THE IMPACT OF DECADAL FLUCTUATIONS IN MEAN PRECIPITATION AND TEMPERATURE ON RUNOFF: A SENSITIVITY STUDY OVER THE UNITED STATES

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Abstract. The nature of climate variability is such that decadal fluctuations in average temperature (up to 1 °C annually or 2 °C seasonally) and precipitation (approximately 10% annually), have occurred in most areas of the United States during the modern climate record (the last 60 years). The impact of these fluctuations on runoff was investigated, using data from 82 streams across the United States that had minimal human interference in natural flows. The effects of recent temperature fluctuations on streamflow are minimal, but the impact of relatively small fluctuations in precipitation (about 10%) are often amplified by a factor of two or more, depending on basin and climate characteristics. This result is particularly significant with respect to predicted changes in temperature due to the greenhouse effect. It appears that without reliable predictions of precipitation changes across drainage basins, little confidence can be placed in hypothesized effects of the warming on annual runoff.

1. Introduction

Results from general circulation models (GCMs) and other analyses indicate that a marked global warming will occur by the middle of the next century associated with increasing CO_2 concentration in the atmosphere (World Meteorological Organization, 1985). A 1 to 4 °C rise in temperature is predicted within the middle latitudes (e.g., Schlesinger and Mitchell, 1985). Increased precipitation is also expected, but the timing and regional character of the increase varies substantially from model to model, ranging from no increase (or even a decrease) in summertime precipitation, to an increase of over 50 mm d^{-1} at other times of the year (Schlesinger and Mitchell, 1985). These climate scenarios have important implications for various human activities such as water resources management. The first step in addressing this issue is to explore the relationships between changing climate and surface water runoff.

2. Background

Langbein (1949) related the mean annual runoff ($\bar{R}$) from 22 drainage basins in the

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United States to the mean annual total precipitation ($\bar{P}$) and the weighted temperature T_w which is defined by:

$$T_w = \sum_{i=1}^{12} (\bar{T}_i \bar{P}_i)/\bar{P}, \qquad (1)$$

where $\bar{T}_i$ is the mean temperature in month i and $\bar{P}_i$ is the total precipitation for month i averaged over the period of record. When T_w is greater than the mean annual temperature ($\bar{T}$), more precipitation occurs during the warmer months compared to the colder months. The opposite is indicated where T_w is less than $\bar{T}$. Across the United States, there are large differences in T_w, $\bar{P}$, and $\bar{R}$. Values of T_w, $\bar{P}$, and $\bar{R}$ near 5 °C, 750 mm, and 300 mm, respectively, are characteristic in the upper Midwest, whereas for areas in the southern Great Plains, more typical values of T_w, $\bar{P}$, and $\bar{R}$ are 20 °C, 750 mm, and 50 mm. Langbein (1949) used these differences to develop the well-known nomogram depicted in Figure 1.

Revelle and Waggoner (1983) applied Langbein's climate-runoff relationships to assess the impact of CO_2-induced changes of temperature and precipitation on runoff from the Colorado River Drainage. They concluded that a 2 °C rise in temperature would decrease runoff nearly three times more than a 10% decrease in precipitation, a result which we evaluate using decadal timescale climate fluctuations from the historical record. Other studies and reports (Stockton and Boggess, 1979; Callaway and Currie, 1985), either directly or indirectly, have also used Langbein's technique in assessing the runoff impacts of changes of temperature and

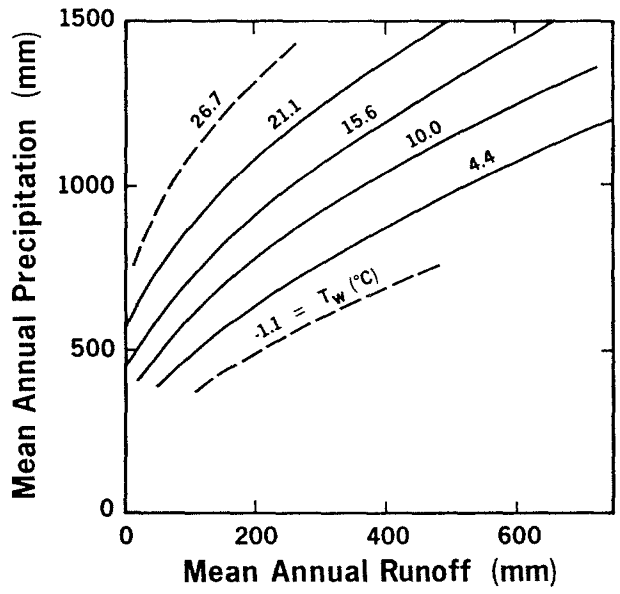


Fig. 1. The relationship between mean annual precipitation and runoff as a function of the weighted temperature (T_w) (after Langbein, 1949).

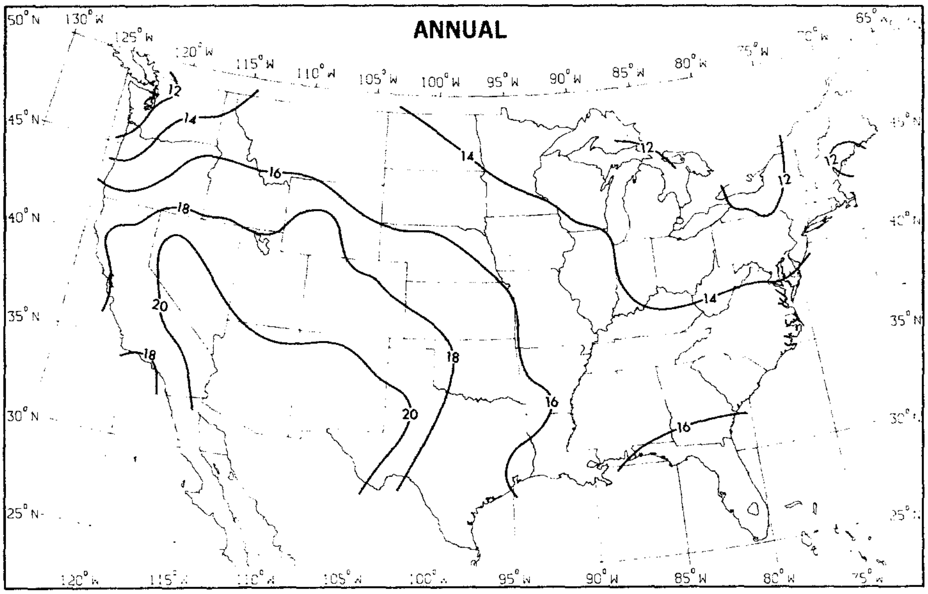
precipitation. In light of the importance of a changing climate to water resources in the United States, it is prudent to test the robustness of such applications.

The Langbein curves are unquestionably very useful for characterizing the *spatial* variation of the hydrological cycle in various climates of the United States because they are based on observed differences among basins. But, can they be used reliably to assess the impact of temporal climate changes on runoff for specific drainage basins? When applied in this way they yield rather dramatic results. For example, a 1 °C increase of temperature in the upper Midwest would imply a 5 to 10% reduction in annual runoff, presumably due to increased evapotranspiration. A 1 °C decrease of temperature in the southern Great Plains would lead to a 25% increase of runoff!

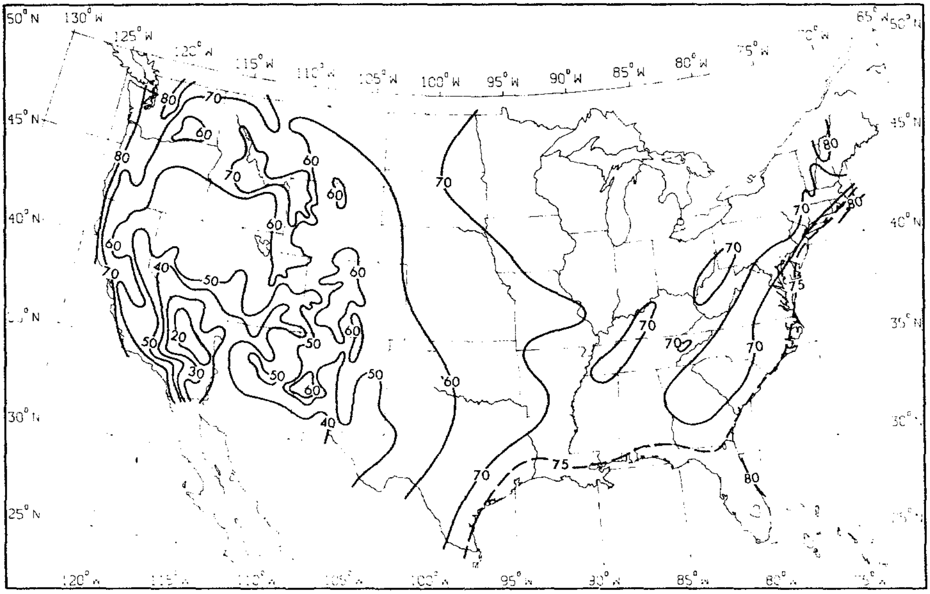
There are, however, many potential problems with these relationships. It is well known that evaporation is not only a function of temperature, but also insolation, humidity, wind speed, surface characteristics and advection effects. Large differences of insolation and humidity occur between areas in the northern and southern United States (Figure 2), enhancing evaporation differences between regions of the country more than if only temperature contrasts were affecting evaporation. For example, not only is the temperature lower in the upper Midwest, but insolation is lower and relative humidity is generally higher. The warmest temperatures are generally in areas with low relative humidity and high annual insolation (e.g., the southwestern United States), but the coolest portions of the country (e.g., the Pacific Northwest, Great Lakes, and New England) generally have only three-quarters as much insolation, and higher relative humidity, compared to the Southwest. The difference in evaporation between these two areas is larger than would otherwise occur if insolation and relative humidity were the same.

