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TRENDS IN FRESHWATER INFLOW TO SAN FRANCISCO BAY FROM THE SACRAMENTO-SAN JOAQUIN DELTA[1]

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ABSTRACT: Outflow from the Sacramento-San Joaquin river system (Delta outflow) provides about 90 percent of the freshwater flow to San Francisco Bay. Because this river system also supplies most of the water used in California, some believed that annual freshwater flow to the Bay had declined by as much as 50 to 60 percent as water use increased. Consequently, we studied trends in actual Delta outflow and precipitation for the period 1921 to 1986, which is when Delta outflow data are available. We found that there has been no decrease in the annual Delta outflow over this period. In fact, a statistically significant increase in annual Delta outflow of 87 cfs/yr has occurred during the period 1921 to 1986. One reason that Delta outflow has increased is because precipitation has increased faster than water use. Other contributing factors include increased runoff from land use changes, water imports from other areas, and the redistribution of ground water. In addition, statistically significant seasonal trends in Delta outflow were found. Over the period 1921-1986 Delta outflow decreased in April and May and increased from July through November. Changes in other months were not statistically significant. These seasonal changes result primarily from the operation of upstream flood control and water development projects, which store water in the spring and release it in the summer and fall. These seasonal changes are also influenced by a climatic shift that has decreased spring snowmelt runoff and increased late summer through winter precipitation.

(KEY TERMS: San Francisco Bay; Delta outflow; nonparametric trend analysis; precipitation.)

INTRODUCTION

San Francisco Bay is the largest estuary along the Pacific coast of the United States (Conomos *et al.*, 1985). Ninety percent of the Bay's freshwater inflow comes from the Sacramento-San Joaquin Delta and its tributary river system, which drains the area enclosed within the dashed line on Figure 1. This watershed includes the Central Valley, one of the richest agricultural regions in the world. The Sacramento-San Joaquin drainage supplied about 55 percent of the freshwater used in California in 1985, or some 2.2 billion cubic feet per day (19 million acre-feet per year), including about 60 percent of the irrigation water and 40 percent of the drinking water (CDWR, 1988). This water is moved throughout the state in complex man-made water systems, with 1.2 trillion cubic feet (27 million acre feet) of reservoir storage and some 1300 miles of aqueduct (described in Kahrl, 1979; CDWR, 1983). Water consumptively used within or exported out of this region would otherwise flow into San Francisco Bay.

Some have claimed that this upstream development reduced the total amount of freshwater reaching the Bay by 50 to 60 percent (Meyer and Davoren, 1981; Nichols *et al.*, 1986; Rozengurt *et al.*, 1987). These alleged reductions in freshwater flow have been blamed for adverse affects on Bay fisheries and water quality (Kjelson *et al.*, 1982; Herrgesell *et al.*, 1983). However, these claims of flow reduction are not based on analyses of the amount of freshwater actually reaching the Bay. Instead, they arise from an inappropriate use of hypothetical flows developed for planning purposes by the California Department of Water Resources (CDWR).

In this paper, we analyze actual freshwater inflow to the San Francisco Bay to quantify annual and seasonal changes. Our study was designed to answer three questions: (1) Has there been a large decline in the annual amount of freshwater reaching San Francisco Bay? (2) Have there been changes in the seasonal patterns of freshwater flow to the Bay? and (3) What are the principal causes of any noted changes?

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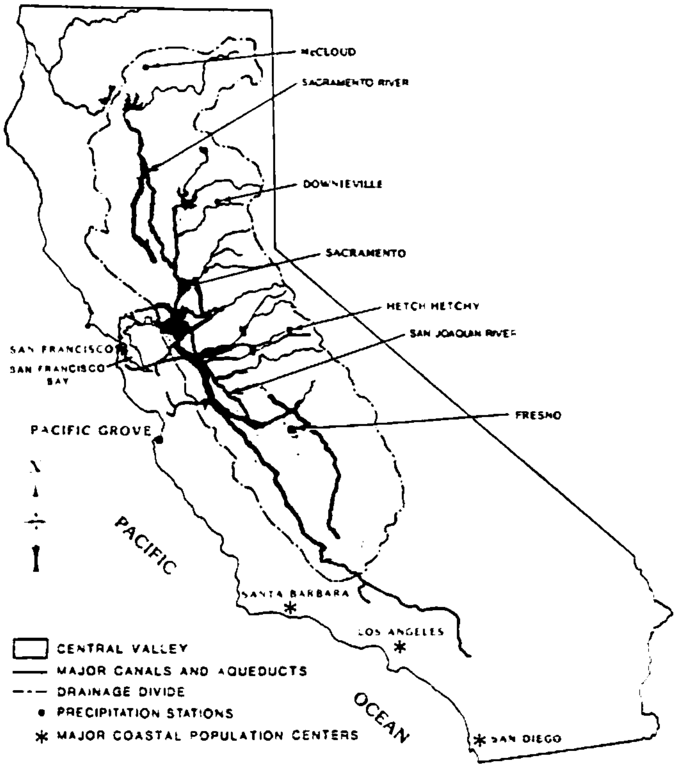

Figure 1. Major Features of California's Central Valley That Influence Freshwater Flow to San Francisco Bay.

THE DATA

Descriptive information on the flow and precipitation data that we analyzed is summarized in Table 1. The starting point for our work was monthly flow and precipitation time series for the period from October 1920 through September 1986 (water years 1921 to 1986). All references to years in this work are to water years unless otherwise noted. The monthly time series were used to compute annual and seasonal time series. Annual water-year precipitation series were formed by summing the total monthly precipitation from October through September for each year. Annual water-year flow series were formed by computing the monthly average flow in cfs for each year. Seasonal time series were formed by separating the monthly time series into 12 monthly data sets where successive values are one year apart (e.g., a January series, a February series, etc.). All three of these time series – monthly, annual, and seasonal – were analyzed in this work.

Actual Delta Outflow

To identify and describe trends in freshwater flow into San Francisco Bay, we analyzed California Department of Water Resources (CDWR) monthly Delta outflow data (Table 1). Delta outflow is the estimated net freshwater flow at Chipps Island at the western edge of the Delta (Figure 2). It is calculated from a water balance around the Delta (Figure 2a) because strong tidal fluctuations preclude direct measurement (CDWR, 1987a, plus updates). It is computed from gauged streamflows and estimated net consumptive use within the Delta resulting from about 1800 agricultural diversions.

We used the available record, which spans the period from October 1920 through September 1986. These data should reflect historic changes in freshwater flow from upstream development because the record covers the period when most of the development occurred. For example, about 95 percent of the total upstream reservoir storage capacity has been built since 1921, exports out of the drainage commenced in 1929, and major features of the Federal Central Valley Project and the California State Water Project were completed in the 1950s and 1960s, respectively (CDWR, 1983).

Precipitation

Because Delta outflow results from precipitation on upstream drainages, we also analyzed precipitation records over the same period (Table 1) at five locations to determine if climatic changes had occurred (CDWR, 1980; NOAA, 1981-1986). These locations, shown in Figure 1, are: McCloud and Downieville in the mountains of the northern part of the drainage; Sacramento in the northern lowlands; Hetch Hetchy in the mountains of the southern part of the drainage; and Fresno in the southern lowlands (Table 1). We selected these stations because they provide good geographic coverage of the upstream watersheds that drain into the Bay, they are among the few that have nearly continuous records for the period from 1921 to 1986, and they have not been affected by major station moves or instrumentation changes.

