THE INFLUENCE OF CLIMATE VARIATIONS ON LONG PERIOD FLUCTUATIONS IN CALIFORNIA STREAMFLOW

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Abstract

There is considerable seasonal-to-interannual variability in the flow of major watersheds in the Sierra Nevadas. This study examines that variability in terms of seasonal average surface weather variables, including atmospheric circulation, temperature, precipitation, and snow.

Of particular importance is an apparent decline in spring-early summer runoff from the Sierra Nevadas first pointed out by M. Roos of the California Department of Water Resources. While measured October-September (water year) and April-July (AMJJ) runoff have increased, the AMJJ/annual fractional runoff has decreased by approximately 10% over the 80+ years of record.

Further inspection shows that many streams in the West have a significant decline in spring-early summer fractional runoff as seen from a network of river gauging stations from Alaska south to Arizona and from California east to the Rockies. The cause of the trends at these stations is complex, involving both precipitation and temperature. For many basins the fractional spring-early summer runoff is affected by climatic behavior across all the seasons. In the Sierra, the decreased AMJJ fraction appears to have been produced by increased precipitation in the late summer, fall, and winter with decreased precipitation in spring. In addition, temperature along the West Coast has increased during the non-summer seasons, enhancing earlier runoff, and possibly evapotranspiration in spring.

Other combinations of temperature and precipitation were involved in fractional runoff trends in other regions. Reversals in temperature and precipitation trends in remote regions over the eastern part of North America suggest that much of these changes were produced by shifts in the long wave patterns of atmospheric circulation, perhaps discounting a greenhouse effect scenario.

Additional studies partially funded by this grant involve the influence of large scale atmospheric features usually emanating from the North Pacific Ocean during winter. These winter atmospheric patterns have strong connections to fluctuations in streamflow in watersheds in California and elsewhere in western North America.

This study involves the influence of large scale atmospheric fluctuations on interannual variations of streamflow in major California drainage basins. Streamflow, although complicated by geological and evapotranspiration effects in a given drainage basin, provides a measure of the influence of climatic variation on the hydrologic system. Aside from its utility in providing the usable portion of precipitation, streamflow has an advantage over point precipitation measurements in that it represents conditions over a rather extensive spatial domain, thereby filtering out high frequency temporal noise. Streamflow also represents the enhanced precipitation that occurs in high elevation and steep terrain, areas which are often poorly sampled.

The central problem that was tackled has much practical utility. Roos (1987, California Department of Water Resources), has noted that although total October-September (water year or WY) stream discharge in major Central California streams (Sacramento, Kings and San Joaquin Rivers) has remained constant or perhaps increased slightly over a long period (Figure 1, where open squares show seasonal values while closed circles indicate the ten year moving mean), spring-early summer (April through July or *AMJJ*) fraction of the total runoff has decreased (Figure 2). The decreasing trend in the late spring runoff fraction shows up in several Sierra streamflow records, suggesting that this phenomenon has at least a regional scale. This trend is of considerable importance to California because the snow pack provides natural storage for the state's water supply, and there is only limited capacity in the actual water reservoirs. It is advantageous if the water supply remains as snow until the winter precipitation season is over since, for flood safety purposes, premature runoff must be "dumped" if reservoirs are to have the capacity to absorb large floods from possible late winter or spring storms. Is the diminishing trend in late spring runoff ratio an effect of a general warming (from the "greenhouse effect"), or is it simply part of the natural climatic variability involving, among other factors, the frequency, intensity, and timing of weather systems?

This phenomena occurred with a statistically based treatment of climate data sets, including several stream gauge records (the major streams are described in Table I), and surface temperature, precipitation, and snow water content at several locations. These tests were designed to determine if the reason for decreasing spring-summer runoff in California is a general temperature increase over the region, or is it caused by changes in the storms that produce precipitation (their timing within the precipitation season or their nature, e.g., cold vs. warm)? To this end we have examined several monthly streamflow, precipitation, temperature and snowfall data for the high elevation Sierra Nevada region. Records of approximately 80 years (and shorter), beginning in the early 1900's were employed.

The Sierra streamflow fluctuations are shown in a broader point of view by an analysis of the trend in streamflow at several (more than 50) stream gauges over Western North America and Hawaii. These trends are shown in Figure 3 for fractional seasonal flow. The 1948-86 period was chosen because much of the decrease in spring-summer fractional runoff in Figure 2 occurs after 1948. The seasons used in this analysis were NDJ (Nov., Dec., Jan.), FMA (Feb., Mar., Apr.), MJJ (May, June, July), and ASO (Aug., Sep., Oct.). The values present, which range from 1 to 1000, are a measure of the significance of the 1948-86 trend, as determined by a Monte Carlo experiment where the observed seasonal data for each streamflow record was randomly shuffled and this resulting trend determined 1000 times. The number shown is the rank of the observed trend within the Monte Carlo stack of 1000. A value of 100 indicates a negative trend with 900 Monte Carlo trend values being larger and a value of 901 indicates a positive trend with 900 Monte Carlo trend values being smaller. Streams with trends of 100 or less or 900 and greater are shaded.

The fractional streamflow trends show:

(1) All Sierra streams have decreasing MJJ trends and several are quite significant statistically (above 80% level of confidence).

(2) In addition to the Sierra streams, a number of streams in regions throughout the west, from Alaska to Arizona show significant decreasing MJJ trends over 1948-1986. Including the Sierra stations, 28 of the 63 total streams had "significant" trends. Only 5 of the 63 total stations show significant increasing trends.

(3) The decreasing MJJ fractional streamflow trends are partially compensated by increasing fractional streamflow trends in the other seasons; both NDJ and FMA show positive trends, although most not highly significant, at the Sierra streams.

(4) Trends in actual measured streamflow (not illustrated here) show a highly significant broad scale pattern: (a) increases of most streams in California, Arizona, the Great Basin, and the Southern Rockies; (b) decreasing streamflow in many streams in the Northwest; and (c) increases in streams in coastal Alaska.

To help interpret this pattern of trends in streamflow, linear trends of surface temperature and precipitation were examined over North America (Figure 4). These were computed using climatic divisional average data in the United States (344 divisions over the coterminous United States, 9 divisions in Alaska) and selected station data over Canada. Trends in FMA and MJJ temperature and precipitation are presented as the differences in the trend line values, 1986 minus 1948. In comparing the temperature and precipitation trends with those of the streamflow, the following points seem important:

(1) The decreasing trends in MJJ fractional streamflow are caused by several seasonal weather factors which often are subtle, but seem to reinforce creation of a noticeable effect. These factors range in importance from one region to the next.

(2) In the Sierra region, increases in precipitation over 1948-1986 occurred in ASO, NDJ, and FMA, and decreases in precipitation occurred in MJJ, contributing to the decreasing MJJ fractional streamflow.

(3) Increases in temperature in California in NDJ and FMA, particularly may have caused more within cool season streamflow, leading to a smaller fraction of late spring-summer MJJ streamflow.

(4) Increased temperature over 1948-1986 during spring and early summer (MJJ) may have also contributed to a smaller traction of MJJ/streamflow through increased annual evapotransporation.

(5) The patterns of observed trends in temperature and precipitation are broad in scale often changing signs over length scales that are large fractions of the continental width. Many previous investigations show that these large scale surface anomalies likely result from shifts in the long waves in the atmospheric flow. This upstream-downstream compensation suggests that much of the decrease in spring-early summer streamflow seen in western streams is accomplished by rearrangements of the atmospheric circulation, and not by an overall Northern Hemisphere warming. This would seem not to be a "greenhouse effect", unless global change is responsible for these shifts in atmospheric circulation.

Long term records of precipitation within and near the Sierra illustrate the low frequency (decade scale) variability in the atmospheric supply to the hydrologic systems of this region (Figure 5 and 6). While the long term trend in annual precipitation strongly resembles the long term trend in annual streamflow, the series of spring precipitation ratio ($AMJJ$/annual) is *not* well related to that of AMJJ/annual spring streamflow. This shows that the changes in the spring-early summer fraction of runoff is not driven primarily by spring precipitation.

Looking further, it is clear that *both* precipitation and temperature anomalies contribute to fluctuations of the spring runoff/annual runoff ratio. This effect can be seen in composites of precipitation and temperature anomalies for the low and high streamflow ratio (*AMJJ*/annual) terciles, illustrated by the tercile composites in Figures 7 and 8. An additional indicator of the possible combined effect of temperature and precipitation is the ratio of February 1st snow water content and early winter precipitation (October through January) (Figure 9). The long term trend in this ratio indicates that snow water content per unit precipitation received has apparently diminished over the last five decades, similar to the trend in spring streamflow. Interestingly, the actual (*not* ratio of) snow water content measured in February (Figure 10) shows little trend.

