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SENSITIVITY OF STREAMFLOW IN THE COLORADO BASIN TO CLIMATIC CHANGES

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ABSTRACT

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Changes in regional temperature and precipitation expected to occur as a result of the accumulation of greenhouse gases may have significant impacts on water resources. We use a conceptual hydrologic model, developed and operated by the National Weather Service, to study the sensitivity of surface runoff in several sub-basins of the Colorado River to these changes. Increases in temperature of 2°C decrease mean annual runoff by 4–12%. A temperature increase of 4°C decreases mean annual runoff by 9–21%. Increases or decreases in annual precipitation of 10–20% result in corresponding changes in mean annual runoff of approximately 10–20%. For the range of scenarios studied, these results suggest that runoff in the basin is somewhat more sensitive to changes in precipitation than to changes in temperature. Seasonal changes were also observed, with peak runoff shifting from June to April or May. Fall and winter flows generally increase, whereas spring and summer flows decrease in most of the scenarios studied. These changes are attributed to an increase of the ratio of rain to snow and to a higher snowline. Although these results suggest that streamflow in the Colorado Basin is less sensitive to climatic changes than previous statistical studies have indicated, the magnitude of possible changes is nonetheless sufficiently great to have significant environmental, economic, and political implications.

INTRODUCTION

The Colorado River is one of the most important river systems in the United States. Although not a large river even by North American standards, the Colorado River flows through some of the most arid regions of the country and is the sole source of water for a region with extensive agriculture, large cities, and a diverse ecosystem. Existing global models suggest that climatic changes will have dramatic impacts on water resources. Water availability, quality, and demand may be affected by higher temperatures, new precipitation patterns, rising sea level, and changes in storm frequency and intensity. Water supply and water management in the Colorado Basin, already contested issues, are likely to be aggravated by these changes. Moreover, potential climatic impacts

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may have significant ramifications for decisions about water allocations and water rights that are likely to be made in the coming decade.

Despite recent advances in modeling the atmosphere and climatic changes, large uncertainties remain about the details of regional hydrologic changes. Until current global climatic models improve both their spatial resolution and their hydrologic parameterizations, information on the hydrologic effects of global climatic changes can best be obtained using regional hydrologic models. At this time, such studies are limited to sensitivity analyses that describe the vulnerability of hydrologic basins to a range of plausible climate scenarios. Although these scenarios cannot be regarded as reliable predictions of future conditions, they do provide insights into regional vulnerabilities.

Studies of the hydrologic impacts of climatic change can be divided into two categories: (1) stochastic methods that rely primarily on statistical techniques for evaluating the hydrologic characteristics of a region or for extending the existing hydrologic record (such as Schwarz (1977), Stockton and Boggess (1979), Revelle and Waggoner (1983)); (2) deterministic or conceptual models that use physically based, mathematical descriptions of hydrologic phenomena (Nemec and Schaake, 1982; Cohen, 1986; Gleick, 1986, 1987a,b; Mather and Feddema, 1986; Flaschka et al., 1987; Bultot et al., 1988). To date, climate impact studies on the Colorado River Basin have been limited to stochastic methods (Stockton and Boggess, 1979; Revelle and Waggoner, 1983). These studies necessarily assume, however, that the relationships among temperature, precipitation, and streamflow will remain unchanged under future climatic conditions. In contrast, we use a conceptual hydrologic model to study the sensitivity of the basin to greenhouse warming. By modeling actual hydrologic processes (e.g. percolation, soil-moisture storage, snowmelt, etc.), deterministic techniques incorporate an additional level of complexity. So long as these hydrologic processes do not change significantly under a CO_2-altered climate, deterministic models should be more robust than derived statistical relationships between meteorologic variables and streamflow. A recent attempt to use a deterministic model to study climatic impacts on a small sub-basin of the Colorado River is presented in Schaake (1990). We expand upon that work by incorporating additional climate scenarios and modeling additional sub-basins.