Unimpaired Delta Outflow

CDWR also estimates the total river flow available for present use, and this is called unimpaired flow (CDWR, 1987b). We analyzed unimpaired flows to help explain trends in actual Delta outflow since trends in unimpaired flows are principally due to

TABLE 1. Descriptive Information on the Flow and Precipitation Data Analyzed in This Study.

Type of Data	Period of Record	No. Values	Median	Mean	Standard Deviation	Range	Lag-1 ACC*	Durbin Watson d**
FLOW DATA (average flow in cfs*)**								
Actual Delta Outflow								
Annual Time Series	1921–1986	66	28,486	30,240	17,743	3,513 – 89,452	0.074	1.84
Monthly Time Series	10/20–9/86	792	15,729	30,441	36,678	–3,578 – 270,412	0.69	0.61
Unimpaired Delta Outflow								
Annual Time Series	1921–1983	63	34,991	39,213	19,598	7,603 – 99,514	–0.01	1.88
Monthly Time Series	10/20–9/83	756	24,008	39,378	40,521	2,472 – 258,426	0.68	0.65
Depletions								
Annual Time Series	1921–1983	63	8,180	9,052	4,924	2,038 – 28,514	–0.23	2.34
Monthly Time Series	10/20–9/83	756	4,464	9,023	15,756	–39,055 – 82,342	0.46	1.13
PRECIPITATION DATA (total precipitation in inches*)**								
McCloud								
Annual Time Series	1921–1986	66	47.67	49.71	15.90	14.11 – 90.68	–0.07	2.12
Monthly Time Series	10/20–9/86	790	2.37	4.15	4.89	0.00 – 23.79	0.44	1.13
Downieville								
Annual Time Series	1921–1986	63	62.41	62.57	18.78	22.00 – 102.65	0.02	1.93
Monthly Time Series	10/20–9/86	773	2.97	5.24	6.24	0.00 – 40.01	0.47	1.07
Sacramento								
Annual Time Series	1921–1986	66	17.00	17.85	6.81	6.71 – 36.57	0.07	1.83
Monthly Time Series	10/20–9/86	792	0.63	1.49	2.01	0.00 – 12.20	0.48	1.06
Hetch Hetchy								
Annual Time Series	1921–1986	66	33.94	35.51	11.41	14.73 – 72.40	–0.17	2.32
Monthly Time Series	10/20–9/86	792	1.77	2.96	3.47	0.00 – 26.23	0.44	1.12
Fresno								
Annual Time Series	1921–1986	66	9.28	10.18	4.00	4.44 – 23.59	–0.17	2.34
Monthly Time Series	10/20–9/86	792	0.31	0.85	1.18	0.00 – 8.56	0.41	1.18

*For the annual time series, this is the one-year lagged autocorrelation coefficient. For the monthly time series, this is the one-month lagged autocorrelation coefficient. The statistical significance of the lag-1 ACC was evaluated in a two-sided t-test of the null hypothesis of no autocorrelation against the alternate hypothesis of autocorrelation (Pancratz, 1983, p. 68). None of the annual lag-1 ACCs are statistically significant at the 5 percent level. All of the monthly lag-1 ACCs are statistically significant at the 5 percent level.

**The Durbin-Watson d statistic is computed for the linear model $y=c_0+c_1T$ where y is flow or precipitation, T is time, and the c_n's are regression coefficients. The statistical significance of this statistic was evaluated in a two-sided test of the null hypothesis of no autocorrelation against the alternate hypothesis of autocorrelation (Draper and Smith, 1981, p. 163). For the annual series, none of the d's are statistically significant at the 5 percent level. For the monthly series, all of the d's are statistically significant at the 5 percent level.

***For the annual series, flow is reported as the annual average in cfs and precipitation as the total annual precipitation in in/yr computed by summing monthly values. For the monthly series, flow is reported as the monthly average in cfs and precipitation as the total monthly precipitation in in/mo computed by summing daily values.

changes in precipitation. Unimpaired flow estimates are available from October 1920 to September 1983 (Table 1).

Unimpaired flow is a computed estimate of the total water supply in areas tributary to the Delta. Unimpaired outflow is not "actual" nor "natural" outflow, but rather it is a hypothetical flow that never occurred at any time. It is computed from a water balance around the valley (shaded area in Figure 1) by summing rim inflows at the periphery of the shaded area in Figure 1 and the valley floor runoff and subtracting the consumptive use of native vegetation in the Delta (CDWR, 1987b). These computations use gauged streamflows adjusted by CDWR to remove the influence of physical facilities (i.e., upstream reservoir storage, exports, etc). Thus, unimpaired flows are a measure of runoff from precipitation in upstream drainages with current land use and the vast network

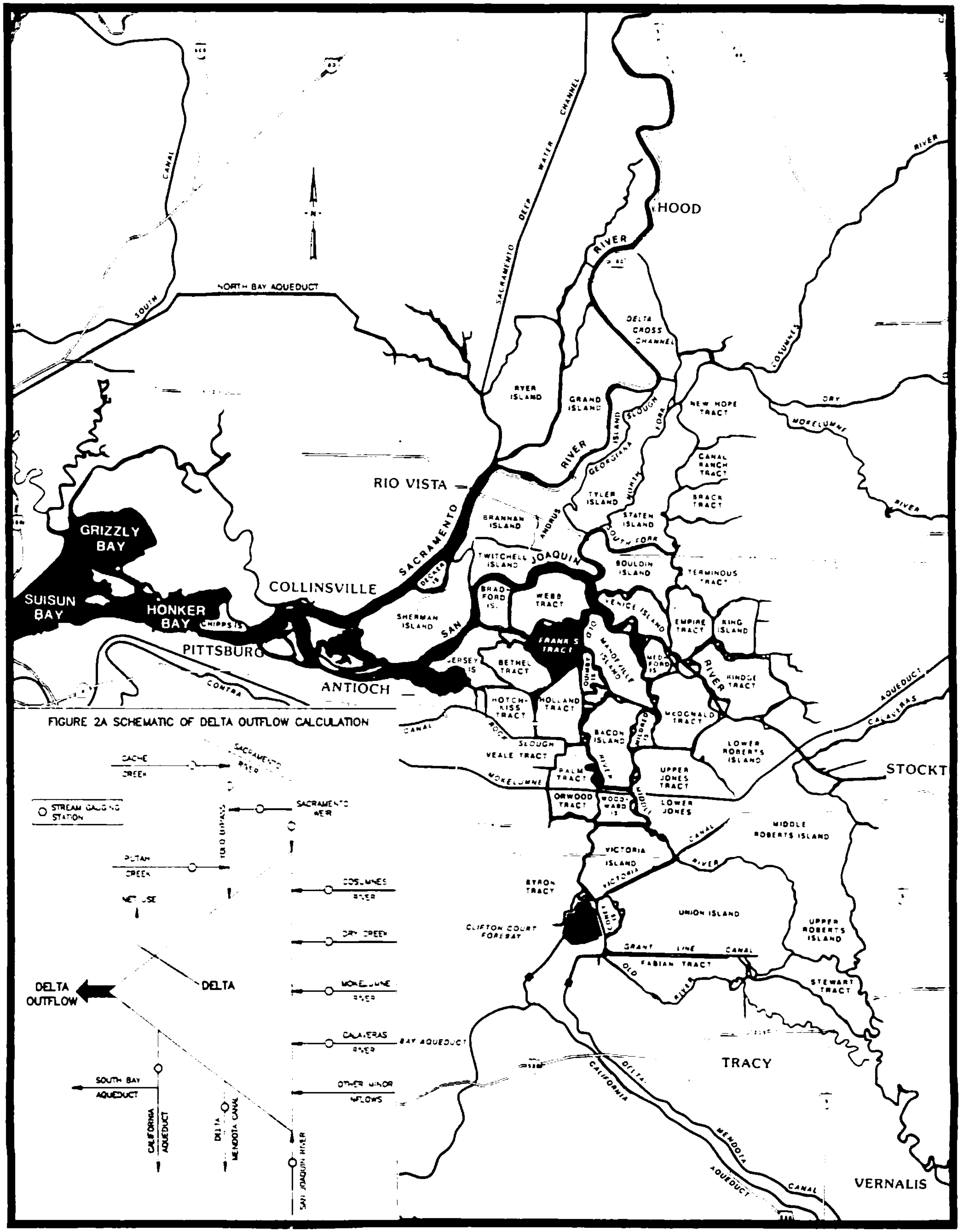

Figure 2. The Sacramento-San Joaquin Delta, the Major Outlet for Freshwater Into San Francisco Bay.