This confounding problem may not be manifest in use of Langbein's Figure 1 to characterize annual runoff *between* regions within the United States, because spatial differences of temperature, insolation and relative humidity are incorporated in the nomogram. However, when Langbein's relationships are used to estimate runoff changes associated with climate fluctuations over time for specific basins, there is a bias toward substantial overestimation of temperature impacts on evapotranspiration. This is because the Langbein curves are based on large differences among several basins in the United States, where macro-climatic factors (e.g., insolation, circulation, and continentality) create a strong *de facto* association between lower temperature, higher humidity, and lower insolation.

The bias in Langbein's curves can be seen in comparisons with other approaches. Nemec and Schaake (1982) also addressed the sensitivity of runoff to climate variations by applying the Sacramento Watershed model (Burnash, 1985), which uses a parametric representation of the physical processes involved in runoff (i.e., coefficients are set by correlations between matched climate, runoff and other data). Changes in runoff were assessed given concomitant changes of evapotranspiration for two basins in the southern United States, an arid basin in Texas and a humid basin in Mississippi. Although they did not try to isolate the impact of tem-



ANNUAL AVERAGE DAILY GLOBAL SOLAR RADIATION ON A HORIZONTAL SURFACE (MJ/m²)



MEAN RELATIVE HUMIDITY (%), ANNUAL

Fig. 2. Annual mean global radial radiation (M_j/m^2d^{-1}) and relative humidity (%) across the United States.

perature changes on runoff, some cogent inferences can be drawn by interpolating between the scenarios of climate change which they tested. For instance, a 4% increase in evapotranspiration (roughly equivalent to a 1 °C rise of temperature in the Nemec and Schaake analysis), with no change in precipitation, yields a 5 to 10% decrease in runoff in the arid basin. Langbein's nomogram (Figure 1) would predict a 25% runoff decrease in the same case. Only a 1 to 2% decrease in runoff is predicted in the humid basin for the same change of evapotranspiration, whereas Langbein's curves yield more than a 5% decrease in runoff. On the other hand, the model simulation indicates that a 10% increase of precipitation is amplified into larger changes of runoff in both basins: by a factor of 2.5 in the humid basin and a factor of 6 in the arid basin! These modeling results are not consistent with the relative impact of changes in precipitation and temperature on runoff derived from Langbein's diagram (Figure 1).

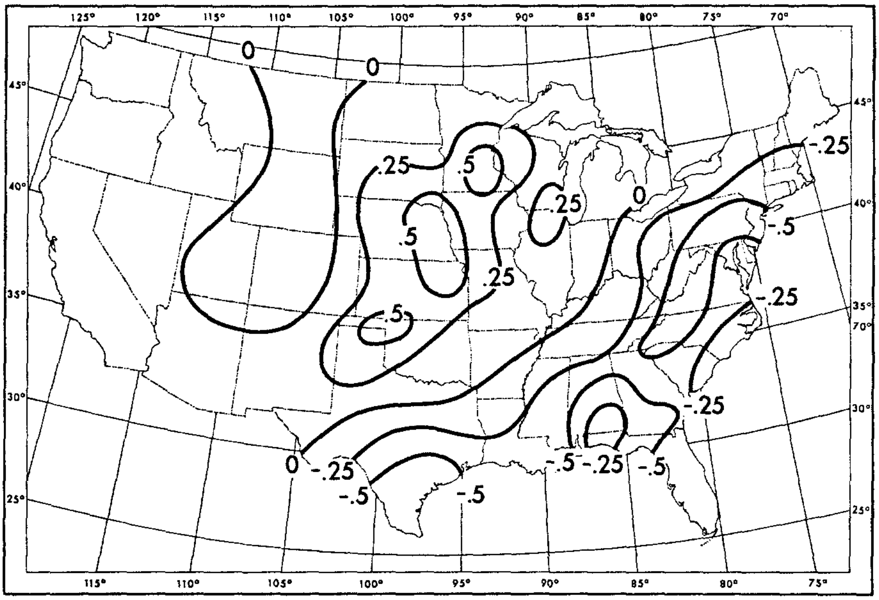
Other recent studies point to the pre-eminence of precipitation over temperature changes in affecting runoff. Wigley and Jones (1985) show by theory and empirical modeling that precipitation changes dominate evapotranspiration changes affecting runoff. They conclude that '...runoff is always more sensitive to precipitation changes than to evapotranspiration changes, particularly for higher (runoff ratios).' This relationship may be obscured, however, when temperature is used as a surrogate for evapotranspiration. Gleick (1986, 1987), using several scenarios of future climate as input to a water–balance model of California's Sacramento Basin, shows that *annual* runoff is affected primarily by precipitation changes, not temperature changes, while the *seasonal* distribution of runoff is affected by changes in mean monthly temperature. He attributed some of the seasonal effects to changes in the snow/rain ratio in the basin and to earlier snowpack melting. Gleick's (1987) water balance model produces increased winter runoff, even in cases of decreased precipitation, by adjusting the amount of precipitation falling as rain instead of snow.

3. An Empirical Approach

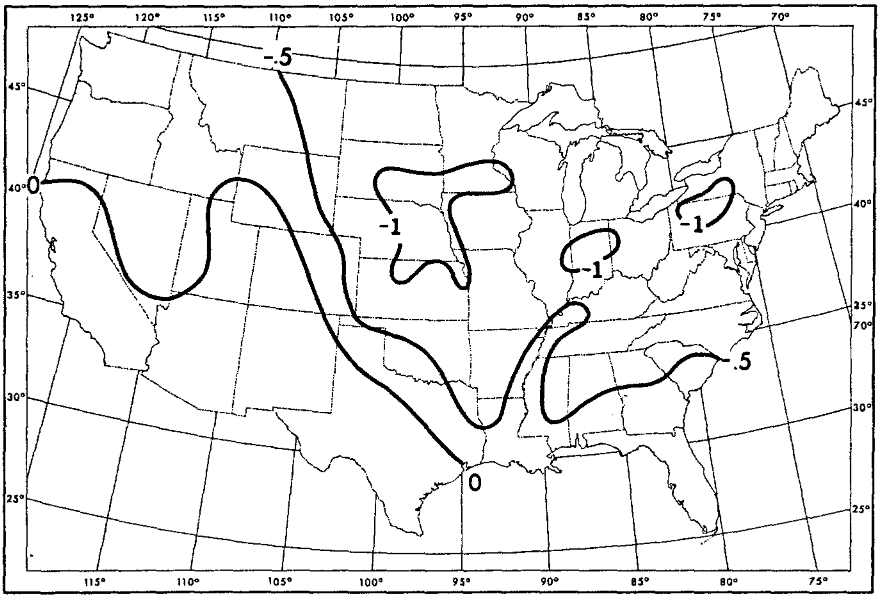
We set out to help clarify the relationships between climate and runoff by analyzing runoff changes associated with actual climate fluctuations in the recent (i.e., post-1930) United States record. We compared the largest 6- to 20-year changes in temperature and precipitation with changes of runoff in relatively undisturbed drainage basins.

We have shown elsewhere (Karl and Riebsame, 1984) that the modern U.S. climate record includes climate fluctuations approaching the magnitude of predicted temperature and precipitation changes due to a doubling of atmospheric CO_2, albeit for relatively short time periods (e.g., a decade or two). Thus, the recent past offers 'natural experiments' to assess the impact of changes in climate on runoff at the decadal time scale.