Linear statistical models were derived (using stepwise regression) for three primary river basins to determine the climatic influence of seasonal precipitation and temperature on (a) seasonal streamflow; and (b) fractional seasonal/annual streamflow. These basins (Smith, Cosumnes, and upper San Joaquin Rivers) were chosen to represent differing mean elevations, low (mean elevation less than 1000 m), mid (elevation between 1000 m and 2000 m), and high (greater than 2000 m). The predictors were seasonal precipitation and air temperature (for summer, fall, winter, and spring) and October streamflow (an indicator of base flow at the beginning of the wet season). Two families of models were built for each season (fall through spring) for each basin, one to predict the actual (volumetric) streamflow and the other to predict the fractional (seasonal to annual streamflow). The period of record for the data used in deriving the models (the training period) was the 37 water years 1950-86. An equal length period (1913-49) was reserved to check the validity of the models against independent data (the test period). To further test the model results, three secondary river basins (Umpqua, American, and Merced Rivers, respectively) were selected for their resemblance (elevational and spatial) to the primary basins. It must be emphasized that the intent of these models was a climatic analysis of the effect of temperature and precipitation on streamflow, not the prediction of streamflow, which is better made using hydrological watershed models.

Skill scores (expressed as a fraction of the total variance accounted for, with 1.00 being a perfect score, shown in Table II) for all primary basins in all seasons was .75 for the training period, and .62 for the test period. The highest score was .92 for the high elevation basin spring actual streamflow during the training period. The lowest score was .30 for the low basin spring actual streamflow during the test period. Variations and mean skill scores in fractional streamflow were similar, but of lesser magnitude. The average change in skill scores (computed for the joint period) from the primary basins to the secondary basins was -.17, with the largest mean change (-.20) occurring in the lowest and most geographically separated basins (Smith and Umpqua Rivers). These results indicate the relative importance of temperature and precipitation in determining regional streamflow response and the validity of extrapolating the results from one basin to another, similar basin. It is interesting to note the highest and lowest scores both occurred during the same season, spring. Spring is the largest single season contributor to annual streamflow for the high elevation basins (where most wet season precipitation falls as snow) and the smallest contributor (of the three seasons modeled) for the low elevation basins (where most precipitation falls as rain). This emphasizes the importance of snow as a storage medium for wet season precipitation.

Figures 11 and 12 illustrate the predictors chosen by regression models for the measured and fractional streamflow, respectively. The relative importance of the predictor variables was dependent, to a large extent, on the elevation of the basins. For the low elevation basin, temperature and fall base flow were never important (at the .95 significance level). For the volumetric streamflow, the only important indicators were the in-season and preceding season precipitation, with only the in-season being important during the winter. This illustrates the "immediate" nature of the low elevation basin streamflow. When precipitation occurs, streamflow occurs. The fractional streamflow was influenced by precipitation in other seasons, but only by precipitation.

The mid-level basin models showed no influence of temperature during the fall, with temperature being of only secondary importance during winter and spring. This was true for both actual and fractional streamflow with in-season temperature being important only for fractional streamflow. Actual streamflow, with the exception of the fall, which only knows about in-season precipitation, is able to remember the precipitation for the two preceding seasons instead of just one. Temperature would probably be a more important contributor, with consequently improved skill scores, if a method for measuring the individual storm temperature profiles can be devised. The temperatures used in this study so far are monthly means. It is anticipated that the height of the freezing level and variations in the lapse rate during individual storm events play a more important role in the mid level basins than in any other basin, but the freezing level is only poorly represented by the monthly mean temperature and the lapse rate not represented at all. The mid level basin spring fractional streamflow was the only model in which October streamflow survived stepwise elimination, and then only as a minor contributor.

Temperature was a significant contributor in all seasons for both actual and fractional streamflow fluctuations in the high elevation basin. The high elevation basin, with its greater ability to store precipitation of any season as snow, has the greatest ability to remember preceding season precipitation. It also has the greatest dependence on monthly and seasonal mean temperatures. The difference of a few degrees in seasonal mean temperatures can cause significant shifts in the timing of maximum streamflow.

This study also benefited from the NOAA funded Experimental Climate Forecast Center at Scripps Institution of Oceanography. Two manuscripts describing results of this work on Sierra runoff trends are in preparation. Also, Larry Riddle is presently incorporating much of this topic into his Master's Thesis at San Diego State University, to be completed within the next year.

In addition to our work on the California fractional runoff trends, this Water Resources Center grant was used to augment three associated studies concerning climatic influences on California streamflow. These were done in collaboration with the U.S. Geological Survey, the NOAA Experimental Climate Forecast Program, and the University of California's INCOR Program. Three articles have been published which explain this work: Cayan and Peterson, 1989; Peterson, *et al.*, 1989; and Enzel, *et al.*, 1989.

In the Cayan and Peterson streamflow study, the annual cycle and non-seasonal variability of streamflow over western North America (including several California stations) was studied in terms of atmospheric forcing elements. This study uses several decades of monthly average streamflow beginning as early as the late 1800's over a network of 38 stations. In addition to a strong annual cycle in mean streamflow and its variance at most of the stations, there is also a distinct annual cycle in the autocorrelation of anomalies that is related to the interplay between temperature and precipitation. Of particular importance to these lag effects is the well-known role of water stored as snow pack, which controls the delay between peak precipitation and peak flow and also introduces persistence into the non-seasonal streamflow anomalies, with time scales from one month to over one year.

The degree to which streamflow is related to winter atmospheric circulation over the North Pacific and western North America was tested using correlations with time averaged, gridded sea level pressure, which begins in 1899. Winter (December through February) mean atmospheric circulation anomaly patterns over the North Pacific are significantly related to streamflow fluctuations over this network, with maximum correlation coefficients between winter sea level pressure and December-August streamflow ranging from 0.3 to about 0.6. For streams along the West Coast corridor, the circulation pattern associated with positive streamflow anomalies is low sea level pressure (SLP) centered off the coast to the west or northwest, indicative of increased winter storms and an anomalous southwesterly wind component. For streams in the interior, positive streamflow anomalies are associated with a positive SLP anomaly stationed remotely over the central North Pacific, as well as negative but generally weaker SLP anomalies locally.

One important influence on streamflow variability is the strength of the Aleutian Low in winter. This is represented by the familiar Pacific North America (PNA) index and also by the Central North Pacific (CNP), an index beginning in 1899 that is the average of the SLP anomaly south of the Aleutians and the western Gulf of Alaska. Relationships of PNA or CNP with streamflow in certain regions can be interpreted as alternations in strength and position of the mean North Pacific storm track entering North America as well as changes in the trade winds over the subtropical North Pacific. Regions whose streamflow is best tuned to the PNA or CNP include coastal Alaska, the northwestern United States, and Hawaii, the latter two regions having the opposite sign anomaly as the former. The pattern of streamflow variations associated with El Niño is similar, but the El Niño signal also includes a tendency for heavier than normal streamflow in the Southwest United States. These indices exhibit significant correlations to streamflow at one to two seasons in advance of the December-August period, which may allow modestly skillful forecasts. It is emphasized that streamflow variability in some areas, such as British Columbia and California, do *not* behave consistently with these broad scale Pacific atmospheric circulation indices, but respond to more local atmospheric anomaly features over the eastern North Pacific. Spatially, streamflow anomalies are fairly well correlated over scales of several hundred kilometers. Inspection of the spatial anomalies of streamflow in this study suggest an asymmetry in the spatial pattern of positive vs. negative streamflow anomalies in the western United States: dry patterns have tended to be larger and more spatially coherent than wet patterns.

The Peterson *et al.*, study concerned effects of climate variability on various properties in one of the West Coast's most important estuaries, San Francisco Bay. A simple conceptual model of estuarine variability in the context of climate forcing was formulated using up to 65 years of estimated mean-monthly delta flow, the cumulative freshwater flow to San Francisco Bay from the Sacramento-San Joaquin River Delta, and salinity observations near the mouth, head, mid-estuary, and coastal ocean. Variations in delta flow, the principal source of variability in the bay, originate from anomalous changes in northern and central California streamflow, much of which is linked to anomalous winter sea level pressure California Pressure Anomaly (CPA) in the eastern Pacific. In years when CPA is strongly negative, precipitation in the watershed is heavy, delta flow is high, and the bay's salinity is low; similarly, when CPA is strongly positive, precipitation is light, delta flow is low, and the bay's salinity is high. Estuarine salinity can be characterized by river to ocean patterns in annual cycles of salinity in relation to delta flow. Salinity (total dissolved solids) data from the relatively pristine mountain streams of the Sierra Nevada show that for a given flow, one observes higher salinities during the rise in winter flow than on the decline. Salinity at locations throughout San Francisco Bay estuary are also higher during the rise in winter flow than the decline (because it takes a finite time for salinity to fully respond to changes in freshwater flow). Thus the pattern of temporal variability in atmospheric pressure anomalies is reflected in the streamflow, then in delta flow, then in estuarine variability.

The Enzel *et al.*, study sought to explain how persistent lake stands were created in the Mojave Desert during the Holocene period. It is commonly thought that the climate conditions that supported lakes over a period of years in the Mojave Desert in southern California, only existed before 8,000 yr BP and that the environment has been arid since. Here we look at a drill core in the Silver Lake playa at the terminus of the Mojave River and find Holocene lake deposits which indicate that shallow lakes existed for at least a few decades. These deposits were radiocarbon dated at 3620 $\pm$90 yr BP, corresponding to the early Neoglacial and the 'little ice age' respectively. To identify the conditions necessary to produce these Holocene lake events we have examined the modern climate and hydrological patterns that produce ephemeral lakes in this usually arid watershed. Available data indicate that there is a link between anomalous winter atmospheric conditions over the North Pacific and Mojave River floods that produced ephemeral lakes in the Silver Lake playa and that the Mojave River filters out small to medium floods and allows only the extreme floods to reach the terminal playa and leave a record of the anomalous conditions. It was suggested that the late Holocene lakes may have resulted from persistent similar atmospheric circulation patterns and winter floods.