of man-made channels in place (e.g., an extensive system of levees, dredged deep-water channels, flood bypass channels, overflow weirs, etc.). These channels and levees substantially increase flows over levels that would occur under "natural" conditions, because they prevent flooding into adjacent swamps and increase stream velocities, reducing the amount of evaporation and transpiration that would otherwise occur (Fox, 1987).

Depletions

The difference between unimpaired and actual Delta outflow is a measure of the amount of water removed from upstream drainages for export and consumptive use. We calculated annual and monthly "depletion" time series by subtracting actual Delta outflow from unimpaired Delta outflow. Depletions represent the amount of freshwater removed from the basin that otherwise would have flowed into San Francisco Bay with present levees and channels.

DATA ANALYSIS

The data described above were analyzed for trends using classical parametric techniques from hydrology (Chow, 1964; Yevjevich, 1972) and nonparametric methods that have become popular in the past decade (Hirsch *et al.*, 1982; Hirsch and Slack, 1984; Gilbert, 1987; Berryman *et al.*, 1988). We emphasize the results from the nonparametric procedures because the data sets violate some of the assumptions underlying the parametric methods. All of the methods used are amply described in the literature. Therefore, we only briefly outline the steps we followed in this work. All of the techniques described here were applied to all three series – annual, seasonal, and monthly – unless specifically excepted.

Smoothing

Each time series was smoothed to portray the essential features of the data. We used a 10-year moving average (Chow, 1964) and LOWESS, which stands for "LOcally WEighted regression Scatter plot Smoothing" (Cleveland, 1979; Chambers *et al.*, 1983). LOWESS was chosen because outliers do not distort the smoothing and it accommodates missing values. We used the version of LOWESS implemented on Systat (Wilkinson, 1986).

Parametric Trend Estimation

First, we estimated the trend in each data set using ordinary least-squares regression (Chow, 1964; Draper and Smith, 1981). We used this procedure, even though it is not optimal for our data, because it is simple and widely understood. A trend was estimated by fitting a straight line to the data with time as the independent variable. For the monthly time series, the month was included as a dummy variable to account for seasonal variability (Draper and Smith, 1981, p. 241; Bowerman and O'Connell, 1987). We do not report the statistical significance of trends calculated in this manner because the data violate some of the underlying assumptions required for such tests (Smith, 1986; Helsel and Hirsch, 1988).

Nonparametric Trend Estimation

Trends were also estimated and their statistical significance assessed using nonparametric procedures because the data sets contained outliers and were not normally distributed. In all cases, we tested the null hypothesis of no trend against the alternate hypothesis of either an upward or downward trend using a two-tailed test. We selected a significance level (α) of 10 percent as commonly used by the U.S. Geological Survey in similar work (Smith *et al.*, 1987). However, most of the trends we report as statistically significant at the 10 percent level are also significant at the 5 percent level. Because the trend procedures used were different for annual and seasonal series, as opposed to monthly series, each type is discussed separately.

Annual and Seasonal Time Series

Successive values in these series are separated by one year, and seasonal cycles are not present. A trend was quantified using Sen's slope estimator (Sen, 1968) as implemented in a Fortran program developed by Battelle Pacific Northwest Laboratory (Gilbert, 1987). In the Sen method, the data are ranked in the order in which they are collected over time, and the slopes of the straight line segments linking all possible pairs of data points are computed. These slopes are ranked, and the Sen slope is the median value. This method is preferred to least-squares for our data because it is not biased by the major floods and droughts at the beginning and end of the data sets.

The statistical significance of trend in these series was tested used the Mann-Kendall test (Mann, 1945;

Kendall, 1975) as implemented in a Fortran Program developed by Battelle (Gilbert, 1987). In this test, the data are time ranked as in the Sen method and assigned the value +1, –1, or 0 according to the sign of the calculated differences of all possible time-ranked pairs. The Mann-Kendall S statistic is then computed as the number of positive differences minus the number of negative differences. Since the distribution of S is nearly normal for the sample sizes evaluated here (Table 1), we used the standard normal deviate Z (computed from S and the variance of S) referred to the cumulative normal distribution to evaluate significance (Gilbert, 1987, p. 211).

Serial correlation between successive values in a data set (i.e., autocorrelation) can result in overestimation of the true statistical significance of trend. Consequently, we checked each annual and seasonal time series for serial correlation using the one-year lagged (lag-1) autocorrelation coefficient (Pancratz, 1983) and the Durbin-Watson d statistic (Draper and Smith, 1981, p. 162). Since these statistics are not defined when missing values are present (Table 1), we estimated missing values in the McCloud and Downieville precipitation records by regressing these two records with one another. The statistical significance of the annual (lag-1) autocorrelation coefficient was tested using Bartlett's approximation for the standard error with the t-distribution (Pankratz, 1983, p. 68). All of the annual (Table 1) and seasonal series were independent at the 5 percent level except the August and September seasonal series. Others have also reported that annual data are either independent or very nearly so (Yevjevich, 1964; Potter, 1979, 1981).

Monthly Time Series

These series comprise monthly data over the period of record, and successive values are separated by one month. The monthly series have strong seasonal cycles and series correlation. Consequently, we used modifications of the Sen slope estimator and Mann-Kendall test that account for the seasonal effects and serial correlation.

A trend was quantified using the seasonal Kendall slope estimator (Hirsch *et al.*, 1982) as implemented in a Fortran program developed by the U.S. Geological Survey (USGS). This is a generalization of Sen's slope estimator. The Sen slope is computed for all data pairs for the same month from the entire data set, the Sen slopes are ranked, and the median of the ranked values is the seasonal Kendall slope.

The statistical significance of a trend in a monthly time series was evaluated with the seasonal Kendall test (Hirsch *et al.*, 1982) corrected for serial correlation (Hirsch and Slack, 1984) as implemented in a Fortran program developed by the USGS. The seasonal Kendall test is an adaptation of the Mann-Kendall test for a trend, in which each month is treated as an independent variable. The Mann-Kendall S statistic and the variance of S are computed separately for each month over all years and the grand test statistic S* is computed as the sum of individual monthly Mann-Kendall S statistics. Serial correlation is accounted for by estimating the covariance between successive months within the same year and including it in the computation of the variance of S*. Since the distribution of S* is nearly normal for the sample sizes evaluated here (Table 1), we used the standard normal deviate Z (computed from S* and the variance of S*) referred to the cumulative normal distribution to evaluate significance (Hirsch *et al.*, 1982).