Figure 3 provides a typical example of the magnitude and spatial coherence of



Summertime precipitation (mm/d) change ($\bar{P}_{1950\text{-}68} - \bar{P}_{1931\text{-}49}$)



Summertime temperature (°C) change ($\bar{T}_{1950\text{-}68} - \bar{T}_{1931\text{-}49}$)

Fig. 3. An example of a 19-year epoch climate fluctuation with (a) increased precipitation in the Great Plains and decreased precipitation in the southeast; (b) concomitant changes of temperature.

the climate fluctuations identified by Karl and Riebsame (1984). A salient characteristic is their rather large areal extent, i.e., large areas of similar sign. The temperature fluctuations are generally of somewhat larger areal extent and are more coherent than the precipitation fluctuations, which reflects the greater spatial variability of monthly and seasonal precipitation anomalies. Nevertheless, the greatest fluctuations of both temperature and precipitation generally span several climate divisions or even several states.

These natural experiments provide the opportunity to assess the robustness of the relationships presented in Figure 1. They also provide a means to check the reliability of relationships between annual or seasonal anomalies of streamflow, precipitation, and temperature derived from regression equations based on interannual departures from the mean. By using multiyear climate fluctuations, we avoid relying on climate differences across space (as did Langbein, 1949), or on large year-to-year changes in climate and runoff (as did Revelle and Wagonner, 1983), to infer climate-runoff relationships under conditions of climate change. The decadal approach more closely emulates long-term climate change, though, of course, it is only one approximation of the manner in which climate can change. Other methods can be used to approximate climate change, e.g., general circulation models can be linked to hydrologic models. Our method should be viewed as an empirical validation and an alternative to such model linking.

3.1. *Data*

Alley and Lins (1986) surveyed regional personnel of the United States Geological Survey to compile a list of stream basins with little or no water diversions and other human impacts. From their original list of roughly 100 gauging stations, we selected 82, seeking a range of location and basin size, and data spanning at least 40 yr through the 1970s or early 1980s. Monthly streamflow measurements from the gauging stations (Figure 4) were combined with the area (A) of the upstream drainage basin to calculate seasonal and water-year (October through September) runoff in mm. That is, streamflow divided by the area of the basin defines basin runoff as used in this study. Basin area ranged from 10 km^2 to 75 000 km^2, with a median value of 2 100 km^2.

Seasonal and water year averages of temperature (corrected for time-of-observation bias, see Karl *et al.*, 1986) and total precipitation were calculated for the climatic divisions most closely corresponding to the drainage basin containing the gauged stream. Each drainage basin was related to a specific climate division (Figure 4). This approach provides at least as good a match between runoff and precipitation data as that achieved in broader analyses such as those by Stockton and Boggess (1979) and Revelle and Waggoner (1983), but it does not attain the detailed linking of runoff and precipitation possible in studies of small, densely instrumented watersheds.

Given the greater spatial variability of precipitation anomalies compared to tem-

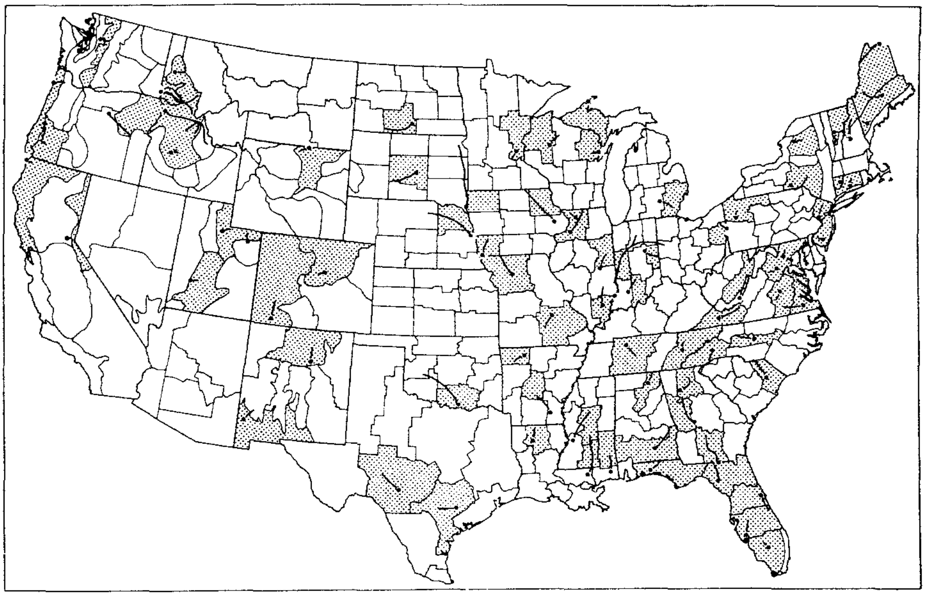


Fig. 4. Network of gaged streams and climate divisions (shaded) used in the analysis. Dots represent the gaging station locations.

perature anomalies, any errors in our analysis introduced by the assumption that the relative magnitude of precipitation fluctuations over the divisions are roughly the same for the drainage basins, will tend to be larger for precipitation than for temperature fluctuations. This would make the relationships between precipitation and runoff somewhat stronger than those which will be reported here. That is, we would underestimate the relative importance of precipitation fluctuations versus temperature fluctuations as they relate to changes of runoff.

A few additional comments on data and research design are in order here given different approaches to climate impact studies taken by climatologists and hydrologists. For instance, while hydrologists focus on links between short-term precipitation amounts and runoff in detailed studies of individual basins, we argue that matching climate divisions and basins is justified by the climatic focus and timeframe of our analysis.

It is also important to note that we do not address *absolute* values of runoff associated with precipitation and temperature. Such analyses require specialized precipitation networks for each watershed, particularly for those hydrologic models which are not heavily parametric. Rather, we analyze *relative* changes in precipitation and runoff between consecutive multi-year periods.

At this time-scale, both temperature and precipitation changes at the local level are highly correlated with climatic division values. Figure 5 shows the relationship between annual precipitation anomalies at any single station and the anomaly calculated over the climatic division in which it resides for the period 1931–84 for

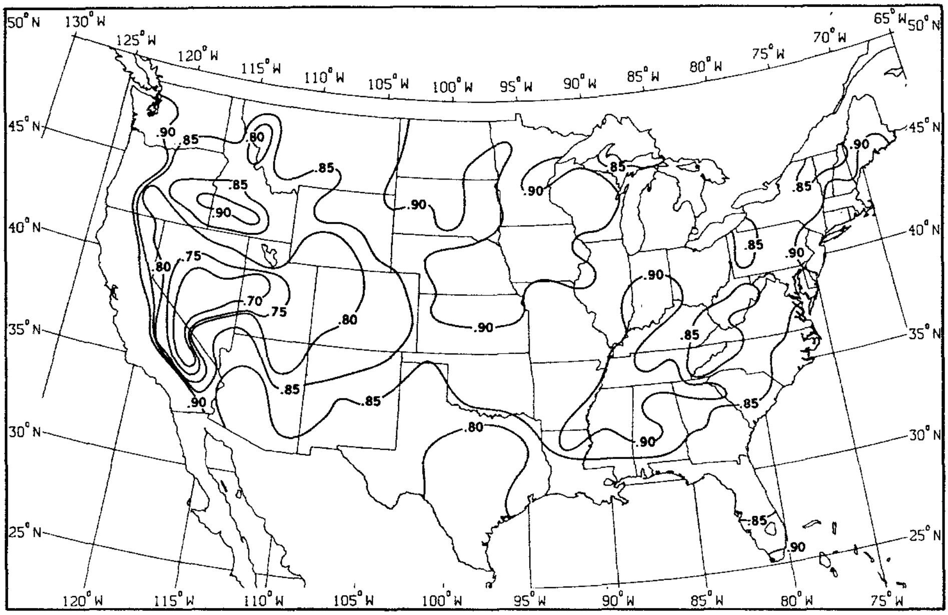


Fig. 5. Correlation of climate division annual precipitation with the annual precipitation at individual stations.

over 1200 stations in the Historical Climate Network (Karl and Williams, 1987). Figure 5 indicates that the precipitation anomalies for a climate division, even over a period as short as one year, are strongly related to point measurements. Even in the mountainous west, where station characteristics (e.g., elevation) vary greatly, only portions of Nevada, California, and Utah exhibit station-to-division correlations less than 0.7. The relationship between divisions and sub-areas like drainage basins will be even stronger.

3.2. *Analytical Methods*

Climate fluctuations derived from division averages for 1931–1984 were related to streamflow measurements and to other basin characteristics. The variables employed, and their abbreviations, are defined in Table I. We first identified 6- to 20-year climate fluctuations in the climate divisions associated with the set of 82 stream basins using the approach described in Karl and Riebsame (1984). One of our goals was the same as that in 1984: to identify cases of climate fluctuations that could be utilized in retrospective climate impact assessments as part of the Climate Impacts, Perception, and Adjustment Experiment (CLIMPAX). The goal of CLIMPAX studies (cf. Kates *et al.*, 1984) is to relate actual climate fluctuations to measurable biophysical and socio-economic impacts by applying longitudinal and case-control methods to matched climate fluctuation and impacts data sets (i.e., 'natural experiments').