Publications

Cayan, Daniel R., and D. H. Peterson, 1989: The influence of North Pacific atmospheric circulation on streamflow in the west. *Geophysical Monograph 55*, from "Aspects of Climate Variability in the Pacific and the Western Americas", D. H. Peterson, editor, 375-397.

Enzel, Y., D. R. Cayan, R. Y. Anderson, and S. G. Wells, 1989: Atmospheric circulation during Holocene Lake stands in the Mojave Desert. *Nature*, **341**, 44-47.

Peterson, David H., D. R. Cayan, J. F. Festa, F. H. Nichols, R. A. Walters, J. V. Slack, S. E. Hager, and L. E. Schemel, 1989: Climate Variability In An Estuary: Effects of Riverflow On San Francisco Bay. *Geophysical Monograph 55*, from "Aspects of Climate Variability in the Pacific and the Western Americas", D. H. Peterson, editor, 419-442.

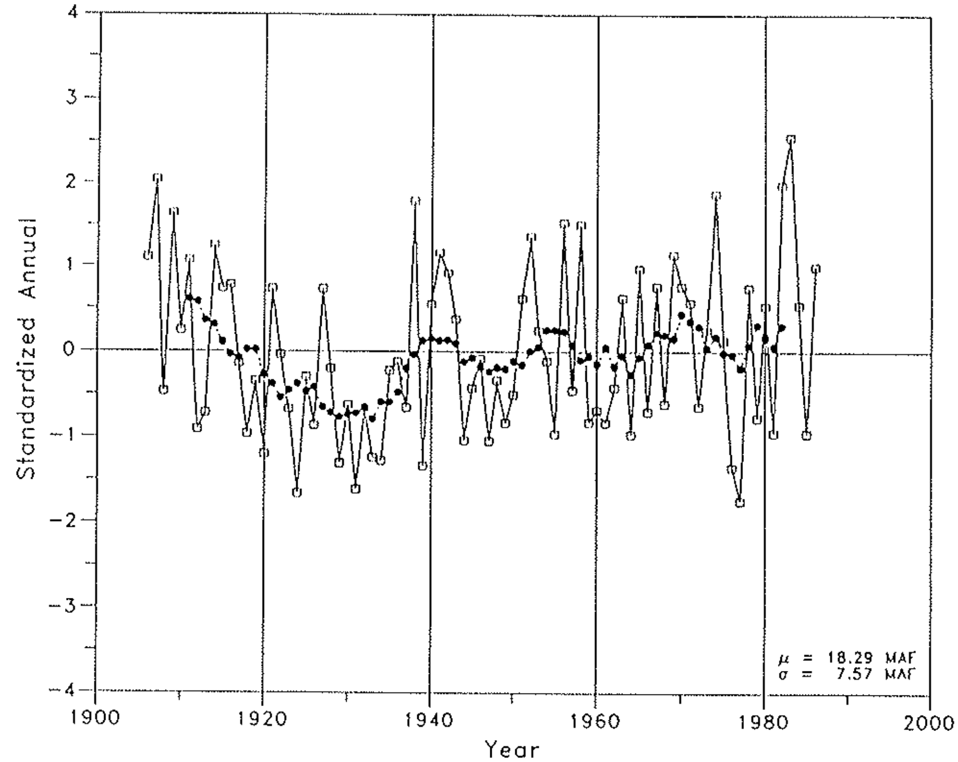

Figure 1. Four Basin Water Year Total Runoff. The open squares show the actual water year total runoff and the closed circles indicate the ten year moving mean runoff.

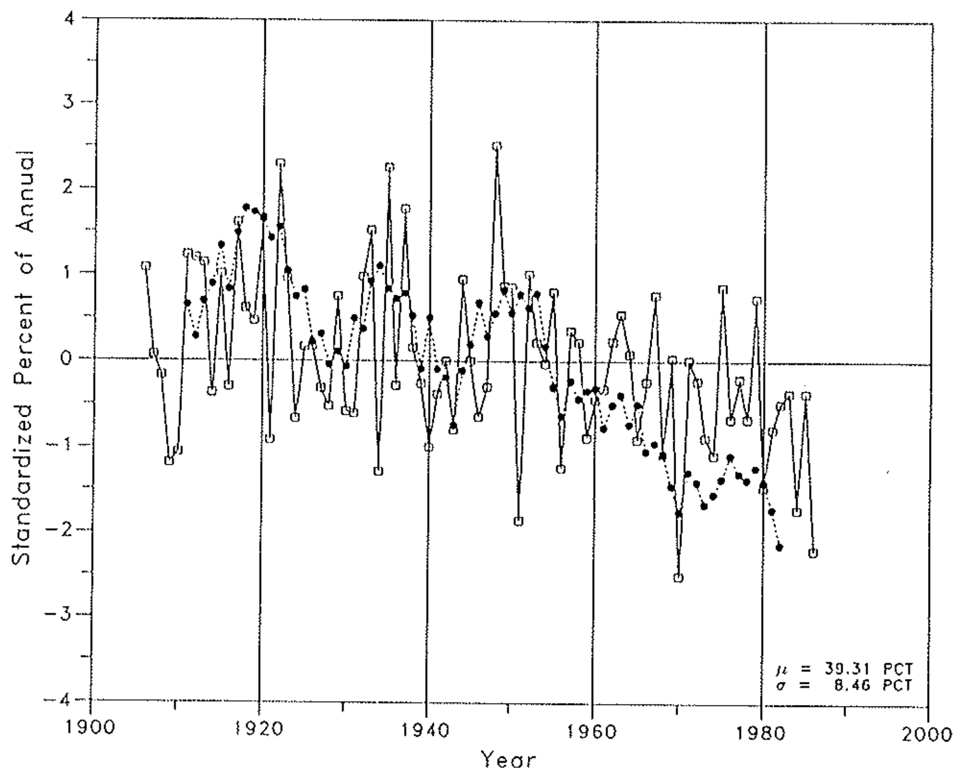

Figure 2. Four Basin Late Spring-Early Summer Runoff Fraction. The portion of the total water year runoff occurring April through July. Symbols are as in Figure 1.

Cosumnes River at Michigan Bar — Mean Basin Elevation: 1121m Area: 1388 km^2
Location: 38.50N 121.04W Period: 1908-1987 Gauge Elevation: 51m Agency: USGS

	O	N	D	J	F	M	A	M	J	J	A	S	Annual
Mean	0.9	4.3	12.9	25.7	34.1	33.6	31.3	19.9	7.2	1.7	0.6	0.4	14.4
CoVar	137.5	220.3	166.7	117.5	91.5	79.2	69.9	70.2	83.9	94.9	100.0	114.3	112.2
Percent	0.23	0.53	2.51	7.48	14.90	19.76	19.45	18.17	11.50	4.18	0.97	0.33	

American River at Fair Oaks — Mean Basin Elevation: 1433m Area: 4890 km^2
Location: 38.64N 121.23W Period: 1905-1986 Gauge Elevation: 22m Agency: USGS

	O	N	D	J	F	M	A	M	J	J	A	S	Annual
Mean	28.0	51.9	92.4	140.5	167.0	174.7	194.2	198.0	131.2	59.7	37.2	30.8	108.8
CoVar	93.5	130.4	117.3	103.6	81.6	71.5	57.6	59.3	71.7	76.1	102.3	109.2	89.5
Percent	2.36	2.14	3.98	7.08	10.76	12.79	13.38	14.87	15.16	10.05	4.58	2.85	

San Joaquin River (Estimated Unimpaired Flow) — Mean Basin Elevation: 2286m Area: 3354 km^2
Location: 37.01N 119.70W Period: 1901-1988 Agency: CalDWR

	O	N	D	J	F	M	A	M	J	J	A	S	Annual
Mean	10.7	16.0	26.6	37.8	51.3	67.8	117.3	207.4	196.0	86.2	27.8	12.3	71.4
CoVar	95.2	105.0	123.0	96.2	76.8	61.0	42.8	43.2	59.0	91.0	88.3	97.0	81.5
Percent	1.43	1.25	1.87	3.11	4.41	5.99	7.91	13.69	24.19	22.86	10.05	3.24	

Merced River at Happy Isles Bridge, Yosemite NP — Mean Basin Elevation: 2743m Area: 469 km^2
Location: 37.73N 119.56W Period: 1916-1987 Gauge Elevation: 1224m Agency: USGS

	O	N	D	J	F	M	A	M	J	J	A	S	Annual
Mean	1.1	1.8	2.5	2.3	3.0	5.0	15.1	36.2	35.4	13.1	3.2	1.3	10.0
CoVar	133.3	169.8	155.1	91.4	72.6	50.6	30.7	36.4	54.0	88.8	108.8	140.0	95.0
Percent	1.06	0.92	1.49	2.10	1.91	2.50	4.20	12.56	30.17	29.49	10.93	2.67	

