington for that decade (see Figure 4). For example, harvest of GAP code "870" (mixed forest, midseral, mixed closure) was identified for the period 1920 and 1940, so it was assumed that 63% of the area was harvested in the 1920s and 37% was harvested in the 1930s. Harvest rate was assumed uniform within the decade. Because Landsat TM images were taken in 1991, no stands could be assigned years of origin after 1990. Although this classification neglects harvest since 1991, rates of harvest have been reduced in Washington since the late 1980s (relative to the 1970s and 1980s, see Figure 4), so this source of error in our analysis is probably minor.

The constructed time histories of stands less than 20 years old for the Snoqualmie catchments are shown in Figure 5, along with the time series derived from the year of origin data. Figure 5 confirms that the constructed harvest histories are able to approximate reasonably the progression of immature stands as indicated by the year of origin data. The greatest error is in the North Fork Snoqualmie, which shows an upward bias.

Although the time history of immature stands is valuable for visual comparison of contrasts in harvest history, it is useful to reduce the time history to a single measure of harvest quantity for comparison with trend results. For the single catchments, the Kendall slope estimate of trend magnitude was computed as [*Hirsch et al.*, 1982]:

$$\beta = \text{median}\left\{\frac{(h_i - h_j)}{(i - j)}\right\}, \qquad (1)$$

where h_i and h_j are the percent of basin area with immature vegetation (vegetation less than 20 years old) in years i and j, and i is always less than j. β is an index of the change in percent area covered by immature vegetation per year. The area of immature vegetation is used in this statistic in order to account explicitly for the recovery of vegetation over time. In using this statistic we assume that observable changes in streamflow response will mainly be due to the presence of very young vegetation. The trend in immature vegetation should be a more powerful predictor of streamflow changes than a statistic based on cumulative harvest which does not allow for recovery. β is resistant to the effects of extreme values in the data. That is, catchments with an abrupt change in harvest near the beginning or end of the record will have a much lower estimate of trend (in absolute value) using the Kendall slope estimator than would be inferred from, for example, a least squares estimator. This means that the Kendall slope estimator will not be as greatly effected by the coarseness in age resolution of the constructed harvest histories. The derived harvest histories tend to smooth both the high- and low-extreme slopes, but the median of the slopes are preserved. The results of the Kendall slope estimate of harvest time histories constructed from GAP data are listed in Table 3.

The contrast in harvest histories for catchment pairs was calculated as the root mean square difference in immature area:

$$\text{RMS} = \sqrt{\sum_t \frac{(h_{jt} - h_{kt})^2}{n}}, \qquad (2)$$

where h_{jt} and h_{kt} are the areas of basin j and k, respectively; in immature stands at time t and n is the length of the record being analyzed. Explicit representation of the recovery of vegetation over time is of greater importance in the case of the paired catchments. Two catchments with equal total harvest fractions over a 50-year time period may have very different hydrologic signatures due to the timing of harvest. By summing our measure of contrast of immature area over time, the RMS statistic is able to capture differences in timing. All catchment pairs with RMS < 5% were excluded from the trend analysis. The coarseness of the derived vegetation history will tend to reduce the RMS of catchment pairs, so this criterion ensures that all basins analyzed experienced a moderate to high level of harvest contrast. Eight of the 40 basin pairs that met the criteria for matching flows were excluded for all time periods on this basis; another four basin pairs were excluded for one or two time periods. The coarseness of the derived vegetation history tends to reduce the RMS of catchment pairs, making this a more conservative criteria.

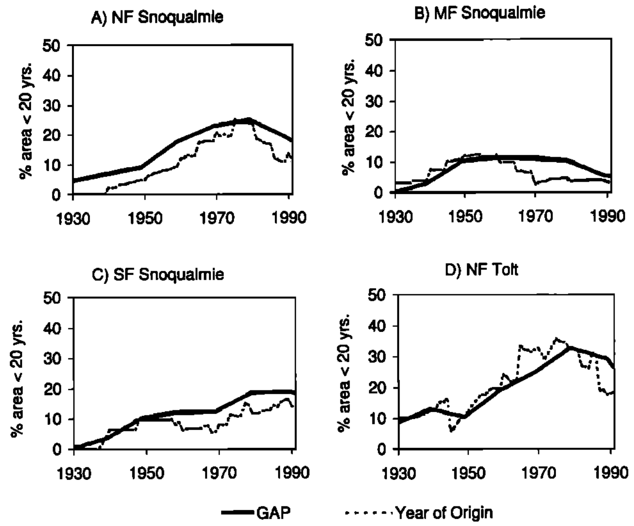

Figure 5. Time series comparison of area in immature forest using the GAP 1991 Classified Landsat TM land cover and year of origin data: (a) NF Snoqualmie, (b) MF Snoqualmie, (c) SF Snoqualmie, and (d) NF Tolt.

2.3. Forest Roads

As indicated above, forest roads affect the runoff response of forested catchments by effectively short-circuiting the natural drainage network through interception of subsurface flow by the road cutslope. However, the extent to which this occurs is dependent on many factors, including the characteristics of individual storms, road geometry and position, and soil properties [*Bowling and Lettenmaier*, 2000]. As an indicator of the degree to which catchment runoff response may be affected by roads, the total length and density of roads in each catchment were computed using digital Topologically Integrated Geographic Encoding and Referencing (TIGER) map data from the U.S. Bureau of Census, as summarized in Table 4. Such general measures cannot account for the time history of road construction or for the fact that only a fraction of the roads will be hydrologically connected to the drainage network [*Bowling and Lettenmaier*, 2000; *Wemple et al.*, 1996; *Rothacher*, 1973]. Recent research in Washington and Oregon roaded catchments has found that between 34 and 75% (mean of 53%) of road runoff drains to a stream [*Bilby et al.*, 1989; *Bowling and Lettenmaier*, 2000; *Reid and Dunne*, 1984; *Wemple et al.*, 1996]. In addition, the values in Table 4 likely underrepresent the extent of the true road network. However, the total length of roads does serve as an index of the degree of runoff pathway change possible due to roads. As shown in Figure 6, the total road density in the selected catchments increases in proportion to the cumulative area harvested. It may take several years for the road network to become integrated with the stream network. However, the hydrologic effects of the roads may persist indefinitely, or at least for much longer than the cutting units themselves. Therefore, in the years following harvest, it is less essential that the indicator statistic for roads reflect the time rate of change of road construction, and the total road density can be used as an indicator variable for evaluation of streamflow changes.

Table 3. Trend in Immature Forest Area[a]

Basin Name/ Gauge ID	Change in Immature Area, % yr^{-1}		
	1930–1991	1945–1991	1960–1991
Cedar River 12115000 (CED)	0.23	0.12	0.83
Chehalis River 12020000 (CHE)	0.24	0.17	0.04
Cispus River 14232500 (CIS)	0.28	0.68	1.32
Duckabush R. 12054000 (DUC)	−0.05	−0.06	−0.07
Green River 12104500 (GRE)	0.17	0.25	0.96
Hoh River 12041200 (HOH)	0.12	0.11	0.23
MF Snoqualmie 12141300 (MSN)	0.09	−0.05	−0.16
Mineral Creek 12083000 (MIN)	0.22	0.22	0.23
Naselle River 12010000 (NAS)	−0.01	−0.41	−0.08
Newhalem Creek 12178100 (NEW)	0.0	0.0	0.0
Nisqually River 12082500 (NIS)	0.14	0.14	0.45
NF Skokomish 12056500 (NSK)	0.04	0.10	0.20
NF Snoqualmie 12142000 (NSN)	0.39	0.38	0.14
NF Stillaguamish 12167000 (NST)	0.15	0.10	0.29
NF Tolt River 12147500 (NFT)	0.45	0.59	0.54
Rex River 12115500 (REX)	0.13	−0.03	0.91
Sauk River 12186000 (SAU)	0.14	0.16	0.09
Skykomish 12134500 (SKY)	0.31	0.43	0.29
Snoqualmie (C) 12149000 (SNOC)	0.19	0.08	0.11
Snoqualmie (S) 12144500 (SNOS)	0.14	0.03	0.08
SF Snoqualmie 12143400 (SSN)	0.31	0.24	0.28
SF Tolt 12147600 (SFT)	0.37	0.52	0.36
Speelyai Creek 14219800 (SPE)	−0.23	−0.29	−0.40

[a]Trees less than 20 years old: Derived from the GAP 1991 Landsat TM landcover classification data set.