TABLE I: Variables used in the analysis of decadal change in runoff

Variable description	Abbreviations	Units
Percent of total runoff in epoch 1 (R_1) observed in epoch 2 (R_2), ((R_2/R_1) × 100%) also denoted as $(R_2/R_1)\%$	$(R_2/R_1)\%$	%
Percent of total precipitation in epoch 1 (P_1) observed in epoch 2 (P_2), ((P_2/P_1) × 100%) also denoted as $(P_2/P_1)\%$	(P_2/P_1)	%
Change in temperature ($\overline{T}$) between epochs ($T_2 - T_1$)	$(T_2 - T_1)$	°C
Change in temperature between epochs when precipitation was constant	$(T_2 - T_1)_c$	°C
Area of drainage basin	A	km^2
Mean annual precipitation for all years of record	$\overline{P}$	mm
Mean annual temperature for all years of record	$\overline{T}$	°C
Weighted temperature	T_w	°C
Available water capacity of soil	AWC	mm
Weighted temperature minus mean annual temperature for all years of record	$T_w - \overline{T}$	°C

The student's *t*-statistic was calculated between all possible pairs of 'consecutive epochs' from 1931 to 1984 for each of the 82 climatic divisions. Consecutive epochs are adjacent spans of years of equal duration ranging from 6 to 20 years. For example, if epoch 1 is 1931 to 1950, then epoch 2 is 1951 to 1970. The *t*-statistic was calculated from temperature or precipitation averages for various seasons as well as for the water-year. The use of the *t*-statistic, as opposed to simply searching for the largest change of mean temperature or precipitation between epochs, emphasizes epochs where the differences are not dominated by a few extreme years. Precipitation data were first transformed to standard normal deviates through the Gamma Distribution by using the method of moments technique as described by Karl and Knight (1986). This prevents extreme precipitation events from dominating the *t*-statistic.

The largest positive and the largest negative *t*-statistic were then identified for each of three categories of epoch length: 6–10, 11–15, and 16–20 yr. Thus, the main sample of climate fluctuations to be related to runoff changes is the set of relative temperature and precipitation changes between consecutive epochs yielding the single largest positive and negative *t*-statistic in each of three categories of epoch length. This sample equals 82 (the number of basins) times 3 (the number of categories), times 2 (for positive and negative *t*-statistics), or about 500 cases for temperature and precipitation separately.

A special subset of fluctuations for each of the three epoch-length classes was formed by choosing the largest positive and negative *t*-statistics for temperature when there was little or no change in precipitation (i.e., precipitation *t*-statistics whose absolute value was less than 0.4). Since the *t*-statistic is approximately distributed as a standard normal deviate for large sample sizes (>30), and has an even larger dispersion for small sample sizes, the use of a 0.4 limiting value ensures that the change in precipitation from one epoch to the next is relatively small. This subset of fluctuations allowed us to search for the effect of temperature change on runoff without the masking influence of precipitation change.

The epoch-to-epoch difference of runoff (streamflow standardized by basin area) was calculated for each drainage basin for the epochs associated with the largest changes in temperature or precipitation. This runoff difference was then compared to the relative temperature and precipitation changes. We describe the resulting climate-runoff relationships using scatter plots and simple correlation. We also conducted more detailed multiple regression analyses of epoch-to-epoch changes of temperature, precipitation, runoff, and various basin characteristics, as described in Sections 4.3 and 4.4.

Climate-runoff relationships were assessed on a water-year basis, October through September, and for several seasons: spring (April, May, June); summer (July, August, September); fall (October, November, December); winter (January, February, March); cold season (November through April); and a warm season (May through October).

4. Results

4.1. *Temperature-runoff relationships*

For the most part, the relationships between changes in temperature and runoff from one epoch to the next (when there were minimal precipitation changes) were not significant. Figure 6 depicts the relationships on a water-year basis for both increasing (Figure 6a) and decreasing (Figure 6b) temperatures separately, and for the full sample (Figure 6c). The average change for the epochs with decreased temperatures is −0.65 °C; for the epochs with increased temperatures, the average change is +0.45 °C.

The sign of concomitant changes of temperature and runoff are in the expected direction. That is, higher temperatures (with precipitation essentially constant) tend to produce slightly decreased runoff and lower temperatures produce the opposite effect. The relationships, however, are very weak. The scatter about the line of best fit indicates that even for changes in temperature as high as 1 °C, there is little effect on runoff. The relationship between runoff and temperature is just as weak when we relax the requirement that precipitation remain essentially stable between epochs.

Similar results are found with respect to seasonal periods (Figure 7). Nearly all the relationships between changes in temperature and runoff were practically and statistically insignificant. The only exception to this occurred in the spring data (Figure 7a), but this weak relationship is not maintained into the summer period. Undoubtedly, the weak negative correlation (as opposed to no correlation) between temperature and runoff during the warm season is largely attributable to the slightly stronger negative correlation between changes of temperature and runoff during the spring.

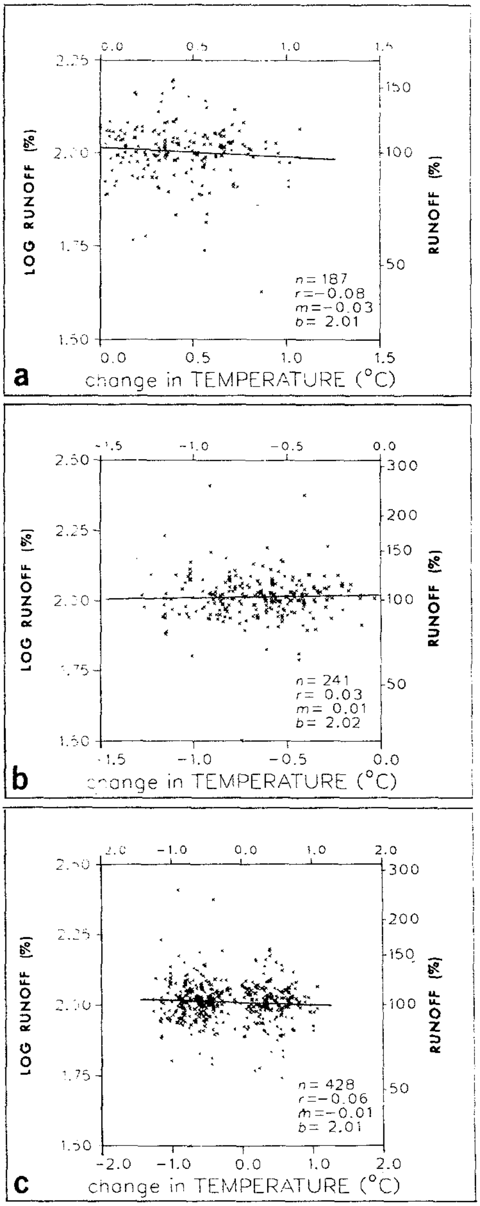


Fig. 6. Relationships between epoch-to-epoch annual changes of temperature and percent of total runoff in epoch 1 observed in epoch 2 $(R_2/R_1)\%$: (a) increasing temperature, (b) decreasing temperature, (c) combined increasing and decreasing temperature. The line of best fit is also depicted, and values given for n: the number of observations; r: the correlation coefficient; m: the slope of the line of best fit; and b: its intercept.