Smith River at Crescent City — Mean Basin Elevation: 457m Area: 1577 km^2
Location: 41.79N 124.05W Period: 1932-1987 Gauge Elevation: 27m Agency: USGS

	O	N	D	J	F	M	A	M	J	J	A	S	Annual
Mean	32.3	140.8	220.8	243.9	221.3	187.2	124.6	79.2	34.2	15.0	9.6	9.8	109.9
CoVar	153.1	86.3	65.7	59.0	51.0	47.9	51.8	55.2	59.3	36.2	27.1	65.4	63.2
Percent	0.75	2.45	10.68	16.74	18.50	16.78	14.19	9.45	6.00	2.60	1.13	0.73	

Umpqua River at Elkton — Mean Basin Elevation: 756m Area: 9539 km^2
Location: 43.59N 123.55W Period: 1906-1987 Gauge Elevation: 28m Agency: USGS

	O	N	D	J	F	M	A	M	J	J	A	S	Annual
Mean	54.9	206.1	383.6	452.2	438.9	350.6	271.8	183.7	106.4	49.4	33.4	34.2	213.8
CoVar	85.5	79.4	70.9	54.5	44.6	44.4	41.6	44.3	48.9	41.5	20.4	29.2	50.4
Percent	1.33	2.14	8.03	14.96	17.63	17.11	13.67	10.60	7.16	4.15	1.93	1.30	

Table I. Primary and Secondary River Basin Description and Statistics. The three basin pairs used in the regression model portion of this study. Mean streamflow is in cubic meters per second, "CoVar" is the coefficient of variation (Std dev/mean), and "Percent" refers to the mean fraction of water year streamflow for each month.

Basin	Period	NDJ	FMA	MJJ	NDJ%	FMA%	MJJ%	Mean
Smith	WY13-49	0.82	0.66	0.30	0.59	0.73	0.40	0.58
	WY50-86	0.85	0.79	0.40	0.85	0.86	0.51	0.71
	WY13-86	0.83	0.69	0.38	0.77	0.81	0.51	0.66
Cosumnes	WY13-49	0.69	0.64	0.74	0.63	0.63	0.67	0.67
	WY50-86	0.61	0.88	0.74	0.70	0.76	0.76	0.74
	WY13-86	0.64	0.78	0.72	0.69	0.67	0.70	0.70
San Joaquin	WY13-49	0.62	0.69	0.77	0.41	0.65	0.55	0.61
	WY50-86	0.84	0.90	0.92	0.78	0.70	0.73	0.81
	WY13-86	0.78	0.81	0.86	0.64	0.67	0.61	0.73
Mean	WY13-49	0.71	0.66	0.60	0.54	0.67	0.54	0.62
	WY50-86	0.77	0.85	0.68	0.78	0.78	0.67	0.75
	WY13-86	0.75	0.76	0.66	0.70	0.72	0.61	0.70
Umpqua	WY13-86	0.67	0.46	0.19	0.58	0.56	0.35	
American	WY13-86	0.64	0.71	0.64	0.56	0.33	0.45	
Merced	WY13-86	0.52	0.38	0.90	0.48	0.62	0.58	
Smi to Ump δR^2		0.01	-0.08	-0.09	-0.13	-0.34	-0.25	-0.15
Cos to Ame δR^2		-0.16	-0.23	-0.20	-0.19	-0.25	-0.16	-0.20
SJq to Mer δR^2		-0.27	-0.42	0.04	-0.16	-0.06	-0.03	-0.15
Mean		-0.14	-0.24	-0.08	-0.16	-0.22	-0.15	-0.17

Table II. Model Run Skill Scores. The skill scores for the runoff models used in this study. The skill score is expressed as the fraction of total variance accounted for, with 1.00 being a perfect score.

NDJ/annual streamflow trend significance

1948 - 1986

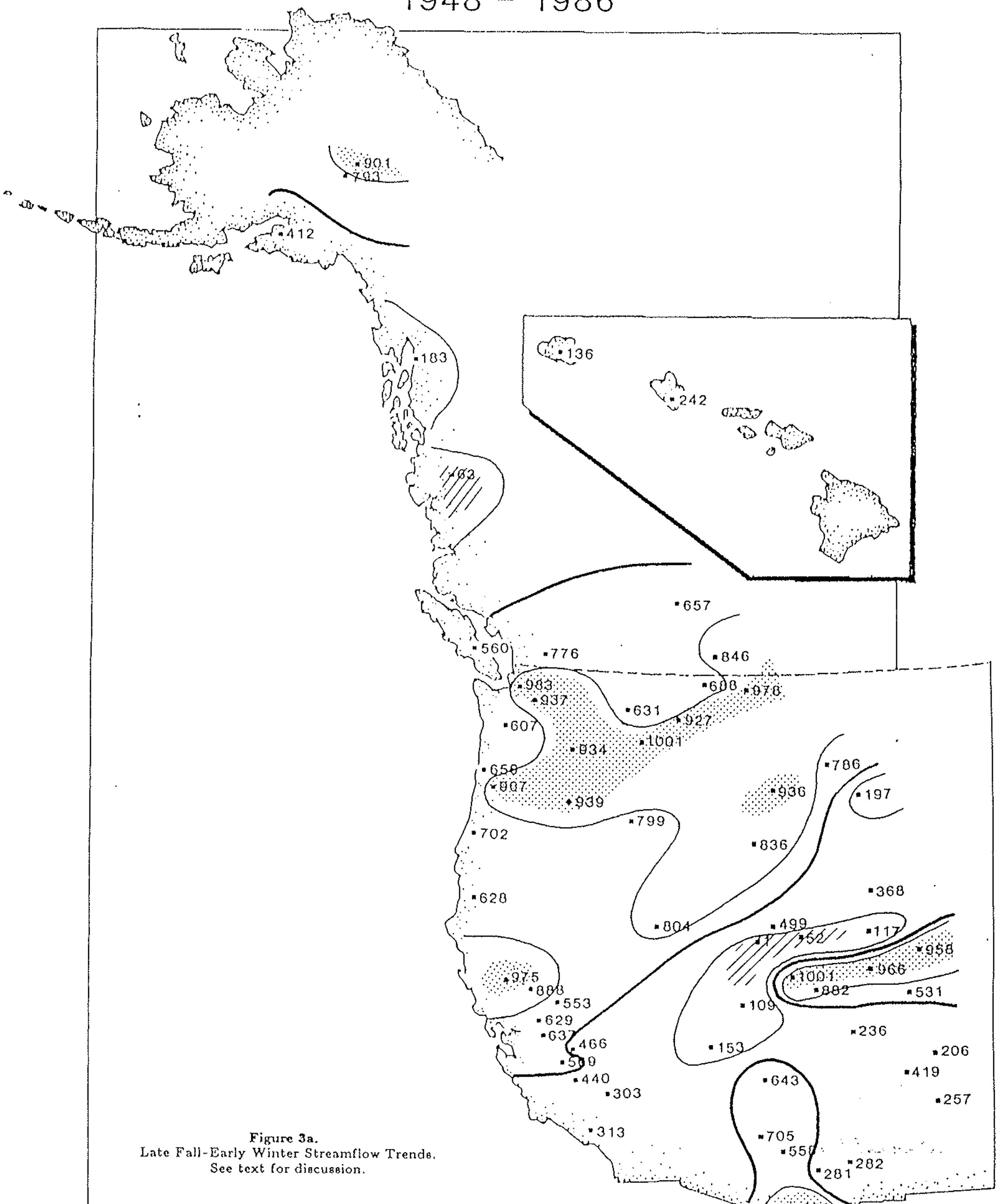

Figure 3a.
Late Fall-Early Winter Streamflow Trends.
See text for discussion.