METHODS OF ANALYSIS

Climate scenarios

To assess the potential impacts of climatic change on runoff in the Colorado River Basin, scenarios of changes in temperature and precipitation were used as inputs to a regional hydrologic model. Currently, we lack the ability to predict the regional-scale details of climatic change; thus, for this study we relied on purely hypothetical scenarios as well as scenarios derived from the outputs of general circulation models (GCMs). These scenarios are listed in Table 1.

TABLE 1

Climate change scenarios used in the NWSRFS model

Hypothetical	Two-Basin Aggregated	White River	East River	Animas River
T + 2°C, P − 20%	–	X	X	X
T + 2°C, P − 10%	X	X	X	X
T + 2°C, P + 0	X	X	X	X
T + 2°C, P + 10%	X	X	X	X
T + 2°C, P + 20%	–	X	X	X
T + 4°C, P − 20	X	X	X	X
T + 4°C, P − 10%	X	X	X	X
T + 4°C, P + 0	X	X	X	X
T + 4°C, P + 10%	X	X	X	X
T + 4°C, P + 20%	X	X	X	X
GCM[1]				
GISS 1: T + 4.8°C, P + 20%	–	X	–	–
GISS 2: T + 4.9°C, P + 10%	X	–	X	X
GFDL: T + 4.7°C, P + 0	X	X	X	X
UKMO 1: T + 6.8°C, P + 30%	X	X	–	–
UKMO 2: T + 6.9°C, P + 10%	X	X	X	X

[1] All GCM scenarios represent annual average changes for an equilibrium ($2X\mathrm{CO}_2$) run.

The values chosen for hypothetical scenarios typically reflect best estimates of changes in important climatic variables, although extreme values are occasionally chosen to explore where a system might fail to perform as expected or designed. Thus, the practice of using hypothetical temperature increases of 1, 2, 3, or 4°C reflects the consensus that greenhouse warming will produce temperature rises in this range, given an equivalent doubling of atmospheric CO_2. Because much greater uncertainty surrounds estimates of change in regional precipitation, both increases and decreases in average annual rainfall are modeled in this study.

General circulation models are imperfect representations of the global atmosphere. They simplify many critical phenomena, notably cloud feedback mechanisms and ocean processes. In addition, their coarse scale substantially constrains any attempt to use GCM results for regional modeling. Single grid points may encompass hundreds of square miles, including mountainous and desert terrain, ocean and land, with GCM data representing average results over these large areas. Despite these limitations, GCM scenarios offer the advantage of internally consistent, regionally based scenarios. When used in combination with hypothetical scenarios, GCM scenarios provide both additional sensitivity runs and a check on the plausibility of hypothetical scenarios. In this project, temperature and precipitation data from three state-of-the-art GCMs were used to develop inputs for use in a hydrologic model of the Colorado River Basin. The data come from the Goddard Institute for Space

Studies (GISS) model, the Geophysical Fluid Dynamics Laboratory (GFDL) model, and the United Kingdom Meteorological Office (UKMO) model (Hansen et al., 1983; Manabe and Weatherald, 1987; Wilson and Mitchell, 1987). In each case, the data reflect an equilibrium run, i.e. CO_2 is doubled all at once, and the model is run until a new equilibrium climate is established. The use of more than one GCM has two advantages: (1) reliance on one GCM may give a false impression of accuracy; (2) the use of more than one GCM highlights model differences and similarities and permits a broader analysis of outcomes and sensitivities.

Hydrologic modeling

The large size of the Colorado Basin complicates the development of a deterministic hydrologic model; indeed, no completely satisfactory basin model could be identified. This study used a deterministic hydrologic model developed and operated by the National Weather Service River Forecasting Service (NWSRFS) in Salt Lake City, Utah.