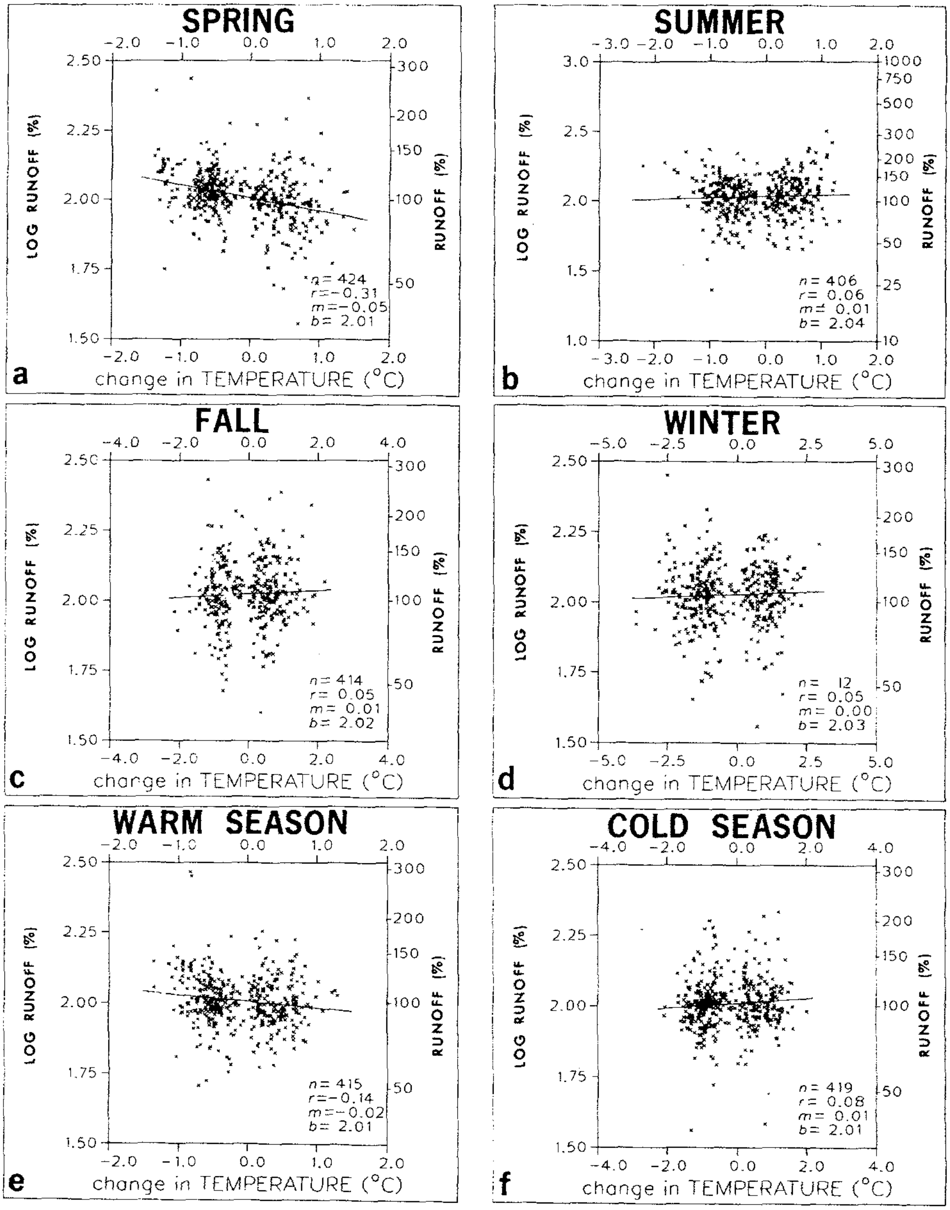


Fig. 7. Same as Figure 6 except for seasons.

4.2. *Precipitation run-off relationships*

Unlike the weak and often statistically insignificant relationships found between changes in temperature and runoff from one epoch to the next, the relationships between precipitation and runoff were highly significant, both from a statistical and practical viewpoint. These strong relationships emerged despite the fact that the drainage basins and climate divisions did not match exactly. They were consistently in the expected direction, and of roughly the magnitude suggested in the few other studies that attempt to separate temperature and precipitation impacts (e.g., Wigley and Jones, 1985). Figure 8 depicts these relationships on a water-year basis for cases of increasing and decreasing precipitation (Figure 8a and b, respectively), and for the combined samples (Figure 8c). Smaller correlation coefficients are observed when cases of increasing or decreasing precipitation are considered separately, an effect which can be attributed to the smaller dispersion of values in the subsamples.

Ratios of precipitation and runoff changes between epochs, with either increasing or decreasing precipitation from the first to the second epoch, are given in Table II. The amplification of precipitation changes as they translate into runoff changes is quite evident. For example, for all cases of decreasing precipitation the second epoch exhibited an average of 87.6% of the precipitation observed in the first epoch. The associated mean runoff in epoch 2 was 77.7% of epoch 1, yielding an amplification factor of 1.13 (87.6 divided by 77.7). A slightly larger amplification (1.24) was evident in the sample of epoch-to-epoch precipitation increases. Note that these values are conservative because they are derived from the average of all precipitation and runoff comparisons in the main sample. Much larger amplification occurred in some of the more arid basins, and in other individual cases, much as Wigley and Jones (1985) suggested.

We found that the amplification factor can be made nearly equal both above and below 100% (no difference between first and second epochs) by applying a log transformation. Thus the amplification factor is similar for cases of increasing and decreasing precipitation (see Table II). This linear amplification can be depicted by

TABLE II: Ratios of precipitation and runoff, for both increased and decreased precipitation with and without the log transformation. The ratio of changes in precipitation and runoff (inverted between increasing and decreasing precipitation to yield values greater than 1.00) gives the amplification factor (right-hand column) from precipitation to runoff changes

		Precipitation	Runoff	Amplification factor
		$(P_2/P_1)\%$	$(R_2/R_1)\%$	
Decreased precipitation		87.6	77.7	1.13
	(log)	1.942	1.890	1.03
Increased precipitation		117.0	145.6	1.24
	(log)	2.068	2.163	1.04

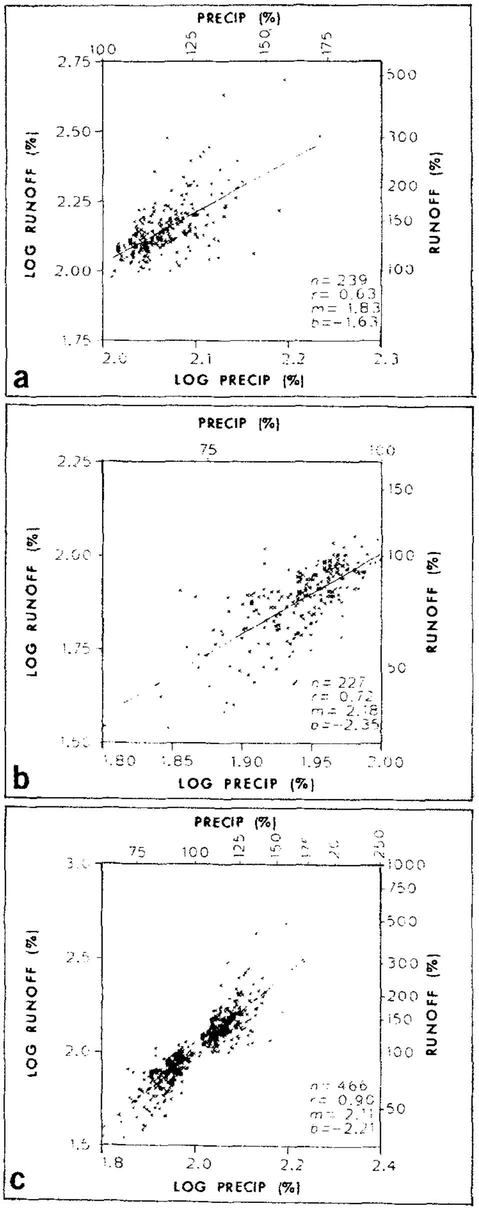


Fig. 8. Relationships between epoch-to-epoch changes of precipitation $(P_2/P_1)\%$ and runoff $(R_2/R_1)\%$: (a) increasing precipitation, (b) decreasing precipitation, (c) combined increasing and decreasing temperature. Abbreviations are the same as Figure 6.

using the relationship between $(R_2/R_1)\%$ and $(P_2/P_1)\%$ calculated for the combined (increasing and decreasing precipitation) sample (Figure 8c):

$$\mathrm{Log}(R_2/R_1)\% = 2.11\,(\mathrm{Log}(P_2/P_1)\%) - 2.21 \tag{2}$$

The satisfactory fit of this regression equation to the data in Figure 8c indicates that the relationship between relative changes in precipitation and runoff can be approximated by a single coefficient both above and below 100%.

On a seasonal basis, all scatter plots of precipitation and runoff changes continue to reveal significant positive correlations (Figure 9), but the relationships are weaker, especially during the warmer months. Lag effects (e.g., snowmelt and soil recharge) probably account for the weaker correlations in the seasonal analyses.

4.3. *Other Factors Affecting Runoff*

The matched climate and runoff data sets also allowed more detailed analysis of some factors affecting the relationship between climate and runoff changes. The variables listed in Table I were used in an 'all possible subset' regression analysis to construct an equation relating the quantity $(R_2/R_1)\%$ – the relative change in runoff from one epoch to the next expressed as a percentage – to $(P_2/P_1)\%$, A, $\bar{P}$, $\bar{T}$, T_w, AWC, and $T_w - \bar{T}$ (defined in Table I). Both subsets of increased and decreased precipitation were combined to construct the regression equation. Interaction variables were introduced by multiplying each of the quantities $\bar{P}$, $\bar{T}$, T_w, AWC, $T_w - \bar{T}$ by the sign of the precipitation change. Thus, one equation can be used to represent the effects of precipitation changes both above and below 100% (cf. discussion of Equation 2, Section 4.2). The selection of variables in the regression equation was based on both physical meaningfulness of the sign of the coefficients, and on the magnitude of the t-statistics of each coefficient.