FMA/annual streamflow trend significance

1948 - 1986

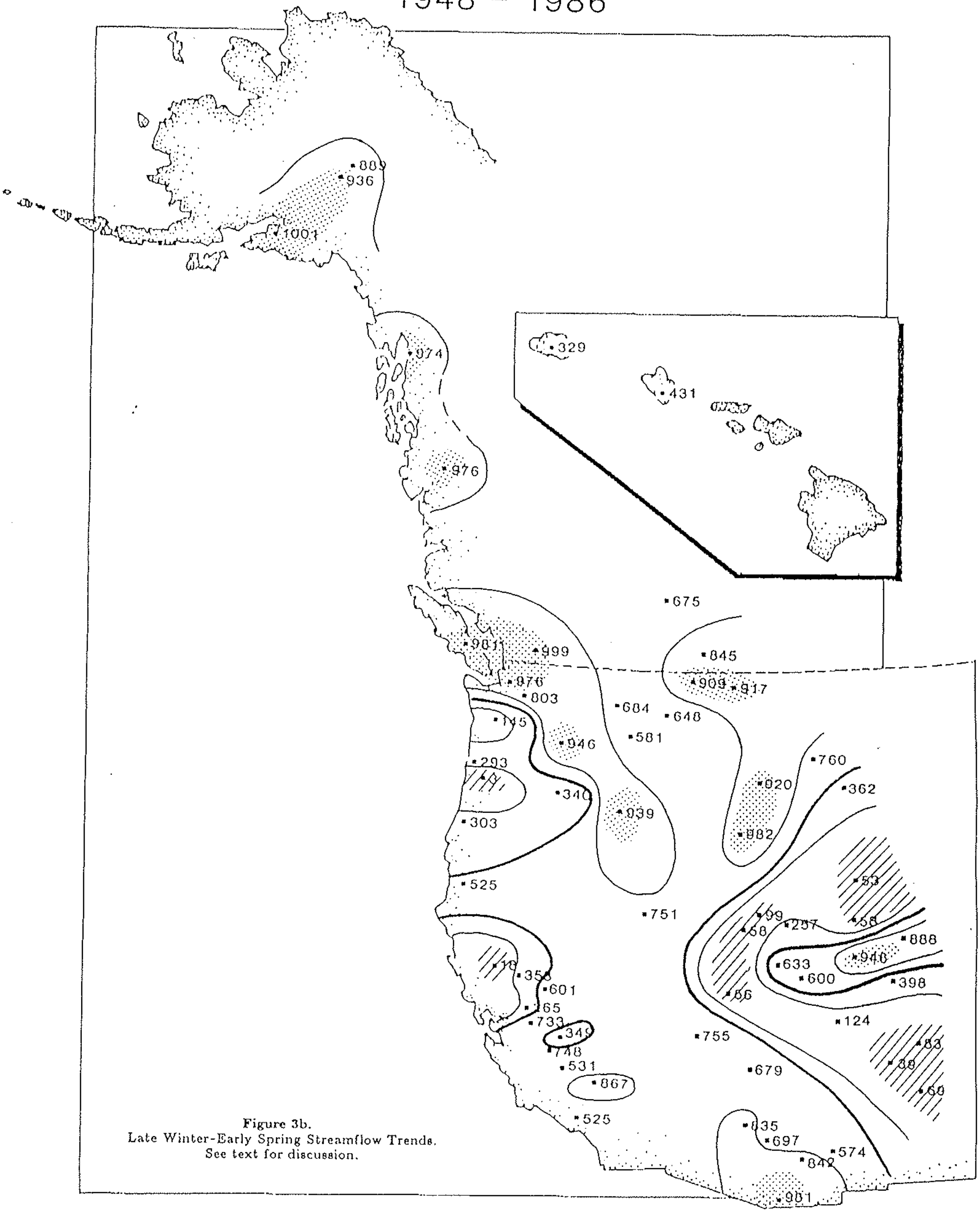

Figure 3b.
Late Winter-Early Spring Streamflow Trends.
See text for discussion.

MJJ/annual streamflow trend significance

1948 - 1986

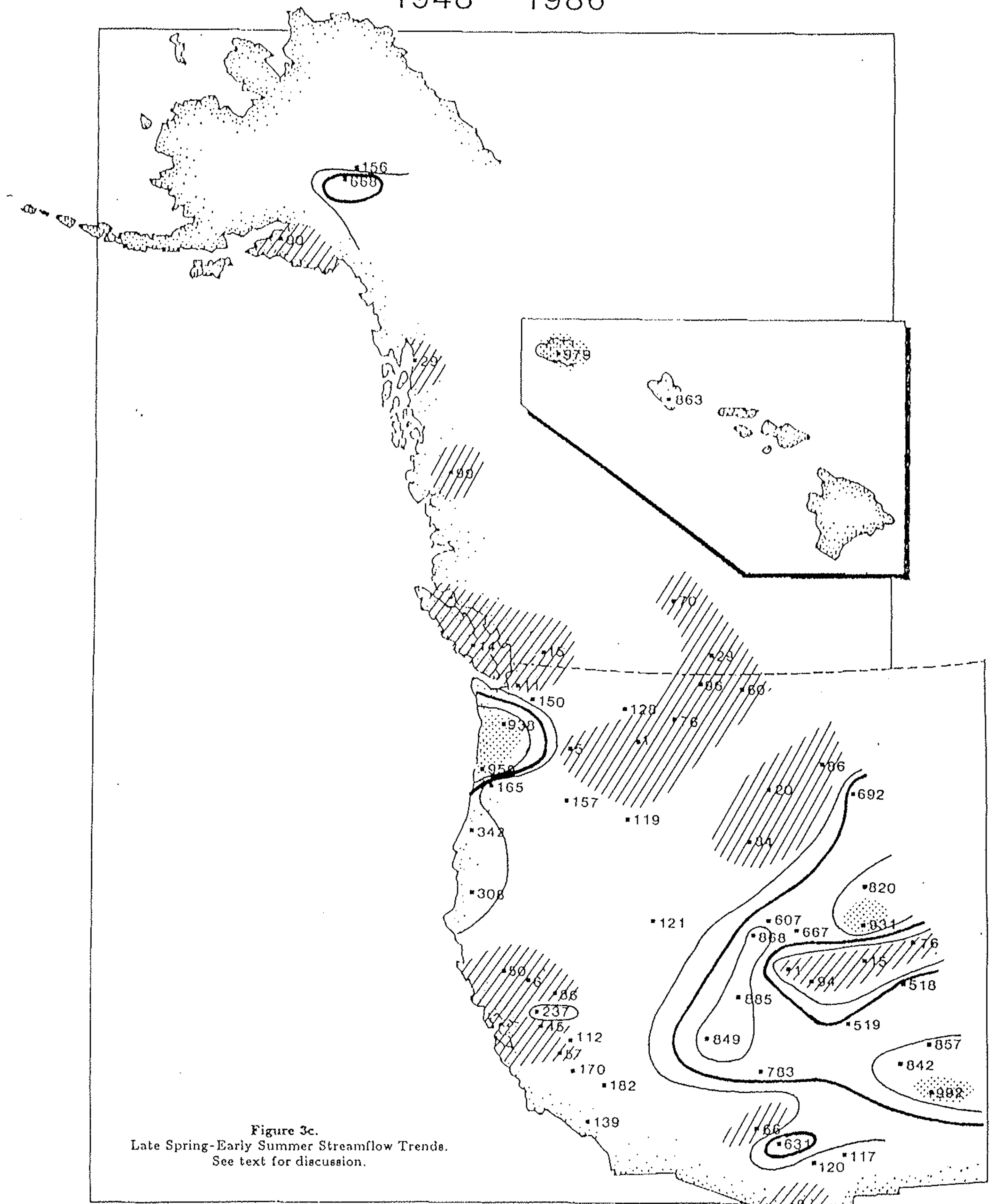

Figure 3c.
Late Spring-Early Summer Streamflow Trends.
See text for discussion.

FMA temperature trend x no. yrs. 1948 - 1986

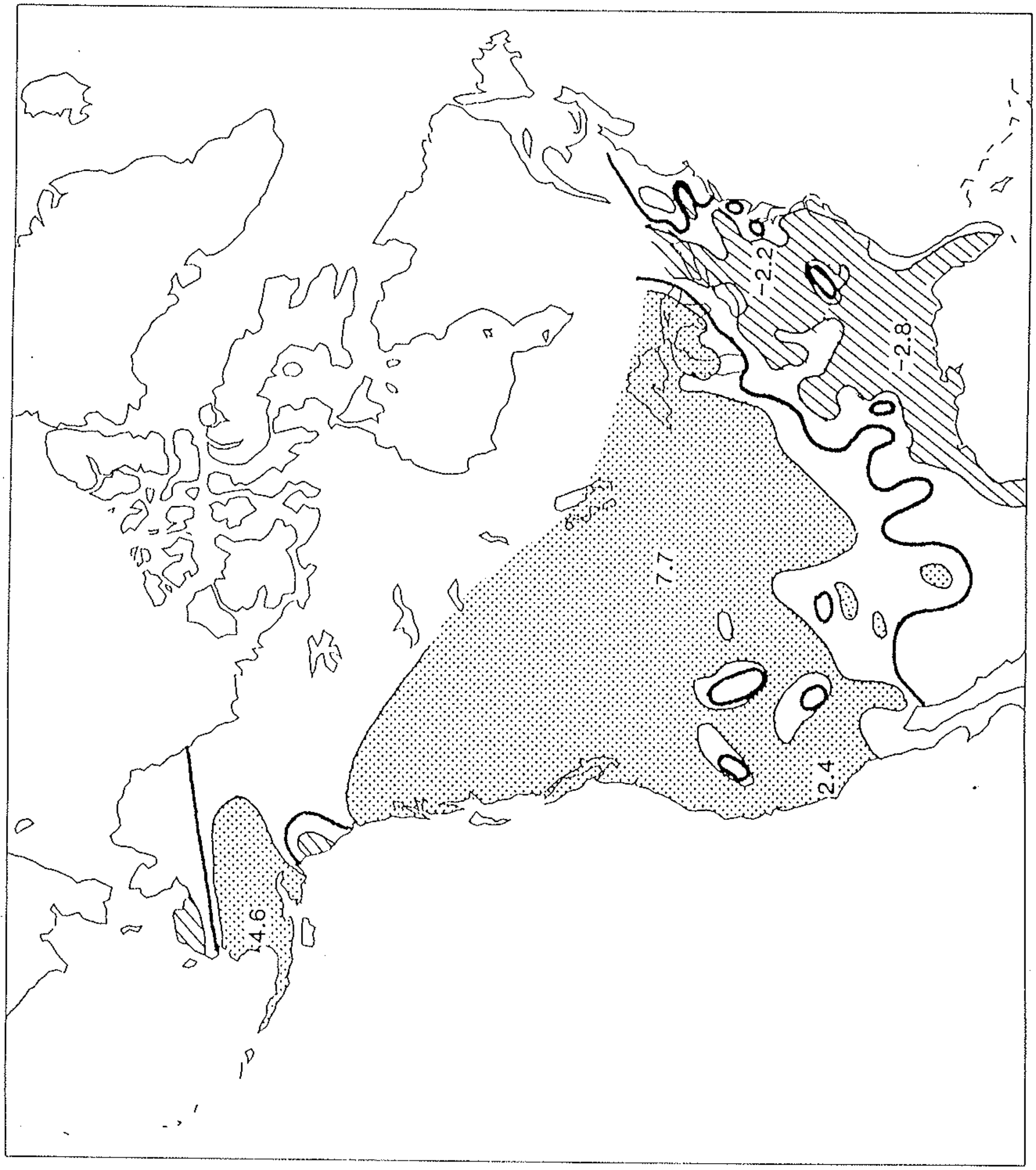

Figure 4a.
Late Winter-Early Spring Temperature Trends.
See text for discussion.