The NWSRFS is comprised of two linked models: a soil-moisture accounting model that calculates gains and losses of water in the soil through various processes (e.g. evaporation, transpiration, infiltration), and a snow accumulation and ablation model that calculates the accumulation of snow and the contribution of snowmelt to soil moisture and runoff. It is the only large-scale model of the Colorado Basin that has been calibrated and tested. The soil-moisture accounting model is a modified version of the Sacramento model described in Burnash et al. (1973). This model is widely used and generally accepted as one of the most reliable in varied climatic conditions on several continents, including both arid and humid regions (Nemec and Schaake, 1982; U.S. Environmental Protection Agency, 1989). The model distributes soil moisture into an upper and lower zone. Movement between zones is described by a physically based percolation equation, the parameters of which are determined by the free-water content in the upper zone and the soil-moisture deficiency of the lower zone. The snowmelt model, described in detail in Anderson (1976), relies on air temperature as an index to energy exchange at the snow–air interface. The inputs to the model are areal temperature and precipitation data; the output is streamflow (surface runoff) on a six-hourly basis.

The NWSRFS models the Upper Colorado Basin as a series of approximately 50 small sub-basins that are linked together. For forecasting purposes, all of the sub-basins are modeled simultaneously. For calibration purposes, however, each of these sub-basins is modeled separately. In addition, an aggregated model has been developed that divides the entire Upper Colorado Basin into two elevation zones and uses a limited number of data stations to predict inflow into Lake Powell. Schaake (1990) used the NWSRFS model to analyze the sensitivity of the Animas River sub-basin to a range of climatic variations. In this study, we selected the Two-Basin Aggregated model and three sub-basins