The multiple regression equation is given in Table III. The statistical significance of the variables listed in Table III can be approximated when the residuals of the predicted value are normally distributed and the number of degrees of freedom are known. The use of the logarithmic function helped satisfy the normality requirement, and since 82 separate drainage basins are used in the analysis, the degrees of

TABLE III: Regression equation for the percent of total runoff in epoch 1 observed in epoch 2 $(R_2/R_1)\%$. r^2 is the variance explained by the equation, b is the intercept, and other symbols are defined in Table I

Predictand	r^2	Predictor	Coefficient	t	Mean
$\mathrm{Log}((R_2/R_1)\%)$	0.856	$\log((P_2/P_1)\%)$	1.77	22.94	2.005
Residuals approximately		$(T_w - T)\,(\mathrm{Sign}\ P_2 - P_1)$	5.65×10^{-3}	6.83	0.0
normally distributed		$(T_w)\,(\mathrm{Sign}\ P_2 - P_1)$	3.01×10^{-3}	4.45	0.4
Mean = 2.018		$(P)\,(\mathrm{Sign}\ P_2 - P_1)$	-1.79×10^{-5}	−2.41	36.9
		b	−1.525		

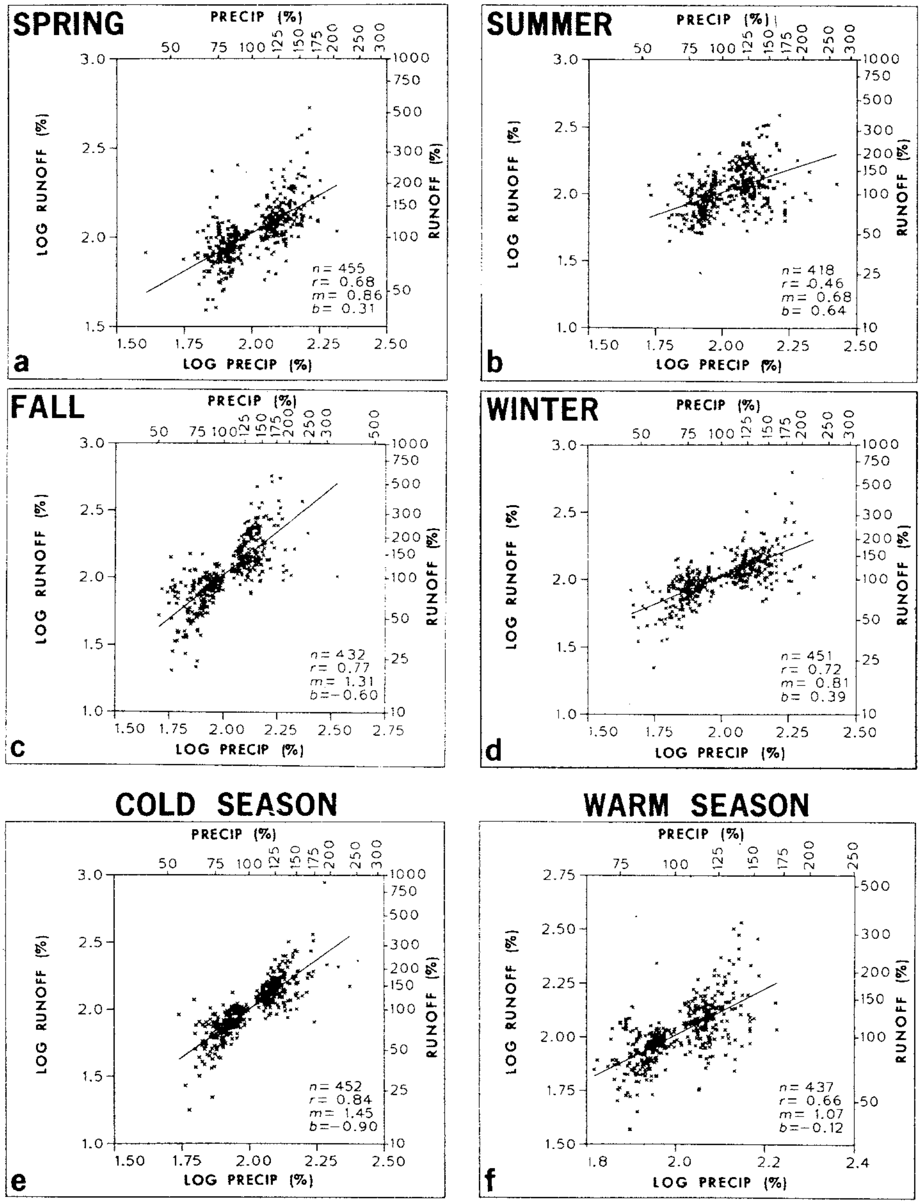


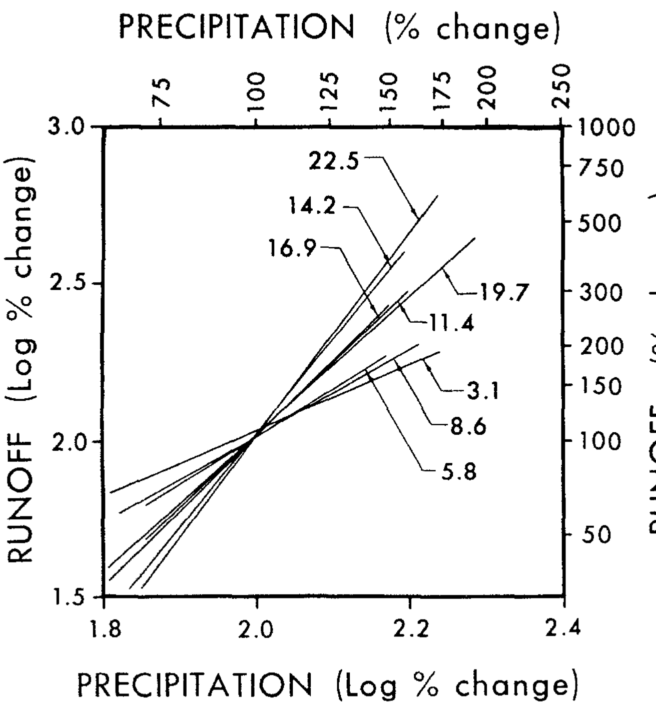
Fig. 9. Same as Figure 8 except for seasons.

freedom are such that the distribution of the *t*-statistics should be approximately normal. This implies that the *p*-value of a *t*-statistic over 2.0 (2.7) is significant at the 0.05 (0.01) level. Of course, these significance levels are only strictly valid for an individual variable in the equation and not for multiple variables.

The quantities $(P_2/P_1)\%$, $T_w - \bar{T}$ and T_w in Table III are all positively related to $(R_2/R_1)\%$ in the regression equation. That is, higher values of these quantities produce larger values of $(R_2/R_1)\%$ when precipitation increases and lower values of $(R_2/R_1)\%$ when precipitation decreases. The positive relation between T_w and the magnitude of the change in runoff can be explained by the fact that basins with high values of T_w normally have low runoff relative to the amount of precipitation they receive, because warmer temperatures are associated with more evaporative losses. In basins with low runoff, small changes (of low numbers) often produce relatively large changes in percent.

Figure 10 demonstrates the nature of the relationship between T_w and $(R_2/R_1)\%$ for various values of $(P_2/P_1)\%$ and thus represents our version of the Langbein nomogram. The increasing slope of the line of best fit between $(P_2/P_1)\%$ and $(R_2/R_1)\%$ with higher values of T_w is indicative of the positive relationship between $(R_2/R_1)\%$ and T_w. The same characteristic can also be found in Figure 1, but it is not immediately obvious.

A larger change in runoff occurs when $T_w - \bar{T} > 0$ than when $T_w - \bar{T} < 0$, that is, when more of the precipitation occurs during the warmer season when evaporative losses are larger. Larger changes of runoff will tend to occur when $T_w - \bar{T} > 0$ because small changes of already low values of R_1 tend to produce high values of $(R_2/R_1)\%$. Similarly, lower values of P are associated with less runoff which makes



$\overline{T}_w = 3.1$	n = 53	r = 0.85	m = 1.03	b = -0.05
$\overline{T}_w = 5.8$	n = 58	r = 0.94	m = 1.50	b = -1.00
$\overline{T}_w = 8.6$	n = 58	r = 0.91	m = 1.36	b = -0.71
$\overline{T}_w = 11.4$	n = 109	r = 0.93	m = 2.31	b = -2.62
$\overline{T}_w = 14.2$	n = 91	r = 0.94	m = 2.96	b = -3.91
$\overline{T}_w = 16.9$	n = 35	r = 0.98	m = 2.31	b = -2.62
$\overline{T}_w = 19.7$	n = 32	r = 0.95	m = 2.17	b = -2.33
$\overline{T}_w = 22.5$	n = 30	r = 0.98	m = 3.22	b = -4.43

Fig. 10. Relationships between epoch-to-epoch changes of precipitation $(P_2/P_1)\%$ and runoff $(R_2/R_1)\%$ as a function of T_w. Abbreviations are the same as Figure 6.

it more likely that for comparable values of $(P_2/P_1)\%$ in two basins, the one with the lower P will experience a greater impact on $(R_2/R_1)\%$.