MJJ temperature trend x no. yrs. 1948 – 1986

Figure 4b.
Late Spring-Early Summer Temperature Trends.
See text for discussion.

FMA precipitation trend x no. yrs. 1948 – 1986

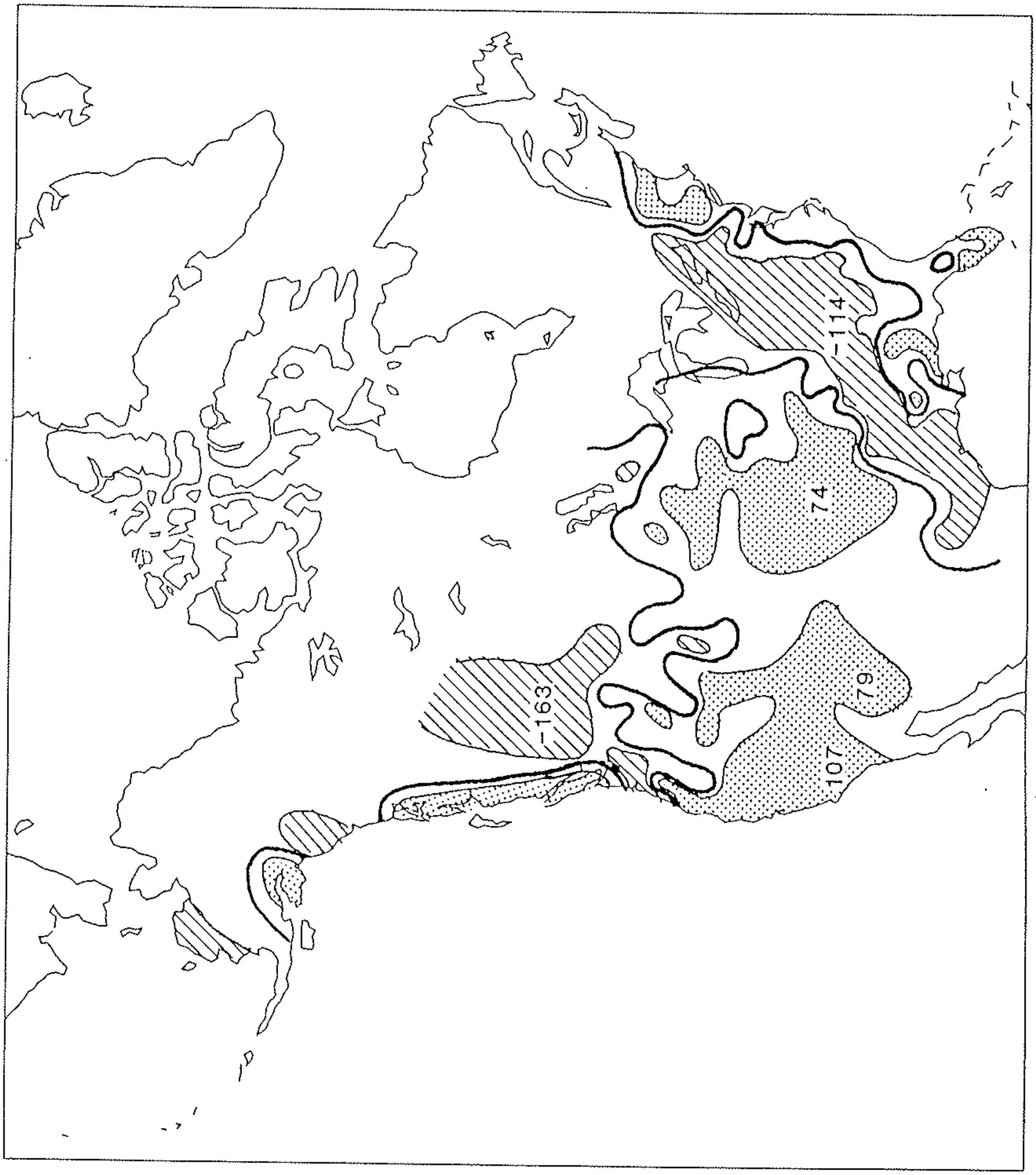

Figure 4c.
Late Winter-Early Spring Precipitation Trends.
See text for discussion.

MJJ precipitation trend x no. yrs. 1948 – 1986

Figure 4d.
Late Spring-Early Summer Precipitation Trends.
See text for discussion.

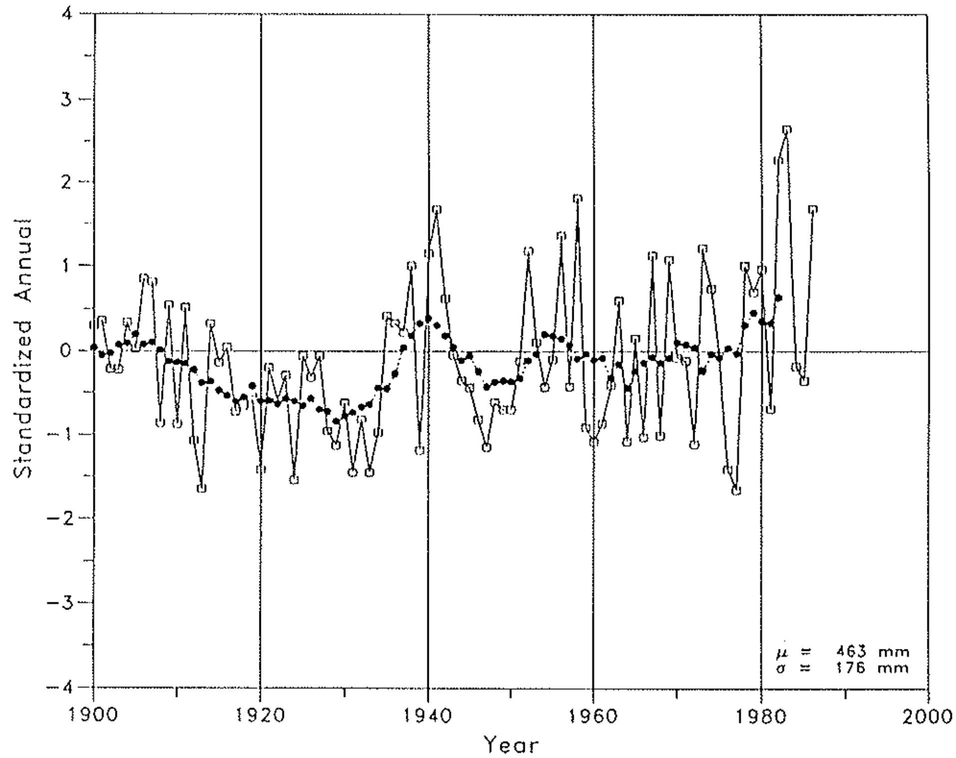

Figure 5. Long Term Trend in Sacramento Water Year Precipitation.

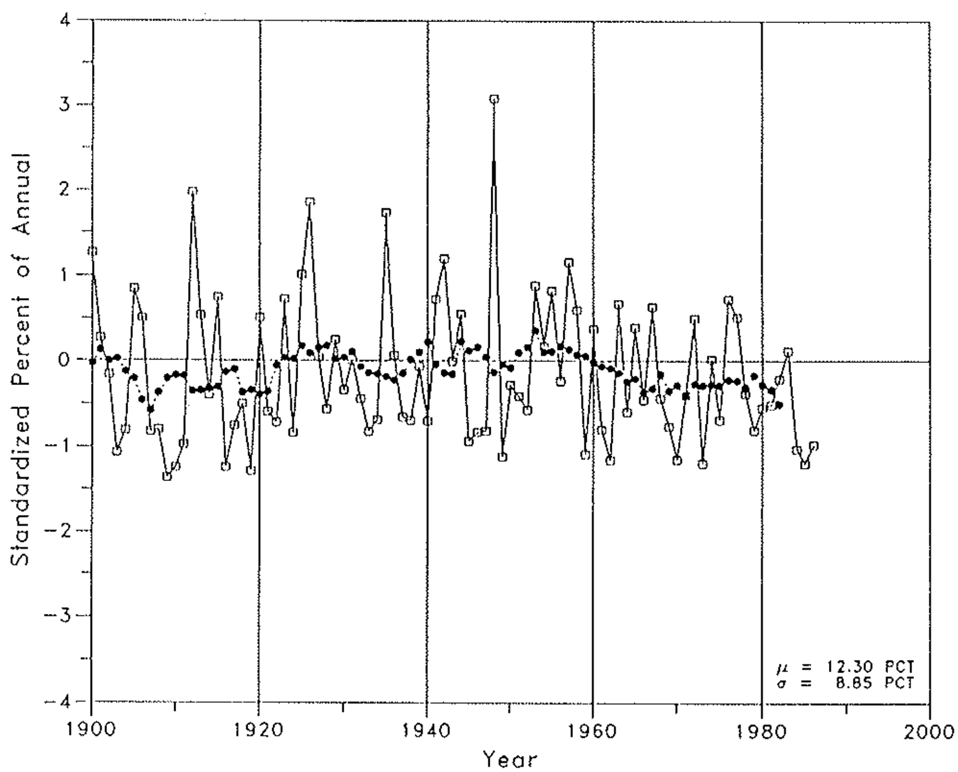

Figure 6. Long Term Trend in Sacramento AMJJ Precipitation.