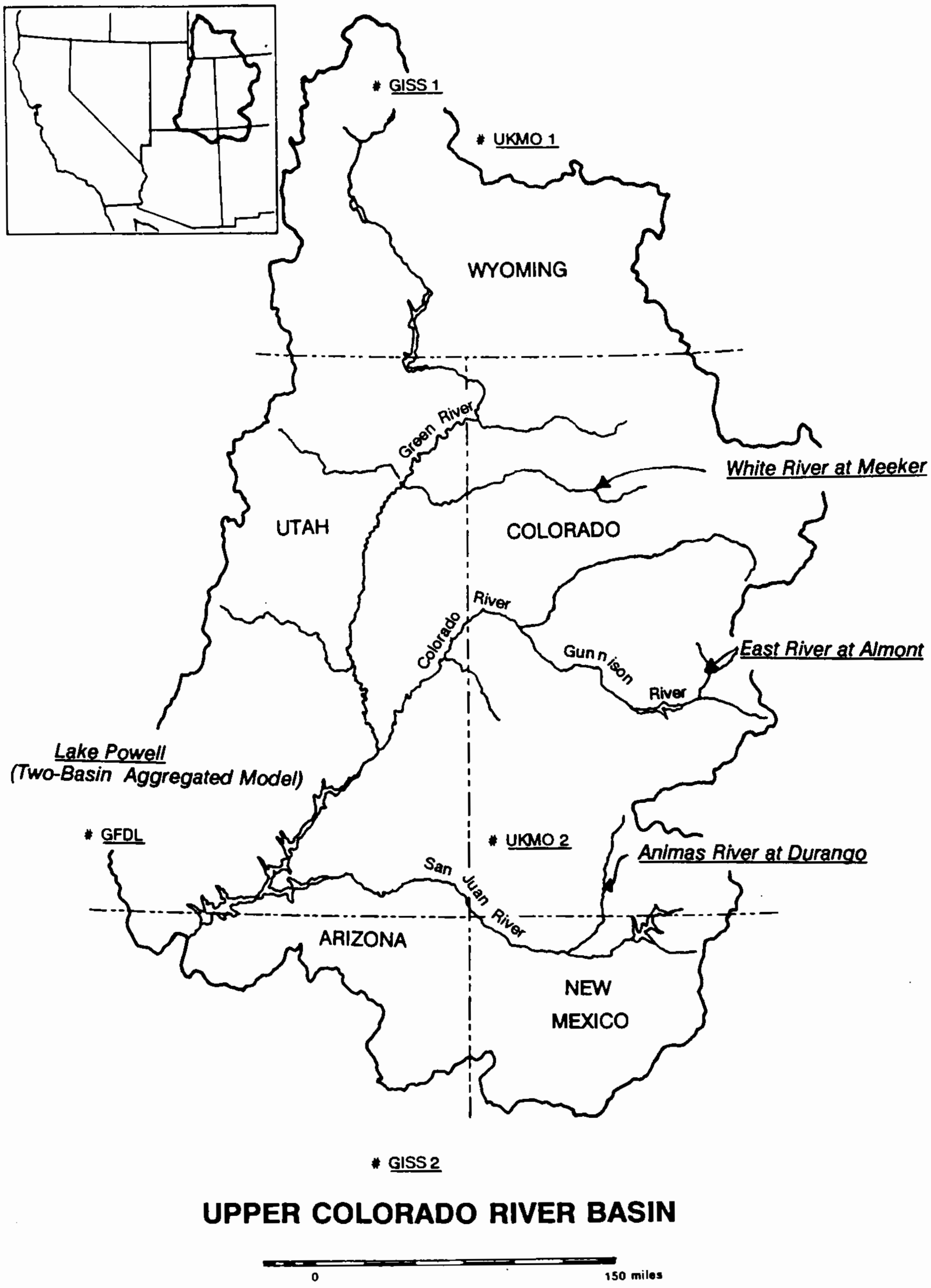


Fig. 1. Map of the Colorado River Basin showing the location of the modeled sub-basins and the mid-points of relevant GCM grid boxes. (Redrawn from Upper Colorado Region Comprehensive Framework Study, Main Report, June 1971).

that were known to make a substantial contribution to basin flow: the White River at Meeker, the East River at Almont, and the Animas River at Durango. The location and characteristics of these basins are given in Fig. 1 and Table 2.

TABLE 2

Characteristics of Colorado River sub-basins

	Drainage area (km^2)	Mean annual discharge ($m^3 s^{-1}$)	Percentage of Upper Basin flow
White River at Meeker	1974	205	4
East River at Almont	1458	108	2
Animas River at Durango	1796	256	5

Model calibration

In the case of the NWSRFS model, all testing and calibration have been done by the National Weather Service in Salt Lake City. The entire 35-year record was used to calibrate each of the sub-basins; thus, the validity of the model for simulation studies has not been established. In all cases, the model has a fairly good fit (Table 3). Correlation coefficients (r^2) for daily flows range from 0.92 to 0.94. Correlation coefficients for monthly flows range from 0.88 to 0.93. On a daily basis, all sub-basin models underpredict high flows and overpredict low flows. On a monthly basis, however, the East River and White River models slightly overpredict high flows, the Two-Basin Aggregated model underpredicts high flows, and the Animas River model shows little bias.

Model results for sets of wet and dry years were also analyzed to assess the ability of the model to reproduce both high and low-flow conditions. The results reveal that although the average bias in mean annual flow is less than 2% for all basins, the five lowest flow years have a mean annual bias of approximately 20% in the Aggregated and White River models, 7% in the East River model, and 3% in the Animas River model. The average bias for the five lowest flow years ranges from 3% (Animas River model) to 16% (Two-Basin Aggregated model). Taken together, these results imply that the East River and Animas

TABLE 3

Calibration results for NWSRFS model

Model	Daily flows (r^2)	Monthly flows (r^2)	Mean annual flow (% bias)	Monthly volume RMS error (mm)
Aggregated	0.94	0.92	−1.25	3.62
White River	0.92	0.88	−0.36	7.98
East River	0.93	0.91	1.05	6.98
Animas River	0.93	0.93	1.14	10.90

River models perform significantly better under conditions of extreme (high or low) flow than the other two models used.