Calculation of Percent Change

Throughout this paper, we use "total percent change" or simply "percent change" to quantify the magnitude of the trend over the period of record referenced to the beginning of the record. This quantity is always calculated as follows:

$$\text{percent change} = 100x(\text{trend}x\text{N}) / [\text{median}+/-1/2(\text{trend}x\text{N})] \quad (1;$$

where N is the number of years in the record (66), the plus (+) sign is used for a decreasing trend and the minus (–) sign for an increasing trend.

ANNUAL TRENDS

Actual Delta Outflow

Annual flow data are plotted in Figures 3a-3c, superimposed over LOWESS smoothed curves. The LOWESS curves indicate that the actual Delta outflow (Figure 3a) has slightly increased even though depletions (Figure 3c), or net water use, have increased markedly. Plots of 10-year moving averages (not shown here) display the same trends and relationships among the three sets of flow data. Similar trend curves published by the U.S. Geological Survey (USGS, 1986, p. 163) show an increasing trend in the two major components of Delta outflow, the Sacramento River and the San Joaquin River (Figure 1). These simple graphical displays clearly indicate that Delta outflow, which is over 90 percent of the

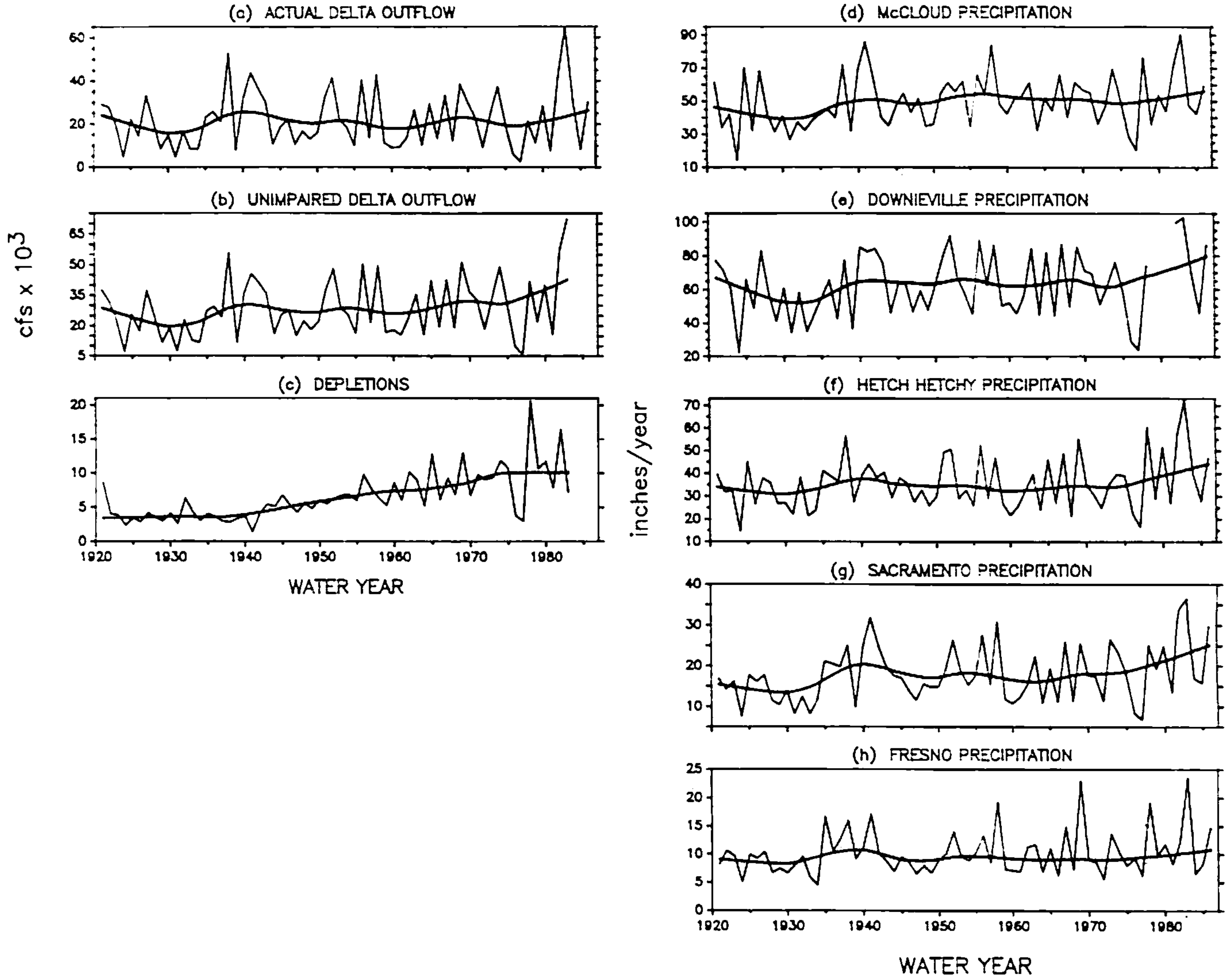

Figure 3. Annual Flow and Precipitation Data. The jagged lines plot the annual average flows and total annual precipitation. The smoothed line is the LOWESS trend curve, computed for f=0.30, where f is the fraction of the points included in the smoothing routine (Cleveland, 1979). Different y-scales are used for each plot.

freshwater flow into San Francisco Bay, has not declined over the period from 1921 to 1986.

The trend analysis (Table 2) confirms that Delta outflow has not decreased. Table 2 compares the "trend" or average rate of change in both annual and monthly time series estimated by two separate methods: least-squares and Sen's slope. Both trend methods indicate that actual Delta outflow has slightly increased over the period 1921 to 1986, in agreement with the LOWESS trend curve (Figure 3a). The nonparametric procedure provides a more accurate estimate of the true, long-term trend in our data sets because it is not biased by outliers. Most of the least-squares trends are higher than their Sen counterparts due to outliers.

The Sen analysis for the annual series indicates that Delta outflow has increased at 41 cfs/yr or by about 9 percent since 1921. Because the two-tailed p-value (0.72) is greater than the significance level of 0.10, the null hypothesis of no trend is accepted and the alternate hypothesis of a trend is rejected. This means that the trend in annual Delta outflow over the period 1921 to 1986 is not inconsistent with the hypothesis of no trend.

The seasonal Kendall results for the monthly series indicate that Delta outflow has increased by 87 cfs/yr or by about 45 percent since 1921. Since the two-tailed p-value (0.032) is less than the significance level of 0.10, the null hypothesis of no trend is rejected and the alternate hypothesis of a trend is accepted.

TABLE 2. Trend Analysis of Annual and Monthly Flow and Precipitation Data.

	Annual Time Series			Monthly Time Series		
	Least-Squares Trend[1]	Sen's Trend[2]	Two-Tailed p-Value[3]	Least-Squares Trend[1]	Seasonal Kendall Trend[2,4]	Two-Tailed p-Value[3]
FLOW DATA	(cfs/yr)	(cfs/yr)		(cfs/yr)	(cfs/yr)	
Actual Delta Outflow	+ 95	+ 41	0.72	+102	+87*	0.03
Unimpaired Delta Outflow	+285	+244	0.12	+285	+89*	0.01
Depletions	+182	+171*	<0.01	+177	+58*	<0.01
PRECIPITATION DATA	(in/yr)	(in/yr)		(in/yr)	(in/yr)	
McCloud	+0.18	+0.20*	0.05	+0.20	+0.29*	0.05
Downieville	+0.20	+0.18	0.18	+0.20	+0.16*	<0.01
Sacramento	+0.10	+0.08*	0.06	+0.11	>+0.00*	<0.01
Hetch Hetchy	+0.13	+0.06	0.31	+0.12	+0.05*	0.07
Fresno	+0.03	+0.02	0.29	+0.046	>+0.00*	0.06

[1] Computed as the slope of the straight line fit to the data using linear least-squares regression. For monthly series, a dummy month variable (Draper and Smith, 1981) was included to account for seasonal variability. The test statistic is not reported because the data violate underlying assumptions of the t-test (Helsel and Hirsch, 1988).