Table 4. Road Length and Road Density[a]

Basin Name	Basin Code	Basin Area, km^2	Road Length, km	Road Density, km km^{-2}
Cedar River	CED	105.4	165.2	1.6
Chehalis River	CHE	292.7	654.4	2.2
Cispus River	CIS	831.4	653.4	0.8
Duckabush R.	DUC	172.2	31.9	0.1
Green River	GRE	249.2	341.3	1.4
Hoh River	HOH	655.3	98.1	0.2
MF Snoqualmie	MSN	398.9	93.1	0.2
Mineral Creek	MIN	194.8	270.5	1.4
Naselle River	NAS	141.9	184.1	1.3
Newhalem Creek	NEW	72.3	6.9	0.1
Nisqually River	NIS	344.5	379.0	1.1
NF Skokomish	NSK	148.1	13.4	0.1
NF Snoqualmie	NSN	165.8	131.4	0.8
NF Stillaguamish	NST	678.6	766.5	1.1
NF Tolt River	NFT	103.0	156.0	1.5
Rex River	REX	34.7	65.6	1.9
Sauk River	SAU	393.7	118.4	0.3
Skykomish	SKY	1385.6	837.6	0.6
Snoqualmie (Carn.)	SNOC	1561.1	1905.9	1.2
Snoqualmie (Snoq.)	SNOS	971.2	1122.4	1.2
SF Snoqualmie	SSN	107.7	118.1	1.1
SF Tolt	SFT	13.8	9.9	0.7
Speelyai Creek	SPE	32.6	47.2	1.4

[a]U.S. Bureau of the Census TIGER/Line 1995 Data.

3. Univariate Trend Analysis

The Kendall slope estimate of harvest rate per year is plotted against the same estimate for the AMS and annual minimum time series, normalized by the time series mean, in Figures 7a and 7b, respectively. In nearly all cases, the AMS show increases in discharge over the period of record for all levels of harvest. The POT series showed similar characteristics. There is no clear relationship between the degree of change in the peak flows and the level of harvest. In contrast, the slope estimates of the annual minimum series shows a preponderance of negative trends for all levels of forest harvest, as evidenced by the number of points falling below the zero line. The MAF series also showed negative trends.

The Mann-Kendall test was used to test for monotonic trends in the discharge series with respect to time. Kendall's S statistic is calculated as

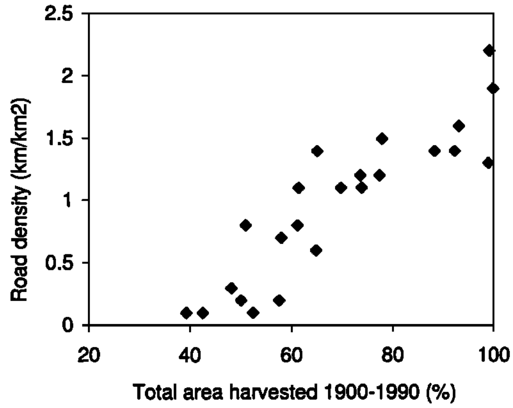

Figure 6. Cumulative percent of basin area harvested (1900–1990) versus road density (1995) for 23 western Washington basins.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i), \quad (3)$$

where $\operatorname{sgn}(x_j - x_i) = 1$ for $x_j > x_i$, -1 for $x_j < x_i$, and 0 for $x_i = x_j$. The null hypothesis of no change is rejected when S is significantly different from zero. Although the Mann-Kendall test requires no distributional assumption, it does assume homoscedasticity [*Helsel and Hirsch*, 1992]. Homoscedasticity was confirmed for all time series for all basins and basin pair difference series by visual analysis using locally weighted scatterplot smoothing (LOWESS), a method of generating a smoothed curve which uses least squares to apply progressively stronger weights to the closest observations. A smoothed curve was first fit to the discharge time series. The residuals of the smoothing were plotted separately and again smoothed to verify that there was no trend in variance. None of the time series was discarded due to trends in variance.

The statistical significance of the trend analysis for the 1960–1996, 1945–1996, and 1930–1996 periods is shown in Figures 8, 9, and 10, respectively. The results for the daily POT series are not shown in these figures; they tend to be similar to results for the instantaneous POT. For the shortest record length, significantly increasing trends were detected in AMS for three basins and two of these also had trends in the instantaneous and daily POT series. Ten other basins had statistically significant increasing trends in either the daily or instantaneous POT series. No statistically significant trends were found for the MAF series. As shown in Figure 11a, these trends in peak flow (instantaneous or daily POT) do not show a consistent pattern with respect to harvest history or road construction.

Perhaps most striking are the statistically significant decreasing trends in annual minimum flows detected in 15 of the 22 minimum time series analyzed (Figure 8d). However, Figure 11b also shows no apparent relationship between detected trends and harvest history or road construction. The apparent lack of relationship between statistically significant trends and the degree of road construction and forest harvest shown in Figures 11a and 11b may in part be related to lack of detectability (large noise) as well as the magnitude of the harvest effect (small signal). This possibility is discussed further in section 4.

The most consistent change in the significance results of trend analysis for the period from 1945 to 1996 (Figure 9) relative to the 1960–1996 record length (Figure 8) is the detection of statistically significant decreasing trends in MAF and trends in the annual minima (10 of 14 analyzed basins). This appears to reflect a large-scale regional climate variation that caused increased streamflows in the 1950s and 1960s, followed by decreased flows after around 1977. This effect is shown in the time series of the North Fork Skokomish River (Figure 12). *Lins and Slack* [1999] evaluated trends in streamflow for 395 stations throughout the United States for record lengths of 30–80 years. For several of the time periods they detected decreasing trends in annual minimum flows and median flows throughout the Pacific Northwest. These decreasing trends are in contrast to the majority of the country, which has experienced no trends or increasing trends. *Lins and Slack* [1999] also found that trends in minimum flow were more prevalent than trends in median flow. They attribute this result to decadal-scale patterns in the North Pacific Ocean.

The Pacific Decadal Oscillation (PDO) refers to an oscillation of sea surface temperatures (SSTs) in the North Pacific [*Mantua et al.*, 1997]. A positive PDO phase has cold SST anomalies in the north central Pacific and warm anomalies along the west coast of North America. The PDO drives climate in the Pacific Northwest, such that a positive PDO phase is associated with warmer and drier climate cycles. The PDO was in negative phase from 1945 to 1976 and positive phase from 1925 to 1945 and from 1977 through about 1996 [*Mantua et al.*, 1997]. This pattern is consistent with our results.

The trend analysis for the longest record length (1930–1996 (Figure 10)) shows that the prevalence of statistically significant decreasing trends in annual minimum observed for the two shorter record lengths was absent (in fact, there were no decreasing trends and two statistically significant increasing trends). As for the other record lengths, there was no apparent relationship between the existence of detectable trends (two for low flows, two for AMS, two for POT, and none for MAF) and harvest or roads (not shown). The large-scale persistence of the annual minimum and MAF cycle and the lack of correlation with forest harvest and roads suggest that other factors, such as regional climate variations due to the PDO, are responsible for the observed trends. The remainder of this paper addresses methods of filtering this climate signal from the discharge record.

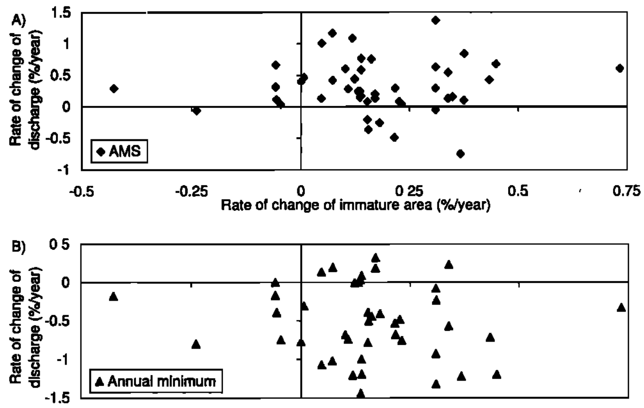

Figure 7. Kendall slope estimate of harvest history versus Kendall slope estimate of discharge series, normalized by the time series mean, for all basins and time periods: (a) AMS and (b) annual minimum.