Model limitations

The greatest weakness of the NWSRFS model is that it has not been properly validated for simulation modeling. Its success as a forecasting tool, however, suggests that the model has the capability to simulate the effects of changes in temperature and precipitation. In addition, a critical assumption of this research is that the NWSRFS model is able to simulate adequately Colorado Basin runoff under climatic conditions different from those for which the model has been calibrated. Although there are reasons for believing that the model possesses this capability for moderate climatic changes, the use of this model (or any model) may be problematic if simulated conditions differ significantly from calibrated conditions. For example, changes may occur in plant transpiration rates and in vegetative cover under a CO_2-altered climate. These types of changes and their effect on streamflow are not accounted for in a model calibrated on current climatic conditions. Ideally, the ability of the model to perform under altered conditions would be tested by a differential split-sample test (Klemes, 1985); however, such a test was not possible in this case. Nevertheless, to the extent that studies focus on relatively short-term and 'moderate' changes in climate, significant changes in model parameters would not be expected (Nemec and Schaake, 1982).

Another limitation of the model is its failure to consider water withdrawals from a basin. Because withdrawals are not accounted for in the model directly, they are implicit in the values chosen for other parameters. Thus, as withdrawals increase in a particular basin, the calibration of all parameters for that basin change to account for the decrease in streamflow. As long as withdrawals remain a relatively small factor in basin streamflow, this omission should not be critical to the model's ability to simulate different climate scenarios. To minimize this problem, in this study sub-basins were selected in which withdrawals were known to be relatively minor.

A further weakness of the Two-Basin Aggregated model is that model parameters have been averaged spatially. In general, the strength of the NWSRFS model is its use of physical parameters to describe hydrologic processes. Thus, although the exact value of a parameter may not be known, a reasonable range of values can be determined from existing data. This becomes increasingly difficult as the scale of the model is increased. For example, it is much more problematic to choose infiltration parameters for the entire Upper Colorado Basin than for a small (and presumably more homogenous) sub-basin. Thus, although the Two-Basin Aggregated model may 'fit' the data as well as any sub-basin model, these results should be treated more skeptically. Nonetheless, because of the time and resources required to study the more than 50 sub-basins, some results from the aggregated model are included in this study because they provide the only means of overviewing the potential impacts of climate change on the entire Upper Colorado Basin.

Application of climate scenarios to the NWSRFS model

In selecting GCM grid-point data for use in hydrologic modeling, we chose not to modify the data in any way (i.e. through interpolation) because we found little justification for doing so. We selected those points that best represent the modeled basins spatially. The East River and Animas River basins were contained by a single grid point from each GCM, although the grid points also contain vast areas outside the basin of interest. The White River was well contained by a single grid point from each of the GISS and GFDL models; however, it fell near the border of two UKMO grid points. Consequently both points were modeled (labeled UKMO 1 and UKMO 2). Selection of grid points for the Two-Basin Aggregated model was less straightforward. In the case of the GISS and GFDL models, there was little difference in the scenarios generated by the adjacent grid points, and thus only one point from each GCM was used. In the case of the UKMO model, however, the adjacent grid points yielded substantially different scenarios so that data from both points were applied to the Two-Basin Aggregated model. Grid point and sub-basin locations are shown in Fig. 1.

Mean monthly changes in temperature and precipitation were used to obtain mean annual changes in temperature and precipitation and then applied uniformly to the long-term historical data. For both GCM and hypothetical scenarios, mean annual changes were applied uniformly to all the historical data. Temperature changes were applied as absolute amounts, whereas precipitation changes were interpreted as percent differences:

$$\delta T = T_{\mathrm{new}} - T_{\mathrm{old}}$$

$$\delta P = \frac{P_{\mathrm{new}} - P_{\mathrm{old}}}{P_{\mathrm{old}}}$$

In reality, changes in precipitation are likely to vary significantly throughout the year. In the absence of accurate information on the distribution of these annual changes, however, we felt that the application of climate scenarios to historical data should be as straightforward as possible and should not incorporate additional assumptions about timing and distribution.