[2] The asterisk (*) indicates that the Sen trend is statistically significant at the $\alpha=0.10$ level in a two-tailed test of the null hypothesis of no trend against the alternate hypothesis of either an upward or downward trend.

[3] This is the attained significance level from the two-tailed hypothesis test described in note No. 2. It is the probability (p) of exceeding the absolute value of the Z-statistic in a two-tailed test. When the p-value is less than the significance level of 0.10, the nonparametric trend is statistically significant.

[4] The seasonal Kendall trend is computed only for monthly series and is a generalization of the Sen trend used for the annual time series.

Since the Z-statistic is positive (Z=+2.15), the trend is upward. This means that a statistically significant increase in monthly Delta outflow has occurred over the period from 1921 to 1986.

The reason that the monthly series yields a statistically significant trend, while the annual series does not, is in part due to the much larger sample size for the monthly series (792 observations versus 66). Further, the monthly series is dominated by strongly increasing trends in the summer and fall months, as discussed in the next section on seasonal trends. These seasonal trends have little influence on the trends in the annual series.

Precipitation

The annual Delta outflow has not declined since 1921, even though depletions have increased (Figure 3c). This could result from some combination of the following four factors: (a) an increase in precipitation in the Sacramento-San Joaquin drainage between 1921 and 1986; (b) an increase in the fraction of precipitation that runs off and contributes to outflow, as a result of changes in land use; (c) increased surface flow resulting from the known ground water overdraft in the San Joaquin Valley; and (d) water imports into the area from other drainages.

We checked the possibility of increased precipitation in the Sacramento-San Joaquin drainage by analyzing precipitation data from five representative locations, as well as unimpaired flow data, to see if they exhibited an increasing trend.

We first regressed the annual Delta outflow on the annual precipitation and unimpaired outflow to determine if there was any relationship between the series. As expected, there was a statistically significant relationship between actual outflow and precipitation at all five of the stations ($r^2=0.89$ to 0.95, $p<0.01$) as well as between actual outflow and unimpaired outflow ($r^2=0.98$, $p<0.01$).

We then evaluated the trend in the five precipitation time series (Table 1). The annual precipitation data are plotted in Figures 3d-3h, superimposed over LOWESS smoothed curves. The LOWESS curves suggest that precipitation has increased at all five stations over the period of record. Similar plots of 10-year moving averages show the same trends at each station. Unimpaired flow (Figure 3b) is the total runoff from upstream drainages. The upward trend in unimpaired flow agrees with the upward trend in precipitation, suggesting that the increasing trend is a basin-wide phenomenon. The unimpaired flow data show that more water has been available for consumptive use in recent years than earlier in the century.

The trend analysis (Table 2) confirms a basin-wide increase in precipitation and runoff upstream from San Francisco Bay. Both the annual and monthly series indicate that precipitation increased over the period 1921 to 1986 at the five stations we studied. All of the increasing trends for the monthly series are statistically significant at the 10 percent level. To assure that we had not fortuitously selected five stations with an increasing trend, we selected five additional stations – Portola, Colfax, and Auburn in the northern mountains and Huntington Lake and Yosemite in the southern mountains – and tested those annual series for trends. All five of these stations also displayed increasing Sen trends that ranged from 0.10 to 0.26 in/yr, comparable to the five original stations (Table 2). The Sen trends at Huntington Lake (0.26 in/yr; $p<0.01$) and at Portola (0.12 in/yr; $p=0.025$) were statistically significant at the 5 percent level. Most of the increase in precipitation seems to have occurred in the mountainous parts of the Sacramento-San Joaquin drainage, which produces the majority of the runoff that ultimately reaches San Francisco Bay.

We do not have time series data on the fraction of annual precipitation that runs off and contributes to outflow. This fraction could have increased due to changes in land use. Land use changes that could increase runoff include replacing high water-using inland marshes with lower water-using irrigated lands (Fox, 1987), replacing native vegetation with paved areas, buildings and other urban land uses (CDWR, 1983, p. 176), and clearing heavily forested areas. These land use changes increase the water supply by reducing consumptive use and by increasing runoff.

We checked for evidence of an increasing fraction of precipitation, increasing ground water overdraft, and imported water appearing as outflow in the following way. First, we regressed the logarithm of actual Delta outflow on monthly precipitation. Then we looked at the trend in the regression residuals. If the relationship between outflow and precipitation is constant in time, the residual should show no trend. If, however, the residuals do show a trend in time, this indicates that the relationship between precipitation and outflow has changed in time (as a result of ground water overdraft, water imports, or a change in the fraction of precipitation that runs off and contributes to outflow).

To check if the relation between actual outflow and precipitation is constant in time, we regressed the logarithm of monthly actual Delta outflow (logQ) on the total monthly precipitation (P) calculated by summing the five individual monthly time series. The residuals were then tested for a trend to determine if a change in the precipitation-runoff relationship could have contributed to the increase in Delta outflow. LogQ was used because the logarithms of monthly outflow are approximately normally distributed, as is common for monthly flow data (Delleur *et al.,* 1976), the resulting regression relationships were approximately linear, and the residuals were approximately normally distributed. Seasonal variability was accounted for by including the month in the regression as a dummy variable (Draper and Smith, 1981, p. 241).

The resulting flow-precipitation relationship and all regression constants were statistically significant (two-tailed $p<0.01$), and the model accounted for 60 percent of the variability in the flow data. The trend in the residuals was evaluated using the seasonal Kendall test corrected for serial correlation (Hirsch and Slack, 1984). The two-tailed p-value for this trend test was 0.091, which is less than the significance level of 0.10. Thus, the null hypothesis of no trend is rejected and the alternate hypothesis of a trend is accepted. Since the Z-statistic is positive ($Z=+1.69$), the trend is upward. This indicates that the increase in the monthly Delta outflow (Table 1; 87 cfs/yr) over the period from 1921 to 1986 is caused in part by a change in the precipitation-runoff relationship.

Unimpaired outflow has increased (Table 2), confirming the increase in precipitation (although unimpaired outflow trends could also be influenced by changes in land use and water imports). The water supply (i.e., unimpaired flow) increased at a faster rate than water was removed from the system (i.e., depletions) over the period from 1921 to 1986, which is why the annual Delta outflow has not decreased. The two-tailed p-values indicate that the monthly trends in unimpaired flow ($p=0.012$) and depletions ($p<0.01$) are statistically significant at the 5 percent level.

To confirm that the trend in precipitation was large enough to account for the observed increase in unimpaired outflow, we made a very rough estimate of the amount of additional runoff that would be generated by the precipitation increase. The calculations are summarized in Table 3. The increase in Delta outflow due to precipitation increases was estimated by multilying the drainage-area-weighted annual Sen trend (Table 2) by a regional area and a regional runoff factor. This rough estimate indicates that the precipitation increase is equivalent to an increase in flow of about 180 cfs/yr.