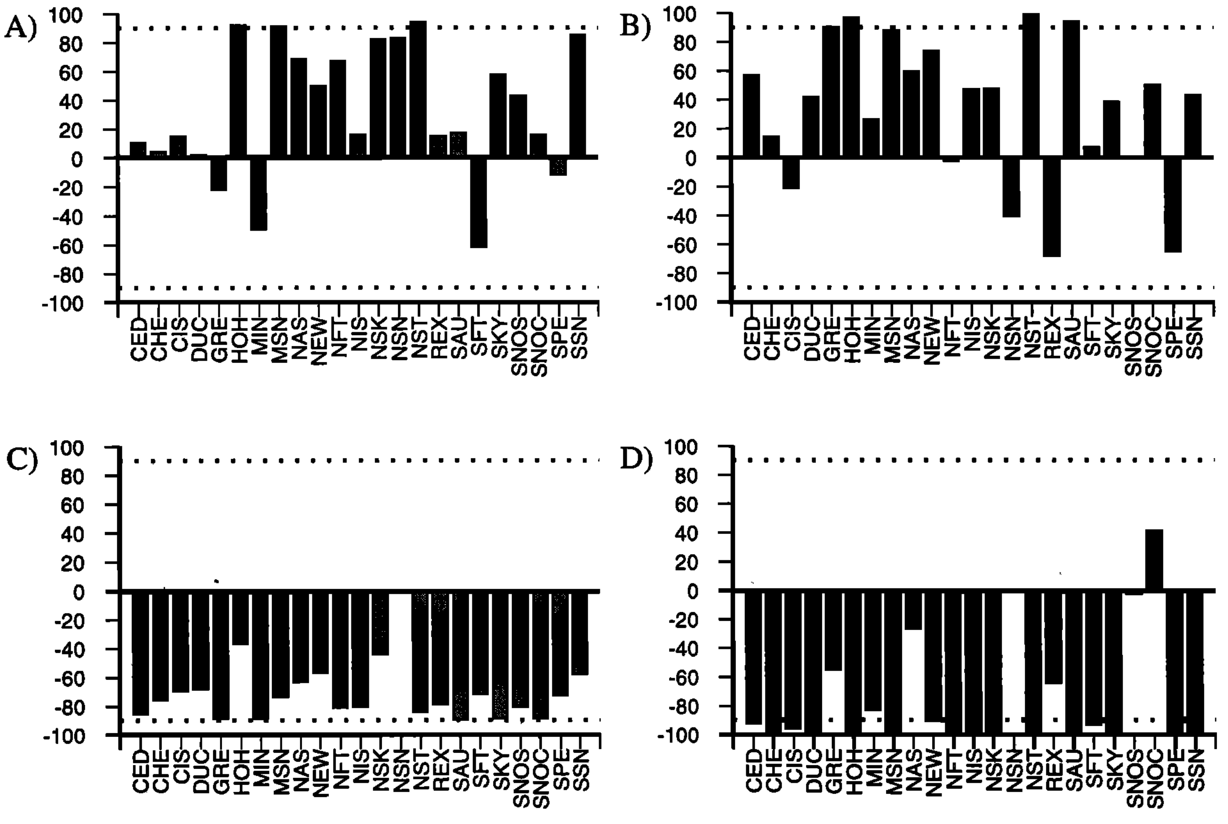

Figure 8. Significance levels for trend analysis of 23 western Washington basins, 1960–1996. Bars exceeding the dashed line are significant at $\alpha \leq 0.1$; three letter basin codes are listed in Tables 3 and 4. (a) AMS, (b) Instantaneous POT, (c) MAF, and (d) annual minima.

4. Paired Basin Analysis

Initially, trend analysis was performed on catchment pair difference series in order to filter out the apparent PDO climate signal. The trend results for catchment pairs are summarized in Figures 13–15 for the 1960–1996, 1945–1996, and 1930–1996 record lengths, respectively. The control catchments were designated as having the lower trend in immature vegetation over the analysis period and are the first catchments listed in Figures 13–15. Both statistically significant increasing and decreasing trends (treatment minus control) were detected for all five flow series analyzed. Most remarkably, statistically significant increasing trends were found for the annual minimum in 11 of the 21 catchment pairs analyzed for the 1960–1996 time period (eight of the catchment pairs could not be analyzed for minimum flows due to problems with the daily flow record for the North Fork Snoqualmie).

As a means of interpreting the detected trends, the minimum detectable difference (MDD), or the smallest trend which could be deemed statistically significant at 0.1 significance by the Mann-Kendall test, was calculated for each of the analyzed paired series. The power of a statistical test is the probability of establishing the existence of a trend of a given magnitude when one really exists. (In contrast, the significance level is the probability of concluding that a trend is present when a trend does not exist.) Unlike the significance level, the power of a test depends on the parameters of the population from which the data are drawn, so that the magnitude of a trend which can be detected is dependent on the sample size, mean, and variance. *Lettenmaier* [1976] showed through Monte Carlo sampling that the power of the nonparametric Spearman's Rho test is similar to that of the t test even when the data are normally distributed. Further, Spearman's Rho has power quite similar to that of the Mann-Kendall test [*Helsel and Hirsch*, 1992]. For simplicity of analysis, the power function of the t test is used here to evaluate the minimum trend that could be considered significant for each time series using a power of 0.5 and a significance of 0.1. Further details of the MDD calculation are given in the appendix. The MDD in percent for all catchment pairs, for all time periods (1930–1995, 1945–1995, 1960–1995), is shown as histograms in Figure 16a for the AMS. Similar plots for the instantaneous POT, MAF, and annual minimum series are shown in Figures 16b–16d, respectively. The results for the daily POT series are similar to the instantaneous POT. The magnitude of the smallest detectable trend tends to decrease for smaller flows, such that smaller trends are detectable in the instantaneous POT series than in the AMS (mean of 22% versus 38%, see Table 5). This is primarily due to the larger sample size in the POT time series but is also related to a smaller residual error variance. The smallest detectable trends on average are found for the MAF (mean of 8%) and minimum series (mean of 21%).

The trend in discharge for all catchment pairs was estimated with Kendall's slope (equation (1)) using the normalized difference series (equation (A3)). The absolute value of the Kendall's slope trend estimate is shown in Figure 17 and Table 5, for comparison with Figure 16. Most of the trend estimates for AMS, POT, and MAF in Figure 17 lie below the limit of detectable trends shown in Figure 16 for the same series.