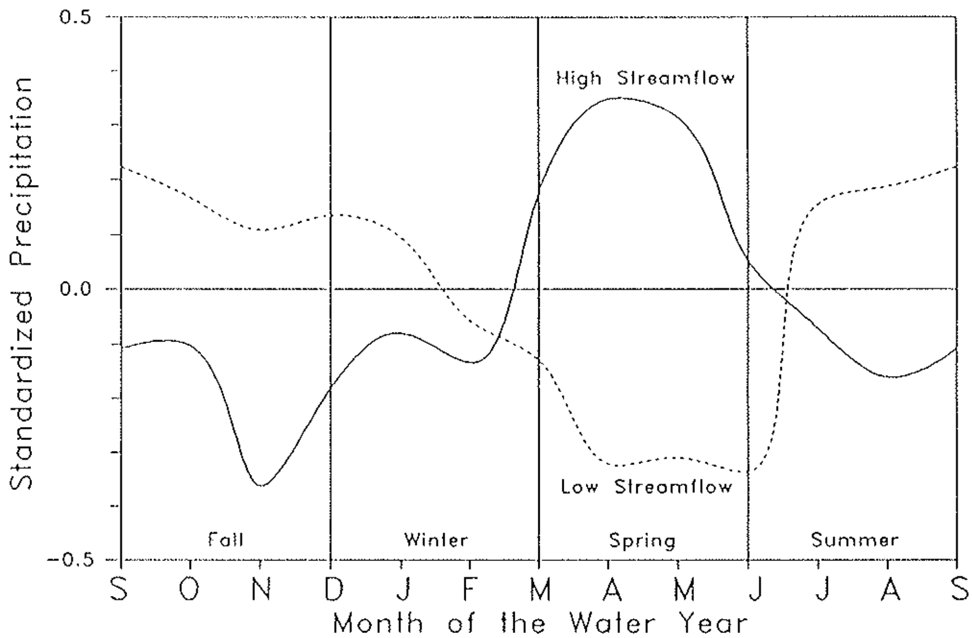

Figure 7. Four Basin High/Low AMJJ Fraction Tercile Precipitation. The mean monthly precipitation for the high and low terciles of AMJJ to water year runoff.

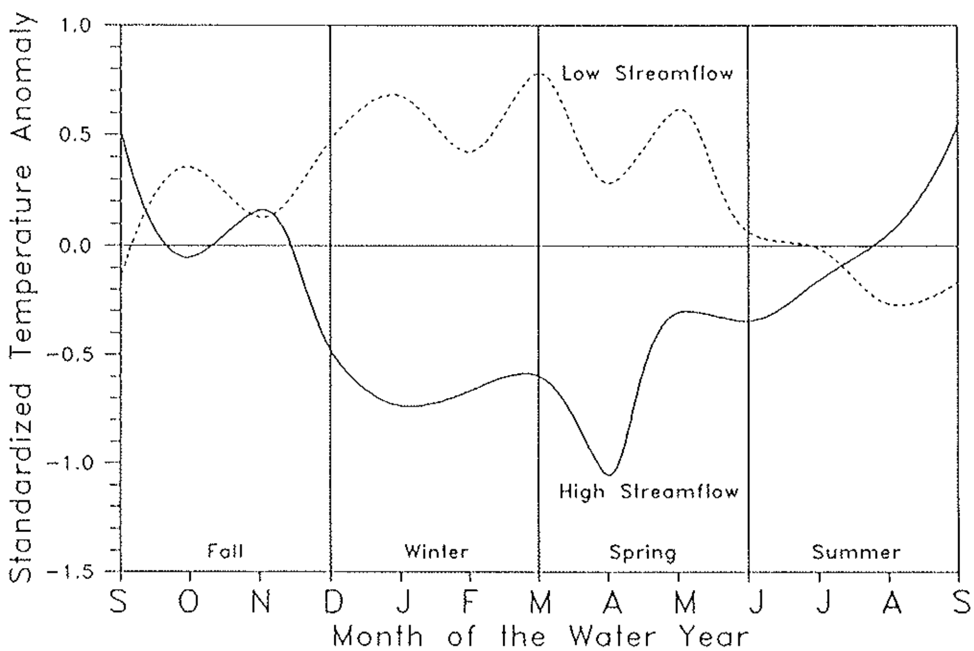

Figure 8. Four Basin High/Low AMJJ Fraction Tercile Temperature Anomalies. The mean monthly air temperature anomalies (departures from the mean) for the high and low terciles of AMJJ to water year runoff. See text for discussion.

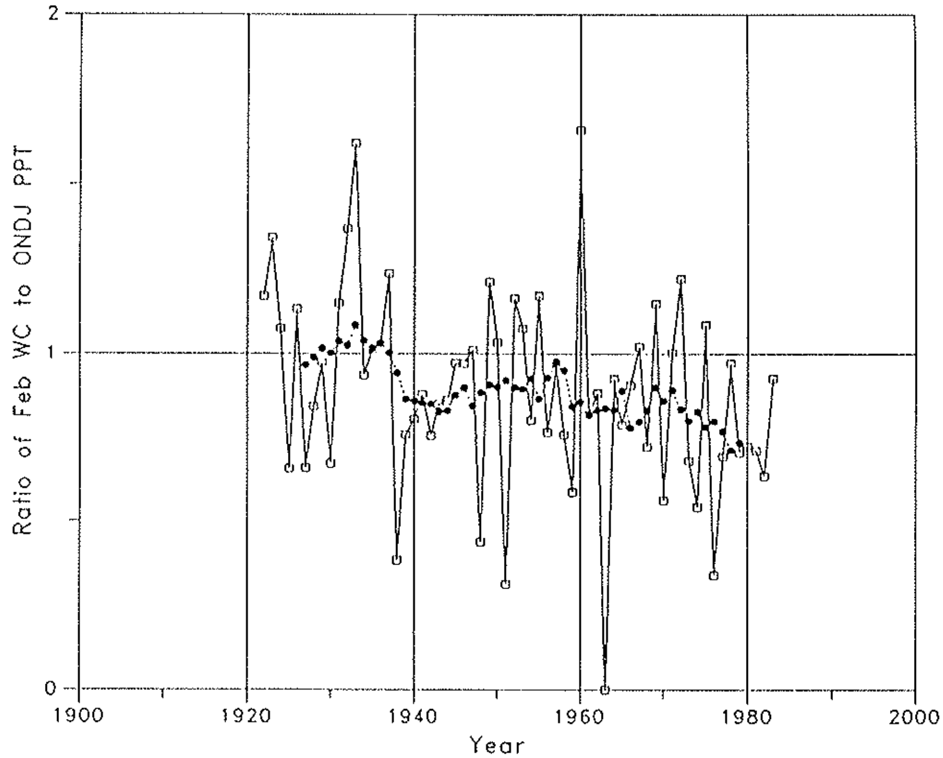

Figure 9. Donner Summit Snow Water Content vs. Nevada City Precipitation. The ratio of snow water content measured at Donner Summit on February 1 to Fall-Early Winter (October through January) precipitation measured at Nevada City.