This rough estimate (Table 3) indicates that the precipitation increase might account for about 70 percent of the increase in annual unimpaired outflow (Table 2; 244 cfs/yr). Thus, one of the main reasons

TABLE 3. An Estimate of the Contribution of the Increasing Trend in Precipitation to the Increasing Trend in Delta Outflow.

Regional Area	Stations Used to Compute Increase in Precipitation	Land Area[1] (mi^2)	Average Annual Increase in Precipitation[2] (in/yr)	Runoff Factor[3]	Increase in Runoff Due to Increase in Precipitation[4] (cfs/yr)
Sacramento Valley Floor	Sacramento	4,946	0.084	0.11	3.4
Sacramento Mountains	Auburn Colfax Downieville McCloud Portola	21,602	0.16	0.46	120
San Joaquin Valley Floor	Fresno	5,434	0.024	0.065	0.62
San Joaquin Mountains	Hetch Hetchy Huntington Lake Yosemite	10,512	0.16	0.41	51
TOTALS		42,494			180

[1] The areas are taken from Bulletin 1, Table 53, pp. 309-310 (SWRCB, 1951).

[2] The annual increase in precipitation is the Sen trend for the annual time series for the five stations in Table 2 plus five additional stations added for this computation (Auburn, Huntington Lake, Colfax, Portola, and Yosemite). Each regional trend (e.g., 0.16 in/yr for the Sacramento Mountains) is a drainage area-weighted average for the region.

[3] The runoff factor was computed as the ratio of average annual unimpaired outflow from each regional area in column (1) as reported in CDWR (1987b) to the total annual precipitation for each area from Rantz's (1969) isohyetal map for the Central Valley, where flow and precipitation are expressed in the same units.

[4] Computed as [areal] x [precipitation increase] x [runoff factor] x [0.0737 $\text{ft}^3\text{yr/in mi}^2\text{ sec}$]. All values, including the total, are reported to two significant figures.

that freshwater flow into San Francisco Bay has not declined is because precipitation has increased enough to offset increases in water use. Additional data, particularly a more recent isohyetal map and trend estimates for additional precipitation stations, would be required to refine this estimate.

Other Factors

Factors other than an increase in precipitation also have contributed to the upward trend in water supply to the Bay. The calculations presented above indicate that roughly 30 percent of the increasing outflow trend is caused by factors other than precipitation increases. These other factors include imports, redistribution of ground water, and land use changes.

Water has been imported into upstream drainages from the Trinity River and Tule Lake since the mid-sixties. These imports averaged about 1100 cfs in 1980. This amounts to an increase of about 17 cfs/yr, if averaged over the period from 1921 to 1986. Return flows from ground water pumped for agricultural and municipal uses may also have increased surface flows, particularly during droughts when users turn to ground water to augment dwindling surface supplies. About 3800 cfs of ground water were pumped in 1980 in the Delta watershed (CDWR, 1983). If only 10 percent of this water were to appear as surface flow, this would represent an increase of about 6 cfs/yr if averaged over the period from 1921 to 1986. Finally, as noted above, land use changes may have increased the fraction of precipitation that runs off and ultimately appears as Delta outflow. This final factor cannot be quantified directly with available information.

SEASONAL TRENDS

We also analyzed monthly Delta outflow and precipitation data to determine whether changes had occurred in individual months. Each monthly flow and precipitation time series was subdivided into 12 independent monthly data sets, referred to as "seasonal" time series. The resulting 96 individual seasonal series were separately analyzed for trend. This work indicates that the statistically significant annual trends found in the monthly time series (Table 2) are due to strong seasonal trends, which differ in both magnitude and direction from month to month.

Actual Delta outflow is plotted for each month in Figure 4, superimposed over LOWESS smoothed curves. The LOWESS curves suggest that outflow has decreased in April, May, and June and increased in all other months over the period from 1921 to 1986. It is interesting to note that the spring declines level out in the post-1960 period after the major facilities shown in Figure 1 were on line. Similar plots of 10-year moving averages show the same trends.

The LOWESS results are confirmed by the trend analysis (Table 4), which shows that declines have taken place in April, May, and June and increases in all other months. Although the two trend methods yield equivalent trend directions (i.e., increasing, or decreasing), trend magnitudes differ between the two procedures due to outliers. The Sen slope is a better representation of the true trend in these data because least-squares unduly weights the outliers, which overestimates the magnitude of trends.

Statistically significant increases in outflow have occurred in summer and fall months. The Sen analysis indicates that July through September flows have significantly increased over the period from 1921 to 1986. Statistically significant decreases in outflow

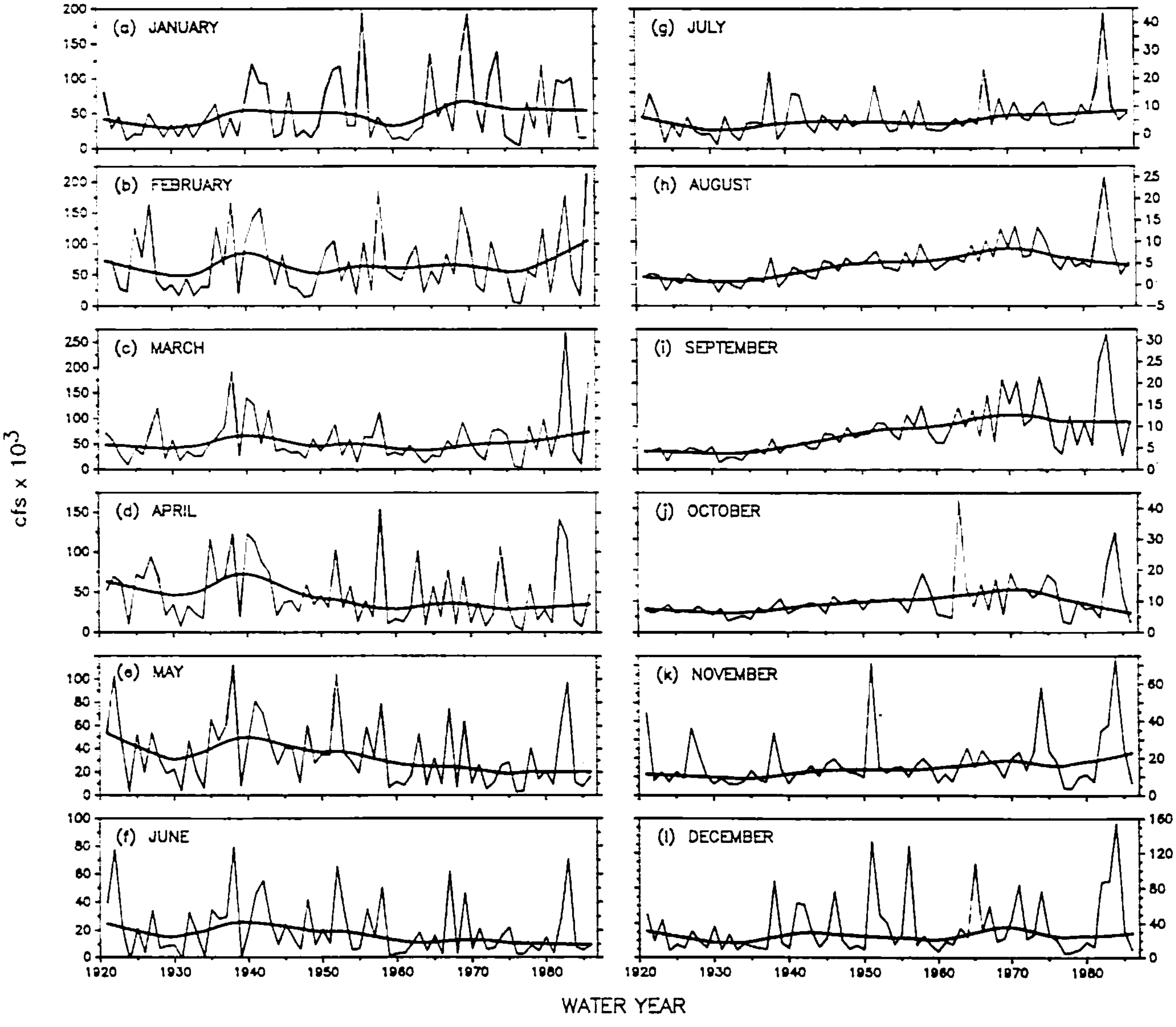

Figure 4. Monthly Average Actual Delta Outflow Computed at Chipps Island. The jagged lines plot the monthly average flows in cfs for each month. The heavier, smoothed line is the LOWESS trend curve, computed for f=0.30, where f is the fraction of the points included in the smoothing routine (Cleveland, 1979). Different y-scales are used for each plot.