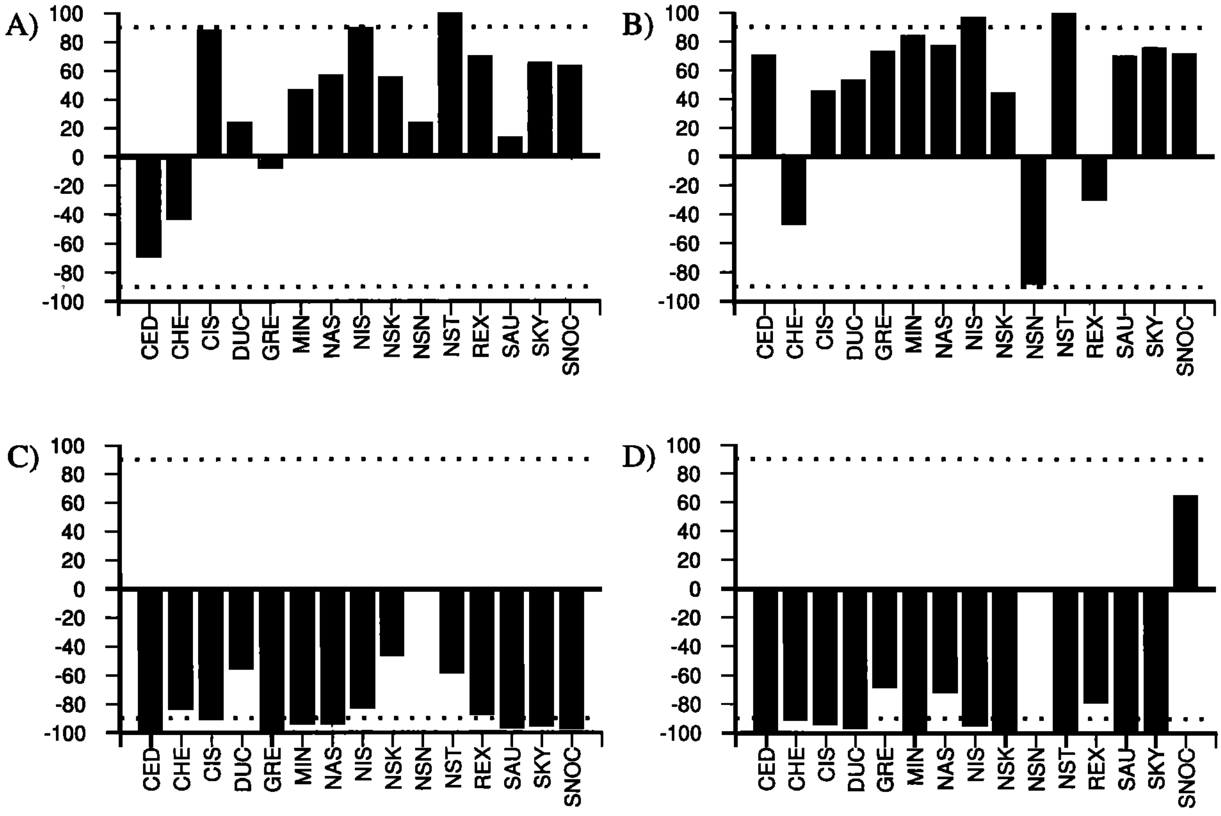

Figure 9. Significance levels for trend analysis of 15 western Washington basins, 1945–1996. Bars exceeding the dashed line are significant at $\alpha \leq 0.1$, three letter basin codes are listed in Tables 3 and 4. (a) AMS, (b) Instantaneous POT, (c) MAF, and (d) annual minima.

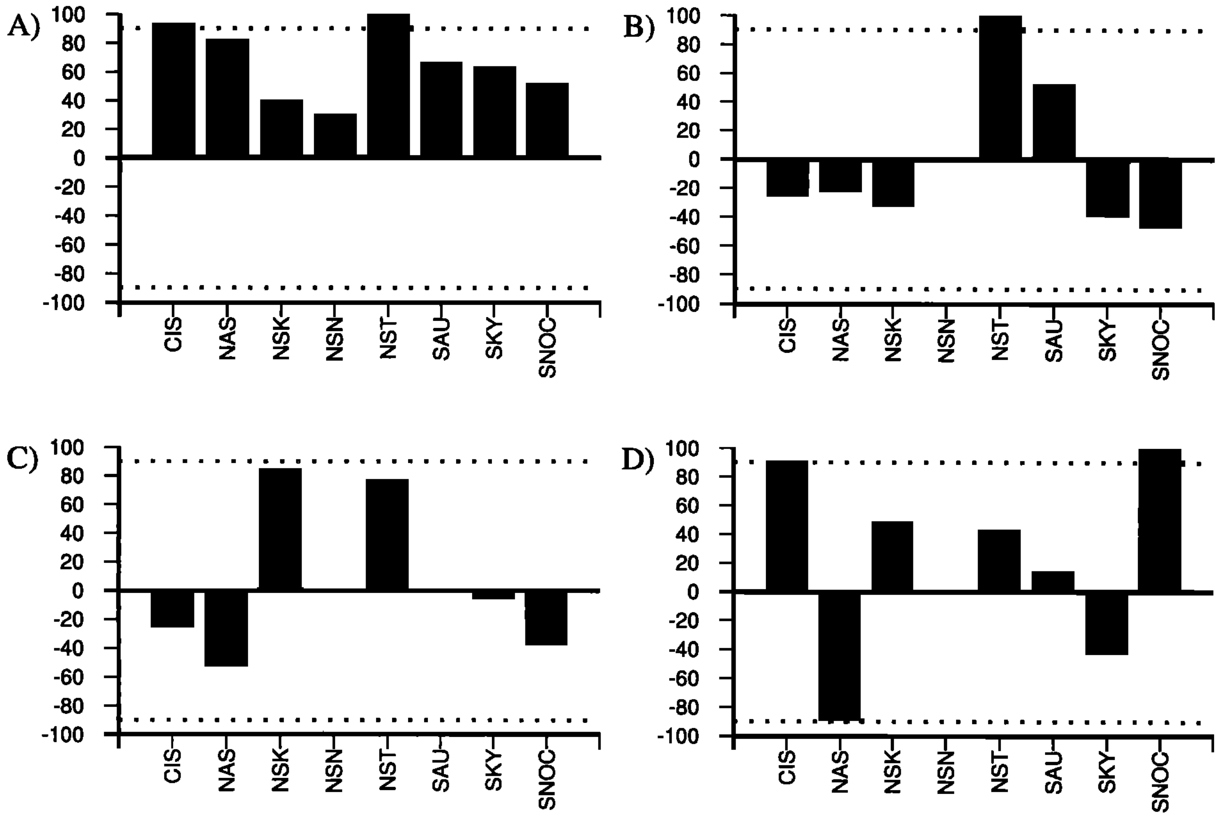

Figure 10. Significance levels for trend analysis of 8 western Washington basins, 1930–1996. Bars exceeding the dashed line are significant at $\alpha \leq 0.1$, three letter basin codes are listed in Tables 3 and 4. (a) AMS, (b) Instantaneous POT, (c) MAF, and (d) annual minima.

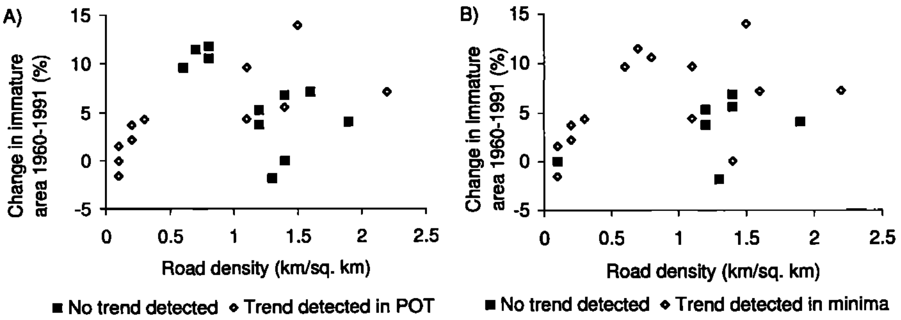

Figure 11. Kendall slope estimate of immature basin area versus road densities for univariate trends results for the 1960–1996 time period: (a) trends detected in POT and (b) trends detected in minimum flows.

However, in the case of the minimum flows a much higher proportion of trend estimates (mean = 17%) lie near the limit of detectability (mean = 21%).

Many studies of forest harvest effects have found statistically significant increases in POT series but not in the AMS. This finding is consistent with an argument that a larger fraction of a basin responds (e.g., is saturated) during the largest storms, so the effect of increases due to forest harvest have less effect. However, the estimated trends shown in Figure 17 are in fact slightly larger for the AMS than for the POT series, which suggests that the apparent prevalence of trends in POT in previous studies could be related to a greater detectability of trends in the POT series and not necessarily to larger underlying trends. To examine whether larger increases occur for smaller floods, the percent differences between treatment and control peak flows were analyzed with respect to flood return period. To determine return period, a generalized pareto distribution was fit to the instantaneous POT series of each of the control catchments. The normalized percent difference series was then plotted along the return interval ordinates of the theoretical control catchment distribution (see Figure 18). The percent difference series was calculated as

$$x_i = 100\left(\frac{X_{ti}}{\mathrm{m\hat{a}f}_t} - \frac{X_{ci}}{\mathrm{m\hat{a}f}_c}\right)\Big/\frac{X_{ci}}{\mathrm{m\hat{a}f}_c}, \quad (4)$$

where X_{ti} and X_{ci} are the treatment and control observations, respectively, at time i, and $\mathrm{m\hat{a}f}_c$ and $\mathrm{m\hat{a}f}_t$ are the predicted regional mean annual flood of the control and treatment catchments, respectively. The regional mean annual floods were estimated using a multiple linear regression with mean annual flood as the dependent variable and basin area, mean annual precipitation and cumulative harvest as the independent variables. Mean annual precipitation was calculated for each basin using data from the Parameter-Elevation Regression on Independent Slopes Model (PRISM) [*Daly*, 1994]. Mean annual flood was calculated as the mean of the AMS from 1980 to 1990. Cumulative harvest was not a significant indicator in the regression. The estimate of mean annual flood based on area and precipitation has a significance level of 0.01. This procedure removes the variability in basin response due to precipitation and basin area from the difference calculation. A LOWESS smoothing was applied to the difference series plot, and the 1.1-, 2-, 5-, 10-, 15-, and 25-year return interval differences were obtained from the smoothed curve. By repeating this process for all basin pairs, histograms of percent difference were created (Figure 19).