4.4. *Runoff Changes Associated With Specified Precipitation Changes*

The multiple regression equation developed in the previous section allows us to relate runoff changes to specified precipitation changes, such as those that might be predicted by climate models or scenarios based on arbitrary increments. For example, the impact on the quantity $(R_2/R_1)\%$ of a 10% precipitation change (i.e., epoch 2 precipitation is 90% – or 110% – of epoch 1 precipitation) is depicted in Figure 11 for basins with varying climate characteristics. Figure 11 was derived from the equation given in Table III, where just over 85% of the variance of $(R_2/R_1)\%$ is explained. It can be seen in Figure 11 that for *precipitation increases* of 10%, the amplification of the response in $(R_2/R_1)\%$ varies considerably depending on the weighted temperature (T_w), the seasonality of precipitation ($T_w - \bar{T}$), and the total annual precipitation ($\bar{P}$). For example, if $P = 1000$ mm, $T_w = 25$ °C, and $T_w - \bar{T} = 10$ °C, the amplification factor is six. That is, a 60% increase of runoff occurs with a 10% increase of precipitation. But, for the same total precipitation where $T_w = 0$ °C and $T_w - \bar{T} = -10$ °C, no amplification of the change in runoff is apparent (an amplification factor of one). For *precipitation decreases* of 10%, the amplification of the response in $(R_2/R_1)\%$ ranges from 3 to 4. That is, a 10% decrease of total precipitation leads to a 30% to 40% decrease in runoff for $\bar{P} = 1000$ mm, $T_w = 25$ °C, and $T_w - \bar{T} = 10$ °C.

It is evident in Figure 11 that any change of $\bar{P}$ alters the amplification factor slightly, but not to the degree that T_w or $T_w - \bar{T}$ alter it. One must be careful however, in interpreting these results because $\bar{P}$, T_w, and $T_w - \bar{T}$ are strongly inter-related in many localities. Much of the effect of varying $\bar{P}$ between basins may be accounted for in the other terms, T_w and $T_w - \bar{T}$.

5. Comparisons with other Studies

This study indicates that only slight changes in runoff in a basin are associated with decadal changes of mean temperature up to ± 1 °C on an annual basis, and as large as ± 2 °C on a seasonal basis. On the other hand, decadal changes of mean annual precipitation of the order of 10% have a substantial impact on runoff, increasing or decreasing runoff often by considerably more than 10%, depending on basin characteristics such as total precipitation or seasonality of precipitation.

The discrepancy between climate-runoff studies using Langbein's analysis and those presented here may be due to a combination of factors. First, Langbein (1949) used only a quarter of the number of drainage basins used in this study. More importantly, as described in Section 1, his results are based on large spatial differences in climate and may not apply equally to relatively small temporal changes in climate at a specific location. We argue that over-emphasis of the impact

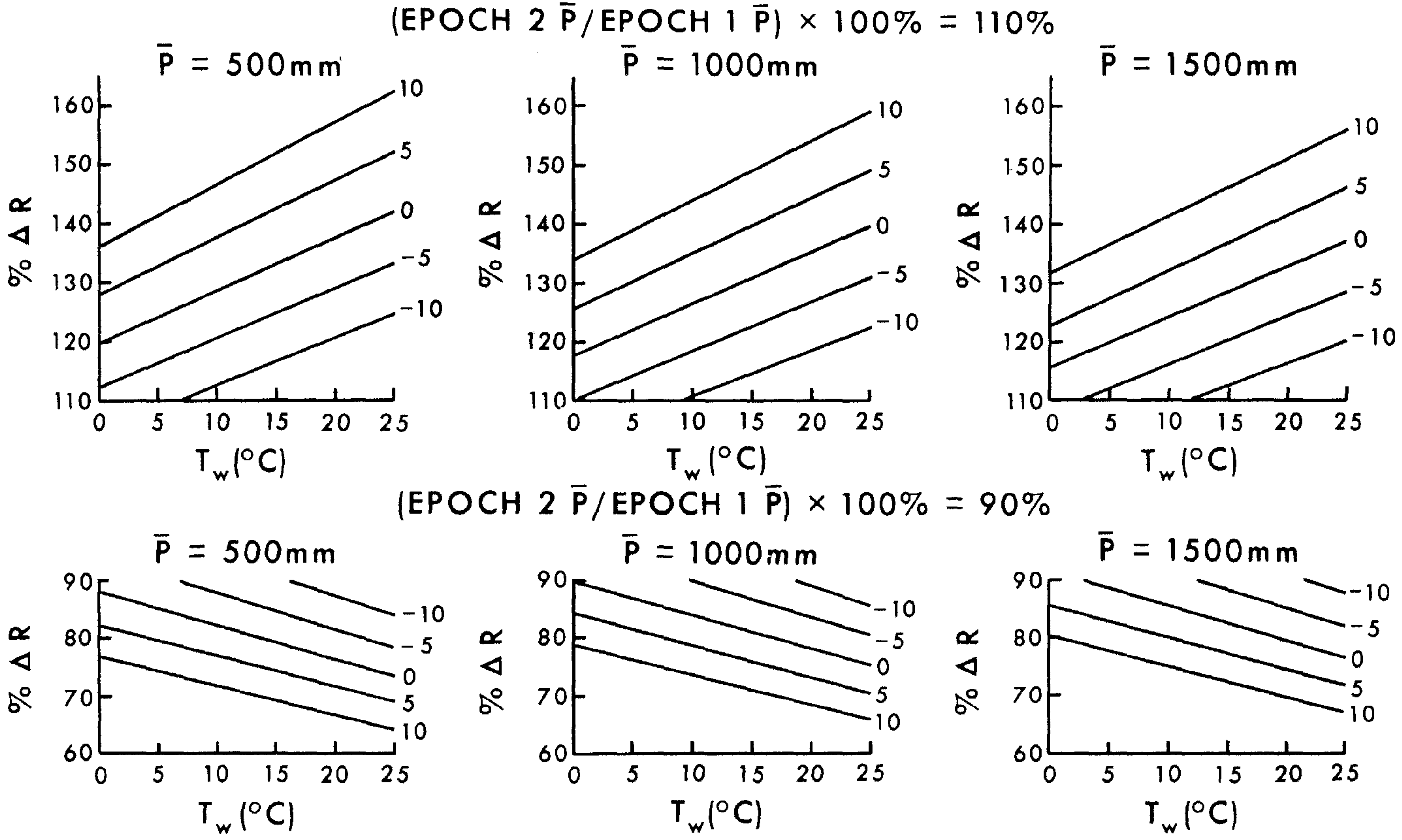


Fig. 11. Relationships between mean annual precipitation ($\overline{P}$), weighted temperature (T_w), seasonality of precipitation ($T_w - \overline{T}$, values given to the right of diagonal lines), change in epoch-to-epoch precipitation $(P_2/P_1) \times 100\%$, and the change in epoch-to-epoch runoff $(R_2/R_1) \times 100\%$.

of temperature changes on runoff in Langbein's relationships is due to changes in insolation, advection, humidity, surface characteristics, and wind speed from basin-to-basin, east-to-west and north-to-south across the U.S. These changes are implicitly considered in Figure 1 because it is constructed from comparisons over space. Such changes are not necessarily pertinent to *in situ* relationships between changing temperature, evapotranspiration, and runoff.

The use of Figure 1 led Revelle and Waggoner (1983) to conclude that temperature rises of 2 °C would have serious impacts on runoff in several U.S. regions, even if precipitation were to increase slightly. In order to demonstrate this point in another way, they derive a multiple regression equation using 46 years of streamflow data for the Colorado River. Their analysis relates the mean annual flow to temperature and precipitation on a year-by-year basis, and leads to the conclusions that 'a rise of 2 °C in temperature would decrease virgin flow by about 29%. Additionally, a 10% decrease in precipitation would reduce the flow by an additional 11%'. They indicate that this result is similar to the estimate given by Stockton and Boggess (1979), who also use the relationships shown in Figure 1 to assess the impact of climate change on water resources.

The data presented by Revelle and Waggoner (1983) for the Colorado River Basin are plotted in Figure 12. As an alternative to treating each year as one case in a multiple regression, where the correlation between annual temperature and precipitation in the basin ($r = -0.40$) adds to the difficulty of determining which variable is causing changes in streamflow, the methodology presented in this paper was used to assess the impact of decadal-scale temperature and precipitation changes on river flow. We illustrate this approach with a case in which the average flow decreased by 14% (86% of the previous epoch) from one 18-year epoch, 1935–1952, to the next 18-year epoch, 1953–1970 (Figure 12a). At the same time, the precipitation decreased by 10% (90% of the previous epoch) and the temperature remained constant. The regression equation which predicts $(R_2/R_1)\%$ (Table III) was checked against the changes found in Figure 12. The value of $(P_2/P_1)\%$ was set to 90% and the other variables were set equal to the appropriate value for the region as represented by the five climatic divisions used by Revelle and Waggoner (1983), i.e., $T_w - \bar{T} = 2$ °C, $T_w = 7$ °C, and $\bar{P} = 332$ mm. The value of $(R_2/R_1)\%$ based on the equation in Table III is 85%, which is very close to the observed value of 86%.