have occurred in April and May. The Sen analysis indicates that since 1921, outflow has declined in April by 56 percent and in May by 64 percent (Table 4). Thus, the major change that has occurred since 1921 is a redistribution of flow from April, May, and June to all other months.

The seasonal trends shown in Table 4 are probably due to two factors – upstream reservoir operation/consumptive use and an apparent shift in climatic conditions. We studied the effect of each of these factors on Delta outflow by comparing monthly trends in the precipitation data with those for the flow data (Figure 5).

Water projects upstream from the Bay are operated to control floods, to supply downstream water users, and to meet in-stream needs, including salinity control, fisheries, recreation, and navigation. Flood control is required because the entire valley was historically subject to almost annual flooding (Thompson, 1960). Reservoir capacity is set aside from mid-October through March for flood control. The increase in actual Delta outflow in these months (Figure 5a) is apparently due to increases in the amount of precipitation and in the fraction of precipitation that contributes to outflow. The monthly unimpaired outflow (Figure 5b) and precipitation data (Figures 5d-5h) indicate that statistically significant increases in runoff and precipitation have occurred throughout the flood season, but predominantly in November, January, and March. The increased amounts of rainfall usually are not captured for use in the present system due to the need to reserve space for flood control. Thus, they have contributed to the annual increase in Delta outflow discussed previously.

Flood control requires that most water storage to satisfy year-round uses must occur primarily from April to June. This use pattern is reflected in the monthly Delta outflow trends (Figure 5a). Statistically significant decreases have occurred in April and May outflow (Table 4), when water is stored. However, not all of the late spring decrease is due to water project operation. Precipitation has

TABLE 4. Trend Analysis of Seasonal Delta Outflow Time Series.[1]

Month	Least-Squares Trend[2] (cfs/yr)	Sen's Trend[3] (cfs/yr)	Total Percent Change[4] (percent)	Two-Tailed p-Value[5]	Lag-1 ACC[6]	Durbin Watson d[7]
October	+123	+108*	+148	<0.01	0.19	1.84
November	+163	+148*	+111	0.013	0.22	1.59
December	+369	+169	+69	0.21	0.12	1.84
January	+489	+134	+38	0.48	0.16	1.75
February	+176	+94	+12	0.75	−0.01	1.89
March	+227	+16	+3	0.91	0.02	1.89
April	−322	−424*	−56	0.025	−0.01	2.08
May	−365	−416*	−64	0.018	0.02	2.07
June	−192	−141	−48	0.14	−0.02	2.08
July	+122	+90*	+405	<0.01	0.16	1.87
August	+152	+133*	+349	<0.01	0.55†	1.59†
September	+187	+172*	+867	<0.01	0.49†	1.64

[1] The seasonal time series in this table were formed by separating the monthly time series (Table 1) into 12 monthly data sets where successive values are one year apart.

[2] Computed as the slope of the straight line fit to the data using linear least-squares regression. Test statistics are not reported because the data violate underlying assumptions of the t-test (Helsel and Hirsch, 1988).

[3] The asterisk (*) indicates that the trend is statistically significant at the $\alpha=0.10$ level in a two-tailed test of the null hypothesis of no trend against the alternate hypothesis of either an upward or downward trend.

[4] The total percent change is computed for the Sen trend from: 100x(trendxN) / [median +/– 1/2(trendxN)] where N = number of years in the record = 66. The plus (+) sign is used for a decreasing trend and the minus (–) sign for an increasing change because the trend is computed with respect to the beginning of the record.

[5] This is the attained significance level from the two-tailed hypothesis test described in note No. 3. It is the probability (p) of exceeding the absolute value of the Z-statistic in a two-tailed test. When the p-value is less than the significance level of 0.10, the nonparametric Sen trend is statistically significant.

[6] The dagger (†) indicates that the one-year lagged autocorrelation coefficient (lag-1 ACC) is statistically significant at the 5 percent level in a two-tailed t-test (Pancratz, 1983). Because the August and September lag-1 ACCs are statistically significant, the two-tailed p-values may overstate the true significance of the Sen trend (i.e., the p-values may be smaller than warranted).

[7] The Durban-Watson d statistic is computed for the linear model $Q=c_0+c_1T$ where Q is the flow, T is time, and the c_ns are regression coefficients. The statistical significance of this statistic was evaluated in a two-sided test of the null hypothesis of no autocorrelation against the alternate hypothesis of autocorrelation (Draper and Smith, 1981, p. 163). The dagger indicates that d is statistically significant at the 5 percent level.

decreased during late spring at all five stations (Figures 5d-5h). Others have reported that April to July unimpaired runoff (i.e., snowmelt runoff) has declined over the period 1921 to 1983 (Roos, 1988).

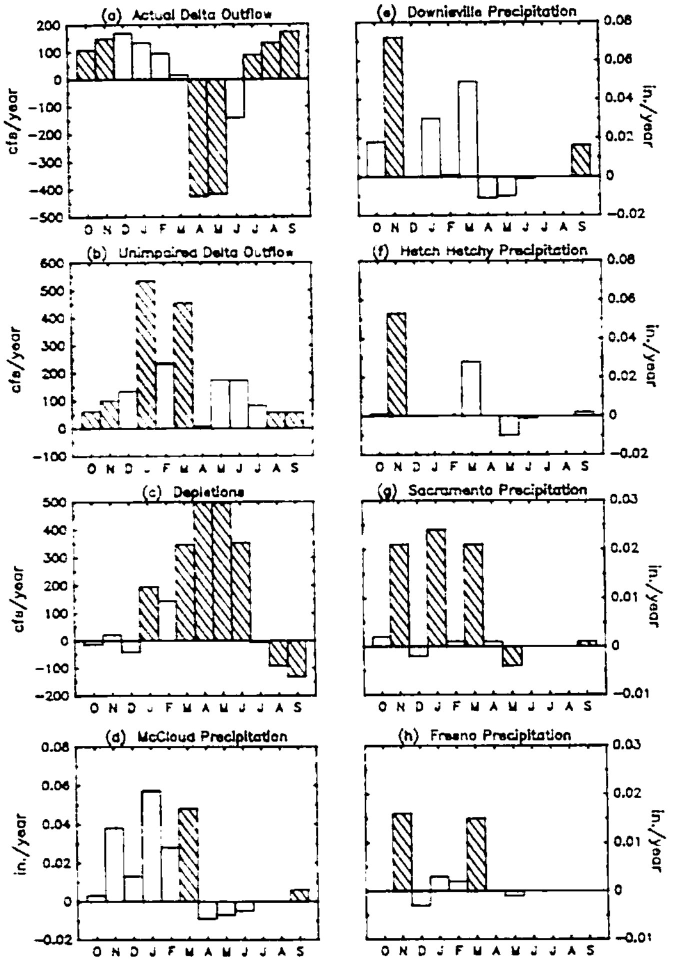

Figure 5. Monthly Trends in Flow and Precipitation. Shaded bars indicate the trend is statistically significant at the 10 percent level in a two-tailed Z test. Unshaded bars indicate the trend is not statistically significant. Different y-scales are used for each plot.