As summarized in Table 6, this analysis shows that on average (over all basin pairs), the percent difference between treatment and control peak flows decreases with increasing return period until the 10-year flood and then increases slightly with return period. These results are influenced in part by uncertainty in the predicted floods for larger return periods due to limited record length. Varying record lengths and the correlation between catchment pairs within the same larger watershed (e.g., the several Snoqualmie River catchments) precludes a rigorous analysis of the statistical significance of the results. However, a rough estimate of the standard error of the mean suggests that the significance threshold is probably of the order of 5–10%. This analysis suggests that an increase in the response of treatment relative to control peaks (that is, increased flows for more heavily harvested basins) decreases with increasing return interval for 1–5-year return period storms. The

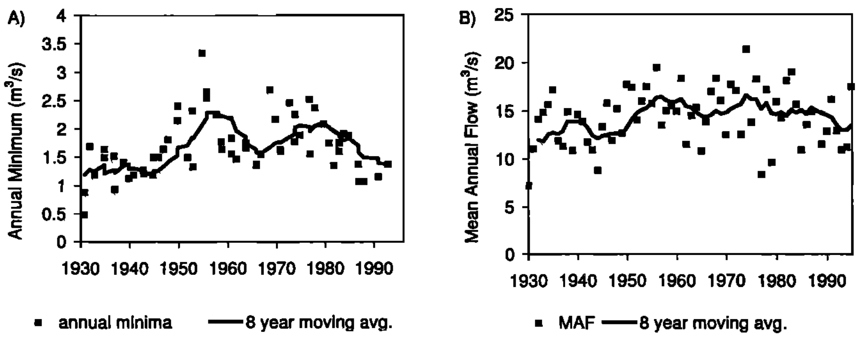

Figure 12. Time series of (a) annual minimum and (b) mean annual flow for the North Fork Skokomish River, showing the cyclical nature of low flows and mean annual flow. The points represent annual observations, and the line represents an 8-year moving average.

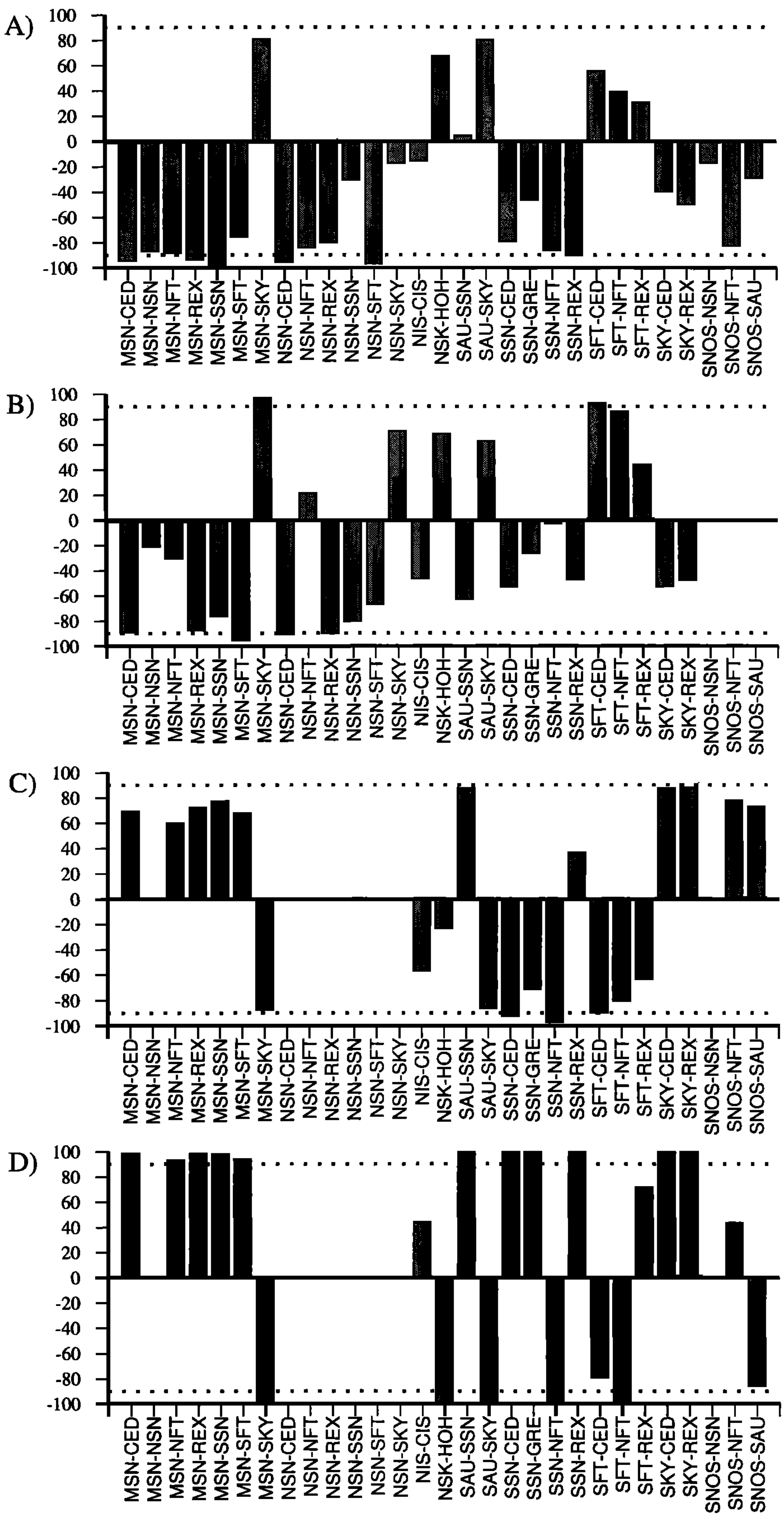

Figure 13. Significance levels for trend analysis of western Washington catchment pairs, 1960–1996. Bars exceeding the dashed line are significant at $\alpha \leq 0.1$. Three letter basin codes are listed in Tables 3 and 4. The control catchment is listed first. (a) AMS, (b) instantaneous POT, (c) MAF, and (d) annual minima.

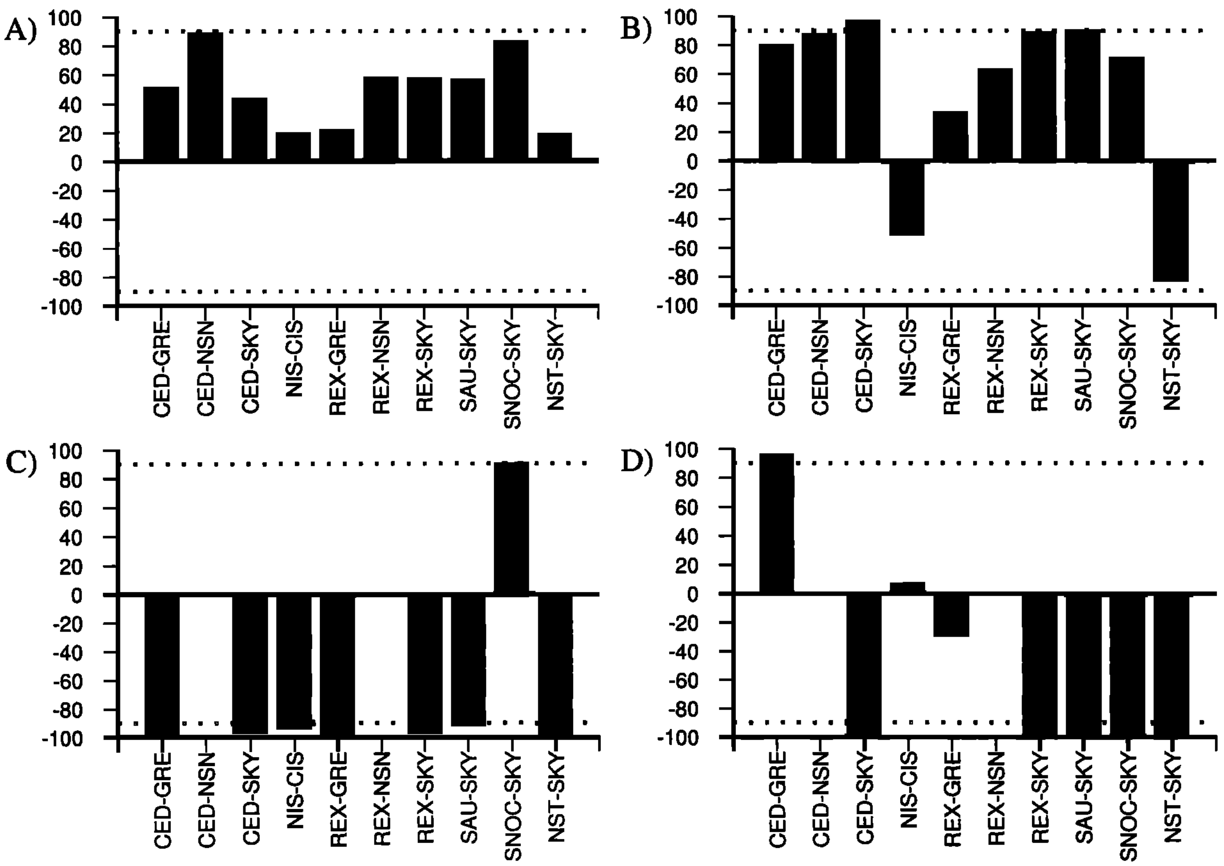

Figure 14. Significance levels for trend analysis of western Washington basin pairs, 1945–1996. Bars exceeding the dashed line are significant at $\alpha \leq 0.1$. Three letter basin codes are listed in Tables 3 and 4. The control catchment is listed first. (a) AMS, (b) instantaneous POT, (c) MAF, and (d) annual minima.