Temperature data in the model were altered by changing the mean elevation of the basin relative to the existing station data using an appropriate lapse rate. For standard calibration runs, the model normalizes temperature station data to the mean elevation of the basin being modeled. To convert this station data, the model uses minimum and maximum lapse rates (to convert minimum and maximum temperature data, respectively). For climate change runs, the elevation of the sub-basin was altered using an average lapse rate, usually between 0.5 and 0.7°C per 100 m. It is important to note that the model results are very sensitive to the lapse rates used for modifying temperature data. The use of higher (lower) lapse rates would reduce (increase) the effect of temperature changes on runoff.

Potential evapotranspiration rates were assumed to follow the general relationship to temperature of 4% per °C as derived by Budyko (1982, p. 119). Wetherald and Manabe (1975) found that global evaporation changes by 3% when temperature changes by 1°C. Accordingly, for the Two-Basin Aggregated model, sensitivity runs were done using potential evapotranspiration rates of both 3 and 4% per °C. As expected, the potential evapotranspiration rate is most important for temperature-dependent scenarios (i.e. increases of temperature with no net change in precipitation). For a temperature increase of 4°C and no net change in precipitation, the use of a 4% per °C evapotranspiration rate rather than a 3% per °C rate decreases mean monthly runoff by an additional 3%. For other scenarios, the effect of the evapotranspiration rate was much less important. All the results reported below incorporate a 4% per °C change in potential evapotranspiration.

RESULTS

Annual flow

For the three Colorado River sub-basins, the magnitude of changes in annual flow induced by the hypothetical scenarios ranged from decreases in mean annual runoff of 33% to increases in mean annual runoff of 19%. The greatest decrease in runoff was seen in the East River for a 4°C increase in temperature in conjunction with a 20% decrease in precipitation. The greatest increase was seen in the White River Basin when a 2°C increase was combined with a 20% increase in precipitation. In all cases, a 10% increase in precipitation was required to offset the effect of a 2°C temperature rise. A 20% increase in precipitation caused runoff to increase in every case. For the Animas River and East River, all six GCM scenarios led to decreases in mean annual runoff, ranging from −8 to −20%. For the White River, two out of the four GCM scenarios show increases in runoff (of 10–12%), whereas the other two scenarios result in decreases in mean annual runoff (of −8 to −10%). Tables 4–7 show these results.

For the Two-Basin Aggregated model, mean annual runoff decreased by 12 and 21% when the respective scenarios of $T + 2$ and $T + 4$°C were applied with no change in precipitation. Using the Two-Basin Aggregated model, three of the four GCM scenarios resulted in decreases in mean annual runoff ranging from −14 to −24%. The fourth scenario resulted in an increase of less than 1%.

All relationships between runoff and precipitation are nearly linear for the range of scenarios studied, with the exception of the $T + 4$°C scenario on the East River. In this case, runoff increases more slowly than precipitation. Model biases undoubtedly affect this relationship. Percentage changes in runoff are

TABLE 4

Annual flow ($m^3 s^{-1}$) of the White River for all scenarios, with numbers in parentheses representing percentage change versus the base case