Figure 12b provides an example where the precipitation remained essentially constant (actually it decreased by 4 mm or 1.2%, well within the noise of the data) between two 13-yr epochs, 1931–1943 versus 1944–1956. Simultaneously, the temperature decreased by nearly 0.5 °C. Despite decreased temperature the flow remained essentially constant (it increased by 0.7%, but this again is within the noise of the measurements). The multiple regression equation developed by Revelle and Waggoner using this data would have predicted more than 5% increase in streamflow. Such an estimate seriously overstates the impact of decadal scale temperature changes on the runoff.

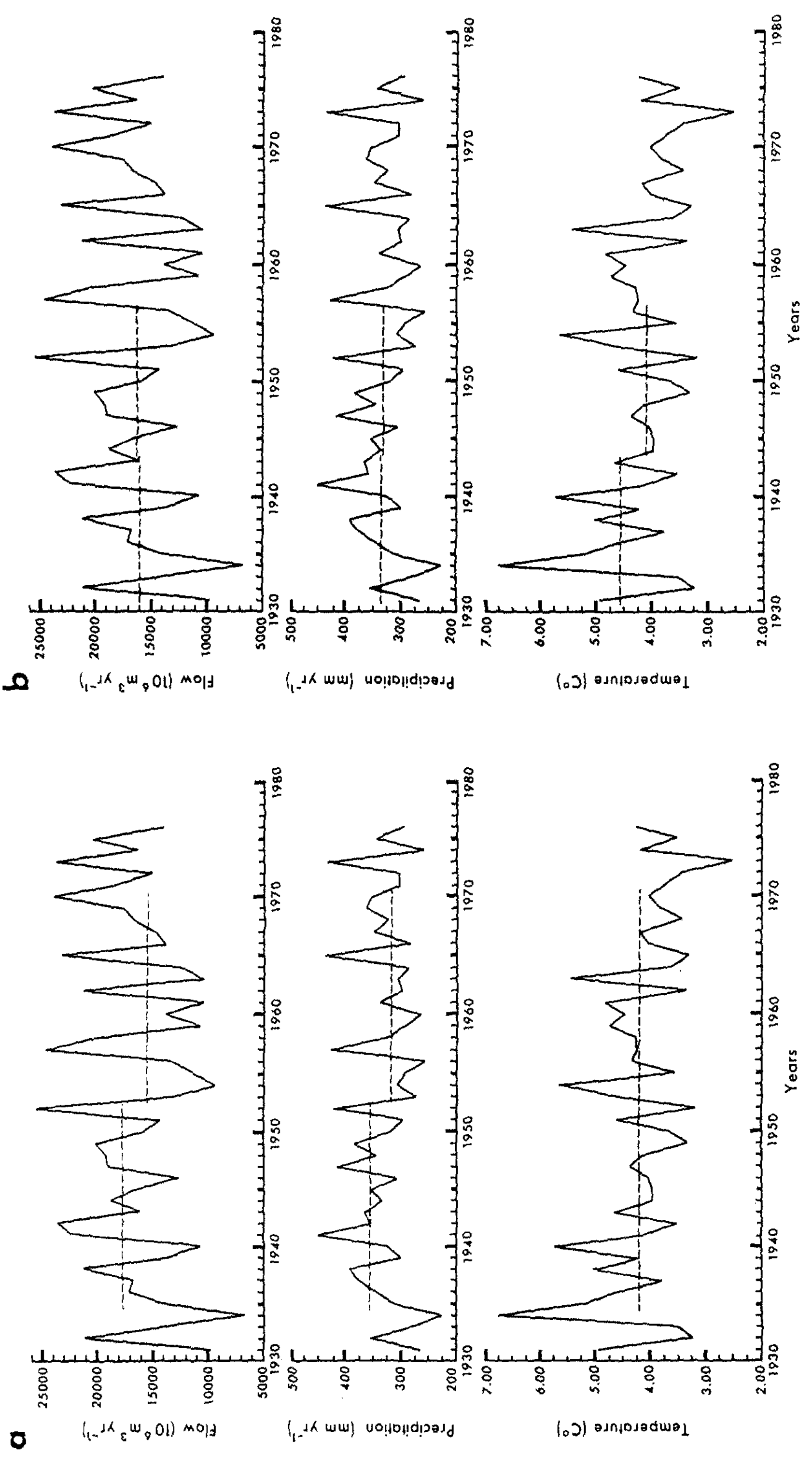


Fig. 12. Annual averages of precipitation, temperature, and virgin flow of the Colorado River at Lees Ferry, 1931–76. Horizotal dashed lines represent consecutive epochs as defined in the text. Data from Revelle and Waggoner (1983).

We next compared runoff changes predicted using Figure 11 (or Table III) with results from Nemec and Schaake (1982). Their model predictions, and the empirical predictions from this study, are reasonably consistent in the two basins they studied. For the arid Pease River Basin (T_w = 20 °C, $\bar{P}$ = 600 mm, and $T_w - \bar{T}$ = 3 °C), a 10% increase of precipitation is amplified by a factor of 6.0 in runoff. Our analysis yields an amplification factor of 4.5. For the more humid Leaf River Basin of Mississippi, our results suggest an amplification factor between precipitation and runoff changes of 2.5–3.0, compared to the modeled value of 2.5. For a 10% decrease of precipitation, Nemec and Schaake found amplification factors of 4.0 and 2.0 for the arid basin and the humid basin, respectively, while our results indicate amplification factors of 2.5–3.0 and 2.0, respectively. Thus, our general empirical results (which did not include the basins Nemec and Schaake analyzed) compare favorably with Nemec and Schaake's modeling results.

6. Conclusions

Analysis of decadal climate fluctuations and associated runoff changes over the past 50 yr in the United States indicates that temperature fluctuations are not as great a factor in runoff changes as suggested in previous studies. This is because relationships between climate and runoff assumed in several previous studies (Langbein's nomogram: Figure 1) tend to overstate the role of evaporation. Our version of Langbein's nomogram (Figure 10), based on temporal fluctuations of climate and runoff in 82 basins with minimum human impact, indicates that precipitation changes may be amplified one to six times in relative runoff changes. However, even 1° to 2° average temperature changes often have little effect on annual runoff. Thus, knowledge of climate warming, such as that expected with increasing CO_2 concentration and other greenhouse gases, is not sufficient to estimate water resource impact. Concomitant estimates of the change in precipitation are necessary.

Current and future efforts in GCM modeling, and other approaches to extrapolating the future greenhouse climate, must better address the magnitude and spatial pattern of precipitation changes if we are to assess impacts on runoff for specific drainage basins. Estimates of precipitation changes from doubled CO_2 concentrations are not consistent from model to model (Schlesinger and Mitchell, 1985). Overall, however, the models tend to predict a stronger hydrologic cycle. Our analyses indicate that increases of precipitation of just a few percent may offset the runoff impacts of even the several degree Celsius warming expected sometime next century. If the precipitation changes are larger than a few percent, then they will likely dominate climate change impacts on runoff. Even small precipitation decreases could be very significant in terms of runoff reductions. The precipitation-to-runoff change amplifications found here and in several other studies should be of particular concern because most models suggest that drying will occur over much of the interior United States (Schlesinger and Mitchell, 1985).

Potentially severe water resource impacts of future climate changes call for closer examination of the relationships between temperature, precipitation, other controlling variables, and runoff. Our analysis suggests that some of the assumptions required to make use of previous work (i.e., Langbein's pioneering work on precipitation-runoff relationships) may be misleading. Natural experiments can help provide needed verification of model simulations based on the climate record. The empirical relationships identified at broad time and space scales in this study should be tested by more detailed analyses of watersheds for which high density precipitation data are available. Past research on individual watersheds has neglected climate change *per se*, but this work should be re-analyzed in light of increasingly credible projections of the greenhouse effect.

Finally, water resource systems are affected not only by changes in the magnitude of runoff, but by changes in its year-to-year variability (Callaway and Currie, 1985; Riebsame, 1988). It would thus be useful to analyze changes in precipitation and temperature as they relate to runoff variability and extreme events. Since recent empirical evidence (Karl, 1988) indicates that marked changes in temperature and precipitation variability have also occurred during the twentieth century in the United States, the method presented here could prove useful in an analysis of higher moments.

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