The water stored in April to June is released in the summer and early fall for consumptive and various in-stream uses including salinity control, fish and wildlife, and navigation. This is reflected in the July to November outflow (Figure 5a), which has increased over the period 1921 to 1986 (Table 4). Part of this increase is due to increases in precipitation from September through November (Figures 5d-5h).

These analyses suggest that a climatic shift has occurred in upstream drainages that has redistributed monthly precipitation. Because most of the rainfall increase has occurred during the flood season when it cannot be captured for future use, it has augmented Delta outflow. Spring precipitation has decreased and late summer through winter precipitation has increased. Similar results have also been reported by the CDWR. Roos (1988) analyzed a number of indices of water supply in areas tributary to the Bay. He found that April through July runoff into the Central Valley (Figure 1) declined since 1921 and markedly since 1950 (Roos, 1988), while the annual volume of runoff increased (Roos, 1988). Because April to July is snowmelt season, this suggests a shift in the fraction of flow resulting from rain instead of snowmelt.

If this climatic/hydrologic shift were to continue, it could have significant adverse effects on California's present water delivery system. The increased winter runoff (Figure 5b) and early snowmelt (Roos, 1988) would be spilled from the reservoirs because of the flood control requirement, instead of going into storage for later use. Carry-over storage of the late spring snowpack would be reduced, decreasing the quantity of water reliably stored for later use.

DISCUSSION

Our analyses demonstrate that there has been no reduction in annual freshwater inflow to San Francisco Bay from the Sacramento-San Joaquin Delta over the period from 1921 to 1986, although seasonal shifts in Delta outflow have occurred. Thus, there is no basis for any contention that long-term average annual reductions in freshwater inflow to San Francisco Bay have occurred. Spring decreases result from exports and the need to store water for later use and to protect the valley from flooding. Changes in this pattern would require changes in reservoir operating rules as well as additional off-stream storage. The increased summer and fall outflows prevent salinity intrusion into the Delta and provide important benefits that must be balanced against any adverse effects that may result from reduced April and May flows.

Previous estimates of reductions in freshwater flow into San Francisco Bay (Meyer and Davoren, 1981; Nichols *et al.*, 1986; Rozengurt *et al.*, 1987) were not based on analyses of actual outflow. Instead, these other estimates are hypothetical because they are based on planning estimates of Delta outflow that never occurred historically. The hypothetical outflow reductions are computed from CDWR's "level-of-development" and "unimpaired" outflows by assuming that "level-of-development" flows are equivalent to "actual" flows and that "unimpaired" flows are equivalent to "natural" flows or those that occurred in

1850. Neither assumption is accurate. The relevant outflows and the computation used to estimate the hypothetical 50 to 60 decline are summarized in Table 5.

The CDWR uses various computer models (e.g., reservoir operations, consumptive use, water balance) to estimate flows that would have been observed with different system configurations, if historic precipitation were repeated. These models are used to calculate two types of flows, "level-of-development" and "unimpaired" Delta outflows. The level-of-development flows are those that would occur if the physical facilities and upstream land use at a given point in time (e.g., 1990) were fixed and the climate since 1921 were repeated (CDWR, 1987a, #28-30). Level-of-development outflows have never occurred historically and are not equal to actual outflow, as shown in Table 5.

Unimpaired outflows, as discussed previously, are those that would have occurred if the climate of 1921 to 1983 were repeated, with no reservoirs, exports, and in-basin water use, but with all existing land uses, channels, and levees in place (CDWR, 1987b). Unimpaired flows are not the same as "natural" flows (Table 5) as CDWR has clearly stated (CDWR, 1987b, p. 1) and as demonstrated by Fox (1987). Further, the unimpaired flows are not equal to the average flow in 1850, as assumed by Nichols *et al.* (1986).

The 1990 level-of-development flows are about 46 percent of the unimpaired flows (Table 5), which represents a reduction of 54 percent (see note to Table 5). Previous estimates of level-of-development flows for 1980 and other years correspond to a reduction of 50 to 60 percent from unimpaired flows. This is the basis of the claim that freshwater flow to the Bay has been reduced. This claim is incorrect because unimpaired and level-of-development flows are hypothetical and never occurred historically. Reductions based on these flows are likewise hypothetical.

Actual Delta outflow analyzed in this work is an estimate of the amount of water that historically reached the Bay from 1921 to 1986 when most of the development of California's large-scale water system had occurred (CDWR, 1983, 1988). Our analyses of actual Delta outflow clearly demonstrate that annual freshwater inflow to the Bay from the Sacramento-San Joaquin Delta has not declined. The actual outflow has averaged 30,240 cfs annually (21.9 million acre feet) over the period from 1921 to 1986 and 33,980 cfs (24.6 million acre feet) over the period 1976 to 1986.

CONCLUSIONS

Two independent trend tests (least-squares regression and Sen's slope) on monthly and annual series indicate that actual Delta outflow has not declined over the period from 1921 to 1986. The monthly Delta outflow time series indicates that a statistically significant increase in actual Delta outflow of 87 cfs/yr, or about 45 percent, has occurred since 1921.

The principal reason that Delta outflow has not decreased is because the water supply has increased faster than water use. The annual unimpaired runoff has increased at 244 cfs/yr, primarily as a result of increases in precipitation (0.02 to 0.26 in/yr) at the stations studied. Other factors, including imports, the redistribution of ground water, and an increase in the fraction of the precipitation that runs off, may also have contributed to the increase in actual Delta outflow.

There have been statistically significant seasonal changes in Delta outflow. Flows have decreased in April and May and increased from July through November. Changes in other months are not statistically significant. This primarily results from the

TABLE 5. Comparison of Actual Delta Outflow With Various Planning Estimates.

Representation of Delta Outflow*	Period of Record	Average Annual Outflow (cfs)	Authority
Actual**	10/20-9/86	30,240	CDWR (1987a, #27 and updates)
Unimpaired**	10/20-9/83	39,210	CDWR (1987b)
Natural	10/20-9/83	18,510	Fox (1987)
1980 Level of Development	10/20-9/78	19,300	CDWR (1983, p. 184)
1990 Level of Development	10/20-9/78	17,950	CDWR (1987, #30d)
2000 Level of Development	10/20-9/78	17,440	CDWR (1987, #30d Rev.)

*The alleged 50 to 60 percent reduction in freshwater flow to San Francisco Bay is computed from:
100x[unimpaired flow – level-of-development flow] / unimpaired flow.
**Analyzed in this work.

operation of upstream flood control and water development projects that store water in the spring and release it in the summer and fall. This seasonal pattern is also affected by a decrease in spring snowmelt runoff and an increase in summer through winter precipitation.

If the seasonal shift in precipitation and runoff continues, additional reservoir storage capacity will be required to maintain present firm yield of California's water system. Decreased flows have occurred during spring when water is stored. Increases have occurred during the winter, when the flows usually cannot be captured for subsequent use because of the flood control reservation.

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