Scenario	Mean	SD	CV	Minimum	Maximum
Base	17.02	4.09	0.24	9.50	26.24
T + 2° P − 20%	13.12 (−22.9%)	2.76	0.21	7.58 (−20.3%)	18.58 (−29.2%)
T + 2° P − 10%	14.66 (−13.9%)	3.24	0.22	8.40 (−11.6%)	21.18 (−19.3%)
T + 2° P + 0	16.32 (−4.1%)	3.82	0.23	9.18 (−3.4%)	23.82 (−9.2%)
T + 2° P + 10%	18.20 (+7.0%)	4.49	0.25	9.98 (+5.0%)	27.28 (+4.0%)
T + 2° P + 20%	20.18 (+18.6%)	5.20	0.26	10.92 (+14.9%)	30.87 (+17.6%)
T + 4° P − 20%	12.56 (−26.2%)	2.74	0.22	7.07 (−25.6%)	18.32 (−30.2%)
T + 4° P − 10%	14.00 (−17.8%)	3.16	0.23	7.85 (−17.4%)	20.84 (−20.6%)
T + 4° P + 0	15.53 (−8.7%)	3.64	0.23	8.67 (−8.8%)	23.47 (−10.6%)
T + 4° P + 10%	17.24 (+1.3%)	4.22	0.24	9.46 (−0.5%)	26.10 (−0.5%)
T + 4° P + 20%	19.10 (+12.2%)	4.94	0.26	10.33 (+8.7%)	29.60 (+12.8%)
GISS 1	18.65 (+9.6%)	4.81	0.26	9.90 (+4.2%)	29.21 (+11.3%)
GFDL	15.26 (−10.4%)	3.59	0.24	8.38 (−11.8%)	23.47 (−10.6%)
UKMO 1	19.12 (+12.3%)	5.02	0.26	9.79 (+3.0%)	30.92 (+17.8%)
UKMO 2	15.70 (−7.7%)	3.81	0.24	8.29 (−12.8%)	25.06 (−4.5%)

dominated by low-flow years, which are generally underpredicted; thus percentage increases in runoff are probably underestimated whereas percentage decreases are overestimated. If this is in fact the case, the actual relationship is somewhat curvilinear and concave-up.

TABLE 5

Annual flow ($m^3 s^{-1}$) of the East River for all scenarios, with numbers in parentheses representing percentage change versus the base case

Scenario	Mean	SD	CV	Minimum	Maximum
Base	9.02	3.32	0.37	3.01	18.66
T + 2° P − 20%	6.49 (−28.1%)	2.37	0.36	2.36 (−21.6%)	14.03 (−24.8%)
T + 2° P − 10%	7.31 (−19.0%)	2.70	0.37	2.60 (−13.6%)	15.72 (−15.8%)
T + 2° P + 0	8.19 (−9.3%)	3.04	0.37	2.84 (−5.7%)	17.46 (−6.4%)
T + 2° P + 10%	9.14 (+1.3%)	3.37	0.37	3.10 (+3.0%)	19.19 (+2.8%)
T + 2° P + 20%	10.12 (+12.1%)	3.69	0.36	3.38 (+12.3%)	20.93 (+12.2%)
T + 4° P − 20%	6.02 (−33.3%)	2.31	0.38	2.13 (−29.3%)	13.65 (−26.8%)
T + 4° P − 10%	6.76 (−25.1%)	2.62	0.38	2.41 (−20.0%)	15.20 (−18.5%)
T + 4° P + 0	7.54 (−16.5%)	2.93	0.38	2.69 (−10.7%)	16.77 (−10.1%)
T + 4° P + 10%	8.74 (−3.2%)	3.38	0.38	3.04 (+1.0%)	19.05 (+2.1%)
T + 4° P + 20%	9.64 (+6.8%)	3.67	0.38	3.32 (+10.3%)	20.67 (+10.8%)
GISS 2	8.04 (−10.9%)	3.16	0.39	2.75 (−8.7%)	17.85 (−4.3%)
GFDL	7.32 (−18.9%)	2.87	0.39	2.53 (−16.0%)	16.44 (−11.9%)
UKMO 2	7.34 (−18.7%)	2.98	0.41	2.51 (−16.6%)	17.17 (−8.0%)

TABLE 6

Annual flow ($m^3 s^{-1}$) of the Animas River for all scenarios, with numbers in parentheses representing percentage change versus the base case