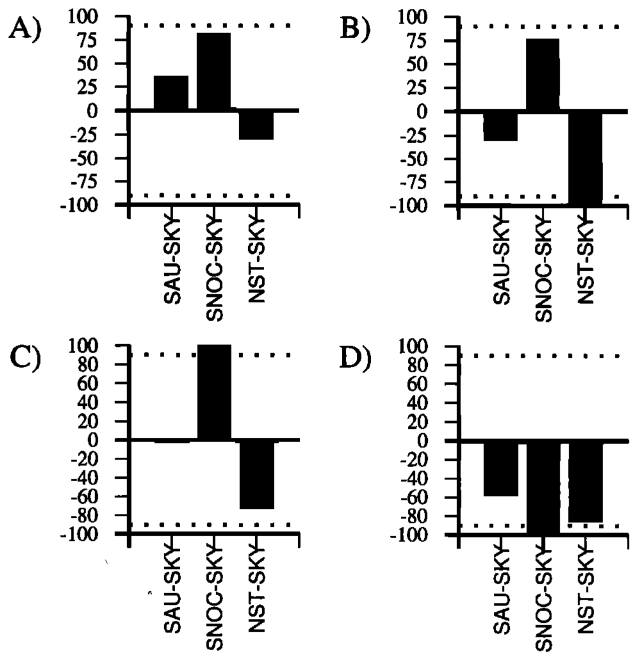

Figure 15. Significance levels for trend analysis of western Washington basin pairs, 1930–1996. Bars exceeding the dashed line are significant at $\alpha \leq 0.1$. Three letter basin codes are listed in Tables 3 and 4. The control catchment is listed first. (a) AMS, (b) instantaneous POT, (c) MAF, and (d) annual minima.

apparent increase for larger return periods may well be a statistical artifact.

Although the general trend of declining flood changes with larger return intervals would be consistent with previous results, this interpretation is clouded by the fact that trends in medians over the basin pairs with return period (second col-

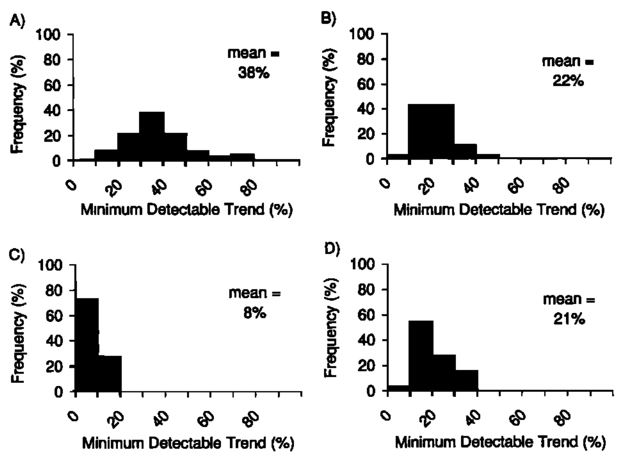

Figure 16. Minimum detectable difference as a percent increase for 41 basin pairs, using a power of 50%: (a) AMS, (b) instantaneous POT, (c) MAF, and (d) annual minimum. The histograms of daily POT are similar to those for instantaneous POT.

Table 5. Analysis of Trend Detectability

	Minimum Detectable Difference (power = 50%)				Kendall Slope Estimate of Trend			
Time Series	Mean of All Pairs, %	NF Tolt, %	NF Snoq, %	Snoq, %	Mean of All Pairs, %	NF Tolt, %	NF Snoq, %	Snoq, %
AMS	38	44	44	23	16	45	51	33
Instant. POT	22	29	29	18	14	28	83	31
Daily POT	22	···	···	···	13	···	···	···
MAF	8	···	···	···	5	···	···	···
Minimum	21	···	···	···	17	···	···	···

Model residuals for NF Tolt, NF Snoq, and Snoq are given. Center dots indicate that the time series was not analyzed for these basins.

umn of Table 6) are not consistent with the trends in the means, and in fact the median changes suggest that for more than half of the basins, the treatment (more harvested catchment) had reduced peak flows relative to the control (less harvested). Further analysis showed that the magnitude (and in some cases, the sign) of the paired differences are dependent on the method of normalization chosen (e.g., use of mean annual flood versus basin area as the denominator in (4). However, the mean percent difference between treatment and control peak flow decreased with increasing return interval (up to 10 years), on average, for all different methods of normalization. Approximately one third of the basin pairs exhibited an increase in percent difference with return period. Perhaps in large part due to the small number of catchment pairs available, this analysis cannot be considered conclusive. It does raise the possibility that Figure 17 results, which show larger changes in AMS than POT, might be an anomaly.

5. Model Residuals Analysis

The Distributed Hydrology-Soil-Vegetation Model (DHSVM) was used to simulate flows for three of the study catchments: the Snoqualmie River at Carnation, the North Fork Snoqualmie near Snoqualmie Falls, and the North Fork Tolt near Carnation. DHSVM is a physically based hydrologic model, which explicitly solves the water and energy balance for each cell of a gridded model domain. Grid cell runoff is routed to the catchment outlet using a unit hydrograph approach [*Maidment et al.*, 1996], which allows simulation of a continuous time series of streamflow (at a 3 hour time step in this case). The governing equations of DHSVM are described by *Wigmosta et al.* [1994] and *Storck et al.* [1995].

DHSVM requires both meteorological forcings (precipitation, air and dewpoint temperature, cloud cover, incoming shortwave and longwave radiation, and wind speed) and land surface characteristics (vegetation, soils, and elevation). Meteorological forcings for the period 1948–1993 were taken from the National Oceanic and Atmospheric Administration (NOAA) surface airways database for the Stampede Pass

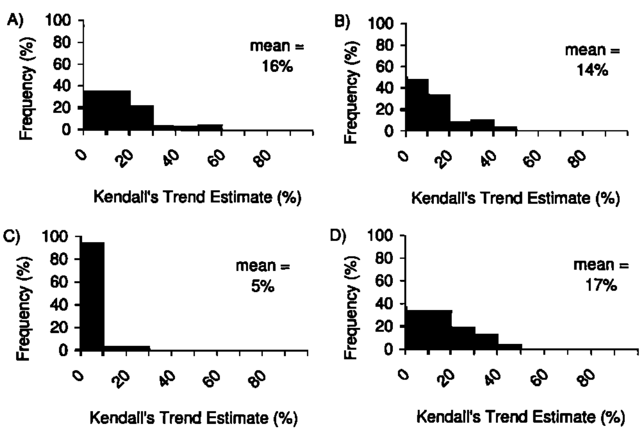

Figure 17. Estimate of trend for 41 basin pairs using the absolute value of Kendall's slope estimate: (a) AMS, (b) instantaneous POT, (c) MAF, and (d) annual minimum. The histograms of daily POT are similar to those for instantaneous POT.