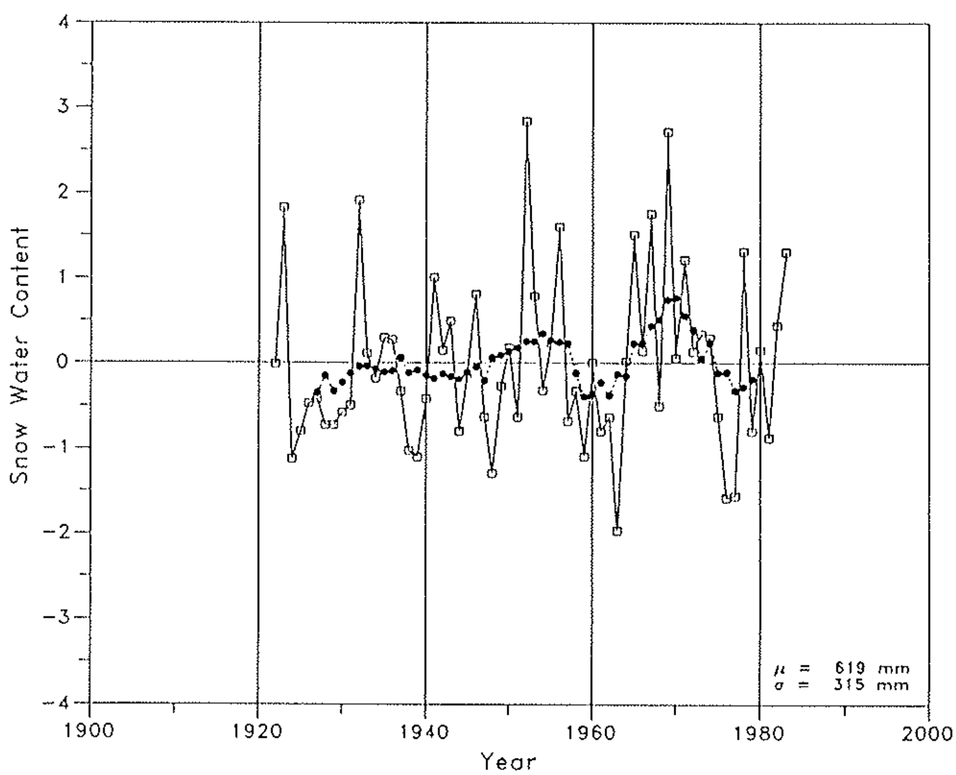

Figure 10. Donner Summit February 1 Snow Water Content. Symbols as in Figure 1.

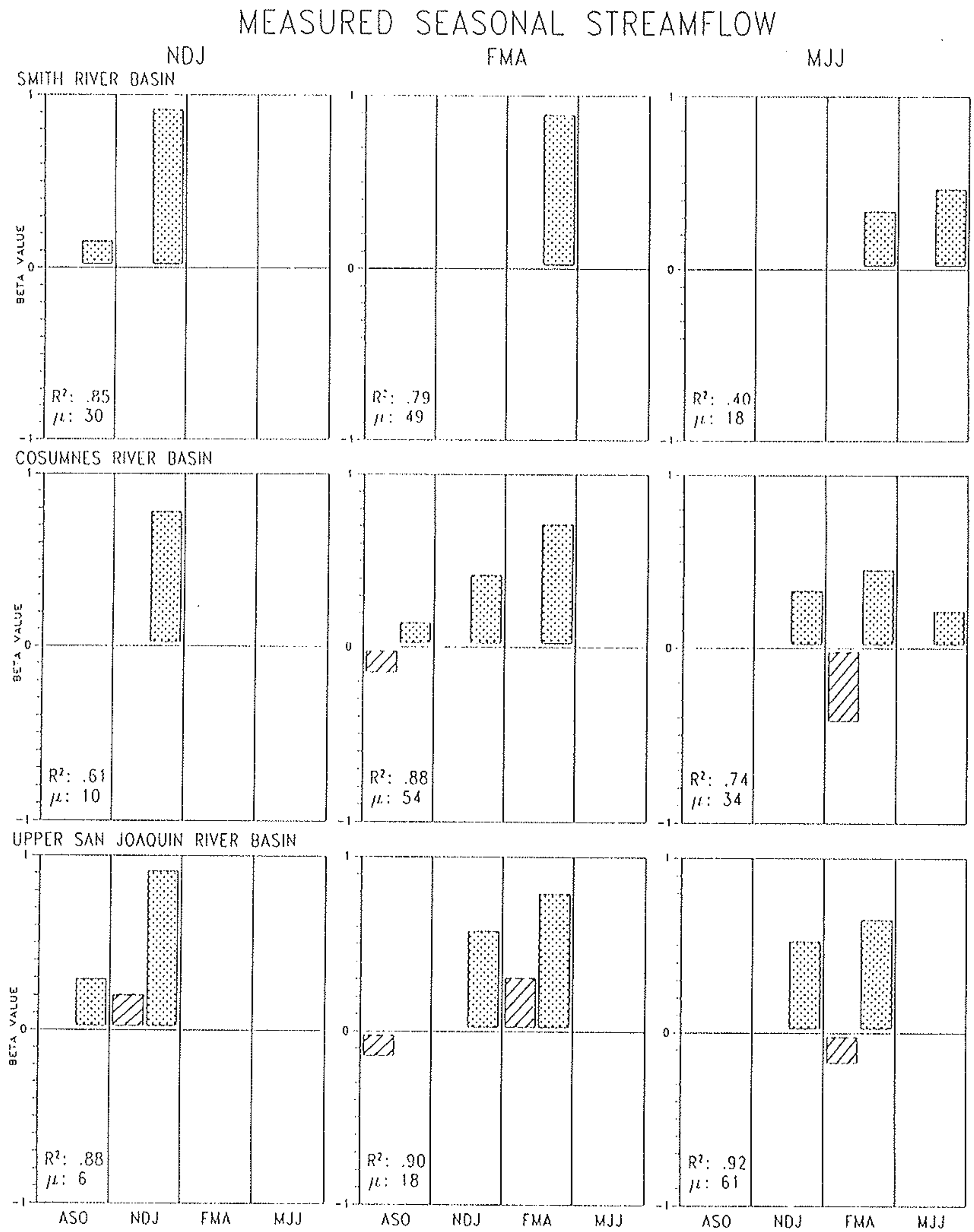

Figure 11. Measured Runoff Model Predictors.

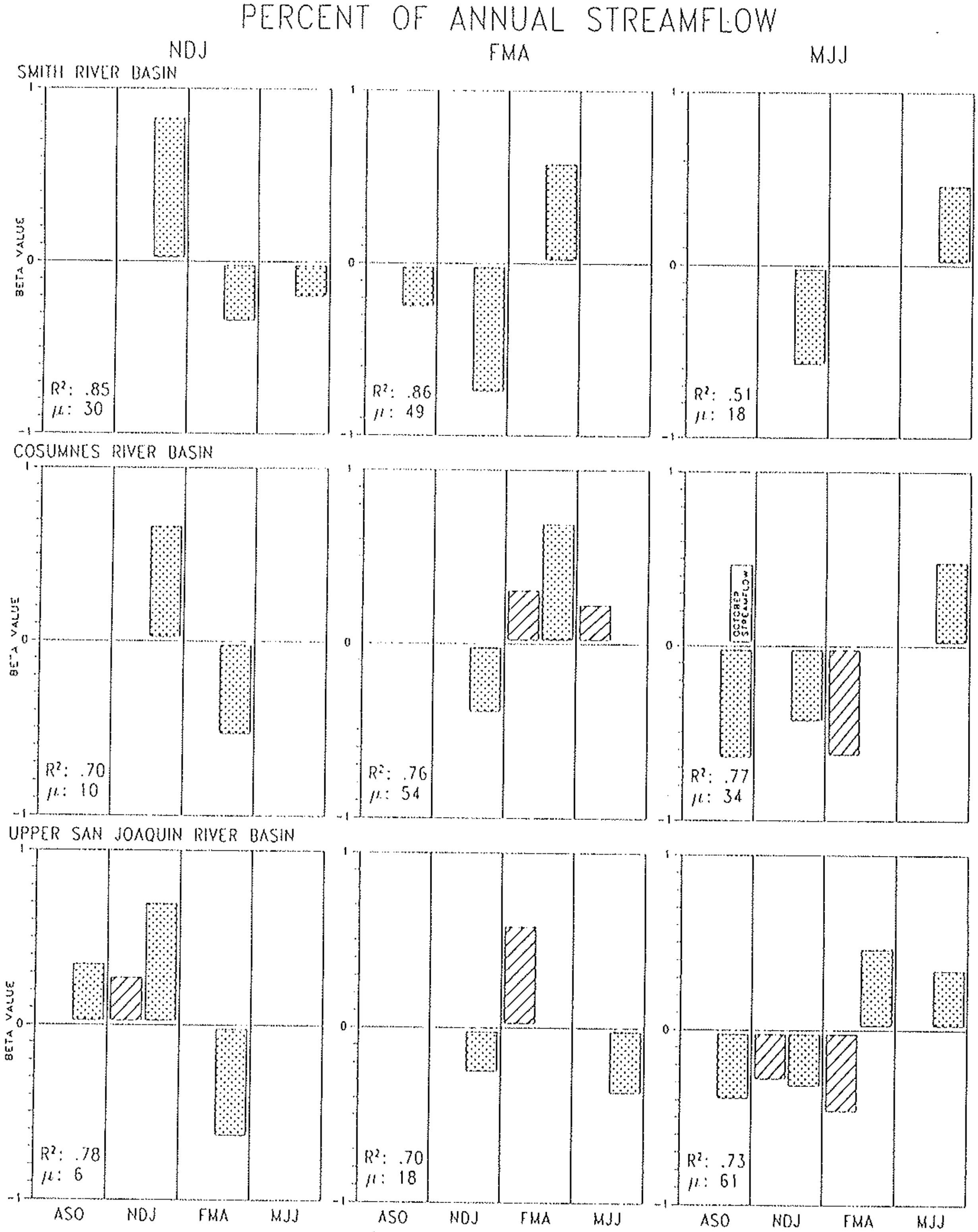

Figure 12. Fractional Runoff Model Predictors.