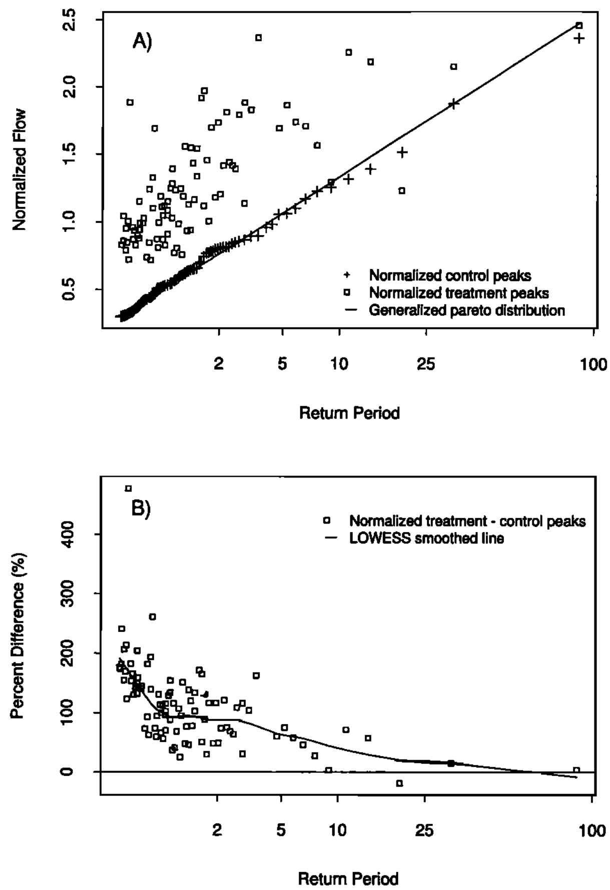

Figure 18. Process of computing the return period of normalized percent difference floods: (a) generalized pareto distribution (solid line) fit to the normalized control catchment flows (pluses). The corresponding treatment catchment flows are shown by squares. (b) Normalized percent difference series plotted with the control catchment ordinates.

weather station (elevation 1206 m, on the Cascade Crest). Air and dewpoint temperature were distributed over the model domain using a fixed lapse rate. Incoming longwave radiation and cloud cover were assumed to be constant over the catchment. The distribution of precipitation and shortwave radiation were determined within DHSVM by orographic precipitation and solar radiation submodels that make use of digital elevation data (see *Storck et al.* [1995] for details). The station used to produce model forcings (Stampede Pass) underwent a change of instrumentation after 1993 that makes subsequent observed records questionable for the purposes of this analysis. Therefore we accepted a slight inconsistency in the record length for the model residuals, as compared with the paired catchment analysis.

The distribution of soil classes over the Snoqualmie River watershed was obtained from GIS-based vector maps provided by the Mount Baker-Snoqualmie National Forest and the Washington Department of Natural Resources. Vegetation overstory type and age was determined from the B. A. Connelly et al. (unpublished data, 1993) data set (see section 2.2). Vegetation parameters (LAI, albedo, roughness height, etc.) were compiled from literature sources, as described by *Storck et al.* [1995].

The model was calibrated for the period March 1983 through November 1986, with land cover adjusted to represent forest conditions as observed in 1986. Following calibration, historic POT series for the period 1948 through 1993 was simulated for the three catchments using 1989 land use conditions. Periods of analysis vary among catchments based on the available length of observed discharge records. The model residuals time series was created by differencing observed and

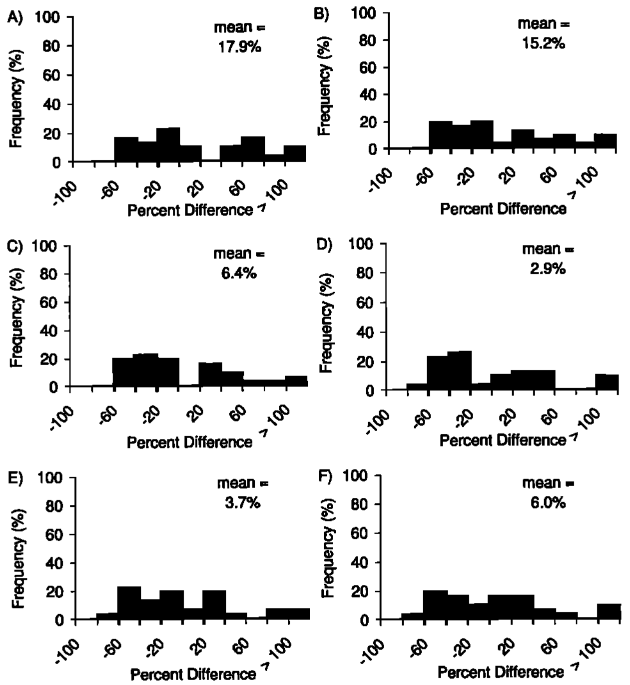

Figure 19. Histograms of normalized percent difference versus return interval for 31 basin pairs. (a) 1.1-year return period, (b) 2-year return period, (c) 5-year return period, (d) 10-year return period, (e) 15-year return period, and (f) 25-year return period. An increasingly negative (positive) percent difference indicates that treatment flows are decreasing (increasing) relative to the control for increasing return period.

Table 6. Discharge Percent Difference Versus Return Period for 31 Basin Pairs

Return Period	Mean, %	Median, %
1.1 year	17.9	−1.6
2 year	15.2	−3.1
5 year	6.4	−14.8
10 year	2.9	−22.5
15 year	3.7	−7.7
25 year	6.0	1.4

simulated discharge for each event in the USGS AMS and POT series. By keeping vegetation constant (somewhat arbitrarily at 1989 conditions), the model acts as a surrogate for an identical catchment pair with static vegetation throughout the period of interest, whereas the "real" system, as represented by discharge observations, undergoes harvest and recovery, which leads to trend (or its absence if vegetation recovery is sufficient to reduce the "signal" of the original harvest). Arguably, if the cumulative effects of forest harvest have changed peak streamflows over time, the model should "fit" the observations around the reference year better than elsewhere in the record, although natural variability makes this difficult to confirm. The residual time series is a function of both model error and changes in "treatment" relative to the reference conditions.

The results of Kendall's test applied to the instantaneous POT and AMS model residuals series (Figure 20) are summarized in Table 7. Statistically significant increasing trends were found for all three catchments. These results differ somewhat from the catchment pair analysis, in which no trends in AMS and instantaneous POT were detected for the NF Tolt (for five basin pairs analyzed) and an increase in AMS was detected in only two cases of eight catchment pairs that included the North Fork Snoqualmie. This apparent contradiction is explainable in terms of the trend detectability. As summarized in Table 5, the MDD in all three modeled catchments is in roughly the same range as for the 41 catchment pairs. However, the observed trend, as estimated using Kendall's slope, is larger for the modeled catchments (see Table 5), implying a greater chance of detection. The larger Kendall's slope values for the model residuals relative to the paired catchments is attributable to the fundamental difference between the two analysis procedures. Because a true control (i.e., unharvested catchment) is not available in the catchment pair analysis, the trend in the difference series is (presumably) due to the current level of contrast in harvested area. However, in the model residuals approach, the observed streamflow series is analyzed with respect to a (simulated) control with a constant land use state over the period of analysis. The trend in the model residuals is therefore related to the total effect of land use changes over the period of analysis, whereas the paired catchment analysis is sensitive only to the aggregate of differences during the period of record, which allows for some cancellation due to, for example, recovery.

6. Discussion

Difficulties in defining the relationship between catchments with statistically significant discharge trends and land use include the complicating effects of climatic fluctuations, continuous harvest patterns that tend to reduce the magnitude of harvest contrasts, and the temporary nature of hydrologic con-

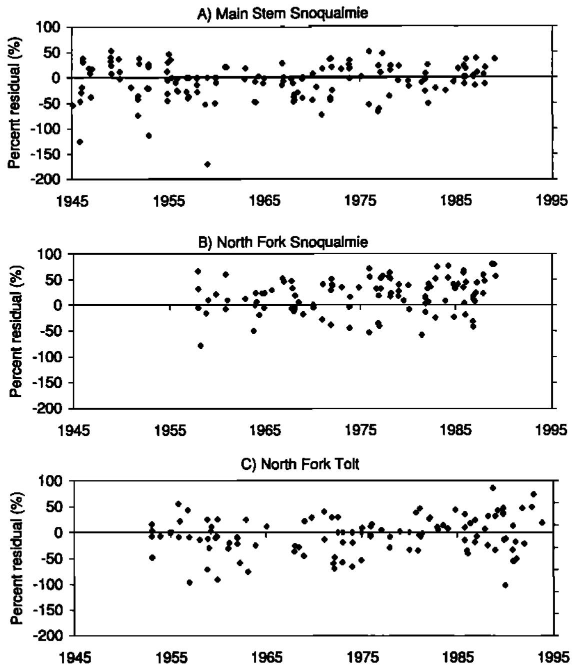

Figure 20. Percent model residuals (observed−predicted) for (a) Main Stem Snoqualmie River, (b) North Fork Snoqualmie River, and (c) North Fork Tolt River.

sequences in catchments in which regrowth has occurred. Aside from experimental catchments, it is nearly impossible to find a treatment/control pair, both of which have moderate to large drainage areas. Coincident harvest in paired catchments makes interpretation of the difference series difficult when responses may be overlapping, depending on the persistence of hydrologic responses to forest harvest and road building. Hydrologic recovery of both low and peak flows depends on different factors and occurs at different timescales. For example, minimum flows depend on the recovery of transpiration as trees mature, while peak flows in western Washington are dependent on the canopy snow interception capacity and aerodynamic attenuation. The signal is further complicated by the effect of roads, which may be variable over time depending on the extent of integration with the stream network. We attempted to account for continuous land use manipulation and recovery by analyzing the presence of trends in the single and paired catchments with respect to a vegetation statistic that incorporates the recovery of vegetation over time. However, the nature of the experimental design (which involves testing for monotonic trend within the period of analysis) precludes the detection of streamflow changes that may have occurred within the period of record but have since been attenuated due to hydrologic recovery. In addition, the offset in timing between land use manipulation and hydrologic response, which is not reflected in our vegetation statistic, could explain the occurrence of trends in streamflow which are inconsistent with the reported trend in vegetation over the period of analysis.

The model residuals analysis provides an alternative method to paired catchment analysis which accounts for both climatic fluctuations and vegetation recovery. However, the method is restricted by the variability of the residual series, the major source of which is model prediction error resulting from errors in estimating the spatial distribution of precipitation and temperature over the catchments. As the meteorological forcing data become less representative of true basin conditions, the ability to detect trends in the residual series is overwhelmed by the variance of the residuals. However, the results suggest that for the Snoqualmie catchments, the residual error variances were small enough that the method was more powerful in detecting trends than was the more conventional paired catchment approach.

Previous studies [e.g., *Jones and Grant*, 1996; *Thomas and Megahan*, 1998] have reported more significant trends for smaller, more numerous, high-flow events. While it is tempting to explain the lack of trend detection for larger events by the (lack of) strength of the signal, such a conclusion may not be appropriate. As event size increases, sample size decreases, with the direct consequence that the required signal to noise ratio (minimum detectable difference) for trend detection increases dramatically. This effect seriously limits the ability to detect trends in floods of the order of the annual maximum. Nevertheless, our analysis does show a decrease in mean treatment response with increasing return interval (up to the 10-year event) for the majority of catchment pairs analyzed. The fact that the median (over catchment pairs) response generally decreases with return period, and for most return periods is negative (treatment, or more heavily harvested catchments, tended to have declining flood magnitudes at any given return period relative to the control, or less harvested catchment), renders this analysis inconclusive. The mechanism or mechanisms controlling the difference in response between the basin pairs is not readily apparent, and further exploration into the nature of treatment response with increasing return interval is required.

7. Conclusions

We explored changes in flood magnitudes between 1930 and 1996 in 23 western Washington basins and the extent to which observed changes may be attributable to forest harvest and road construction. Trend analysis of the discharge records at 23 individual sites suggests that the signal is dominated by climatic fluctuations, especially a shift in the Pacific Decadal Oscillation in the late 1970s. Streamflow trends related to the PDO shift are most apparent in low flows and mean annual flows, which are less variable than flood flows, as captured in the annual maxima series (AMS) and peaks over threshold (POT). Furthermore, the climatically related trends are most prevalent in the 1960–1996 period of record, for which the 1977 PDO shift occurred at about the halfway point.

By creating catchment pair difference series, the effects of climatic variations were removed, leaving land use change as the most likely explanatory factor for any trends observed. Analysis of the basin pair difference series suggests the following:

1. There is a preponderance of statistically significant

Table 7. Model Residuals Trend Analysis (1960–1993)

Basin	Maxima[a]	Instant. POT
Snoqualmie (Carnation)	90%	99%
North Fork Tolt	···	95%
North Fork Snoqualmie	99%	99%
Total increasing	+2/3	+3/3

[a]Numbers represent the significance level of the Kendall S statistic, dots indicate significance level less than 90%.

trends in the minimum flows in the post-1960 period during which most forest harvest has occurred. These trends are consistent with an interpretation of increased summer flows due to decreased evapotranspiration following forest harvest.

2. Although both positive and negative trends were detected in the annual maximum and POT series, the total number of trends detected does not exceed that expected by chance. The absence of trends in the peak flow series is largely explainable by the minimum detectable difference, which is generally larger than the inferred trend magnitudes.

3. Regionalization of inferred trends for all basin pairs using a generalized pareto distribution shows an apparent increase in flood peaks for treatment (greater harvest) relative to control (lesser harvest) peaks, the mean magnitude of which decreases with increasing return interval up to about the 10-year return period. For larger return periods, there is no apparent change in treatment relative to control flood magnitudes. In large part due to the small number of catchment pairs available, this analysis cannot be considered conclusive.

4. An analysis of the residuals of flood peaks predicted using a spatially distributed hydrology model (which acts as a surrogate control catchment) from observed flood peaks showed increases in the treatment relative to control series for most of the flood peak variables (AMS, POT) and catchments (three, all within the Snoqualmie River basin) analyzed. Analysis of the inferred trend using the residuals method suggests that it should be more easily detected due in part to reduced variance and increased strength of the trend signal.

Appendix: Calculating the Minimum Detectable Difference (MDD)

The power of the t test is given by

$$1 - \beta = 1 - F_x\left(W_{(1-\alpha/2)} - \frac{|\tau_{\min}|}{\mathrm{var}\,(\hat{\tau})^{1/2}}\right), \quad \text{(A1)}$$

where F_x is the cumulative normal distribution of x, $W_{(1-\alpha/2)}$ is the normal deviate at cumulative probability $1 - \alpha/2$, var $(\hat{\tau})$ is the variance of the trend estimate, $(1 - \beta)$ is the power, and $\tau_{\min}$ is the smallest trend per time step which would be considered significant at significance level α and power $(1 - \beta)$. Here $\tau_{\min}\, n$ is the total change over the period of analysis, where n is the number of days of record. Figure A1 illustrates the relationship of some of these variables. The variance of the trend estimate is related to the variance of the time series residual by

$$\mathrm{var}\,(\hat{\tau}) = \sigma_\varepsilon^2 \Big/ \sum_t (t_t - \bar{t}_n)^2, \quad \text{(A2)}$$

where t_i is the Julian day of observation x_t, $\bar{t}_n$ is the mean of all t, and σ_ε^2 is the variance of the residual. For this application, σ_ε^2 was assumed equal to the time series variance, where the time series is the normalized difference series of treatment and control pairs:

$$x_t = \frac{x_{tt}}{\bar{x}_t} - \frac{x_{ct}}{\bar{x}_c}. \quad \text{(A3)}$$

Alternatively, σ_ε^2 could have been computed as the residual of the time series from a fitted trend line but ignoring the trend results in relatively little error in the MDD estimate. The minimum detectable daily trend, $\tau_{\min}$, was calculated by inverting equation (A1), for all basin pairs using a power of 0.5 and a significance of 0.1. Note that $\tau_{\min}$ is equivalent to the difference in the fraction of mean flow per day. The corresponding percent increase in discharge over the period of record, relative to the control, is determined by

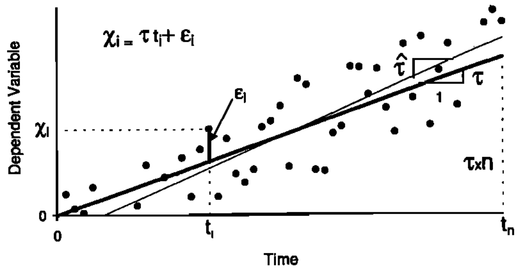

Figure A1. Illustration of variables used in the MDD analysis. The thin line represents the trend estimated from the sample X_t. The thick line represents the true population trend.

$$\tau_{\min}^* = 100(\tau_{\min} n). \quad \text{(A4)}$$

The MDD ($\tau_{\min}^*$) in percent for all catchment pairs, for all time periods (1930–1995, 1945–1995, and 1960–1995), are shown as histograms in Figure 16.

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