Scenario	Mean	SD	CV	Minimum	Maximum
Base	21.54	7.53	0.35	9.41	36.84
$T + 2° P - 20\%$	15.91 (−26.1%)	5.62	0.35	6.49 (−31.0%)	26.71 (−27.5%)
$T + 2° P - 10\%$	17.94 (−16.7%)	6.35	0.35	7.39 (−21.4%)	29.82 (−19.1%)
$T + 2° P + 0$	20.04 (−7.0%)	7.10	0.35	8.31 (−11.6%)	33.37 (−9.4%)
$T + 2° P + 10\%$	22.24 (+3.2%)	7.86	0.35	9.31 (−1.0%)	37.08 (+0.6%)
$T + 2° P + 20\%$	24.58 (+14.1%)	8.63	0.35	10.34 (+9.9%)	41.14 (+11.7%)
$T + 4° P - 20\%$	14.74 (−31.6%)	5.21	0.35	5.89 (−37.4%)	25.04 (−32.0%)
$T + 4° P - 10\%$	16.60 (−22.9%)	5.90	0.36	6.67 (−29.1%)	28.01 (−24.0%)
$T + 4° P + 0$	18.52 (−14.0%)	6.61	0.36	7.49 (−20.4%)	30.98 (−15.4%)
$T + 4° P + 10\%$	20.54 (−4.6%)	7.32	0.36	8.40 (−10.7%)	34.20 (−7.2%)
$T + 4° P + 20\%$	22.64 (+5.1%)	8.04	0.36	9.40 (−0.1%)	37.62 (+2.1%)
GISS 2	19.78 (−8.2%)	7.14	0.36	8.02 (−14.7%)	33.15 (−10.0%)
GFDL	17.97 (−16.6%)	6.48	0.36	7.23 (−23.1%)	30.32 (−17.7%)
UKMO 2	18.20 (−15.5%)	6.62	0.36	7.12 (−24.3%)	31.25 (−15.2%)

The statistical significance of these results was estimated following the method used by Klemes (1985, appendix B). For each scenario, the mean and standard deviation (μ,σ) of the annual flow series were treated as perfect estimates of the true mean and standard deviation for the distribution of annual flows. Subsequently, 125 series of 35-year flows were randomly

TABLE 7

Annual flow ($m^3 s^{-1}$) into Lake Powell (Two-Basin Aggregated model) for all scenarios, with numbers in parentheses representing percentage change versus the base case

Scenario	Mean	SD	CV	Minimum	Maximum
Base	427.8	116.7	0.27	175.3	666.7
$T + 2° P - 10\%$	328.1 (−23.3%)	94.6	0.29	131.3 (−25.1%)	506.3 (−24.1%)
$T + 2° P + 0$	377.8 (−11.7%)	106.7	0.28	153.5 (−12.4%)	560.5 (−15.5%)
$T + 2° P + 10\%$	430.4 (+0.6%)	119.2	0.28	176.2 (+0.5%)	639.8 (−4.0%)
$T + 4° P - 20\%$	252.2 (−41.0%)	77.1	0.31	98.6 (−43.8%)	449.1 (−32.6%)
$T + 4° P - 10\%$	294.3 (−31.2%)	88.4	0.30	113.1 (−35.5%)	488.1 (−26.8%)
$T + 4° P + 0$	339.1 (−20.7%)	99.9	0.30	132.0 (−24.0%)	527.7 (−20.8%)
$T + 4° P + 10\%$	386.5 (−9.7%)	111.7	0.29	153.0 (−12.7%)	568.3 (−14.8%)
$T + 4° P + 20\%$	436.2 (+2.0%)	123.7	0.28	173.8 (−0.9%)	632.9 (−5.1%)
GISS 2	369.5 (−13.6%)	109.7	0.30	141.8 (−19.1%)	556.5 (−16.5%)
GFDL	327.4 (−23.5%)	98.4	0.30	124.4 (−29.0%)	519.0 (−22.1%)
UKMO 1	428.5 (+0.2%)	129.1	0.30	160.7 (−8.3%)	628.6 (−5.7%)
UKMO 2	338.0 (−21.0%)	105.4	0.31	124.1 (−29.2%)	544.8 (−18.3%)

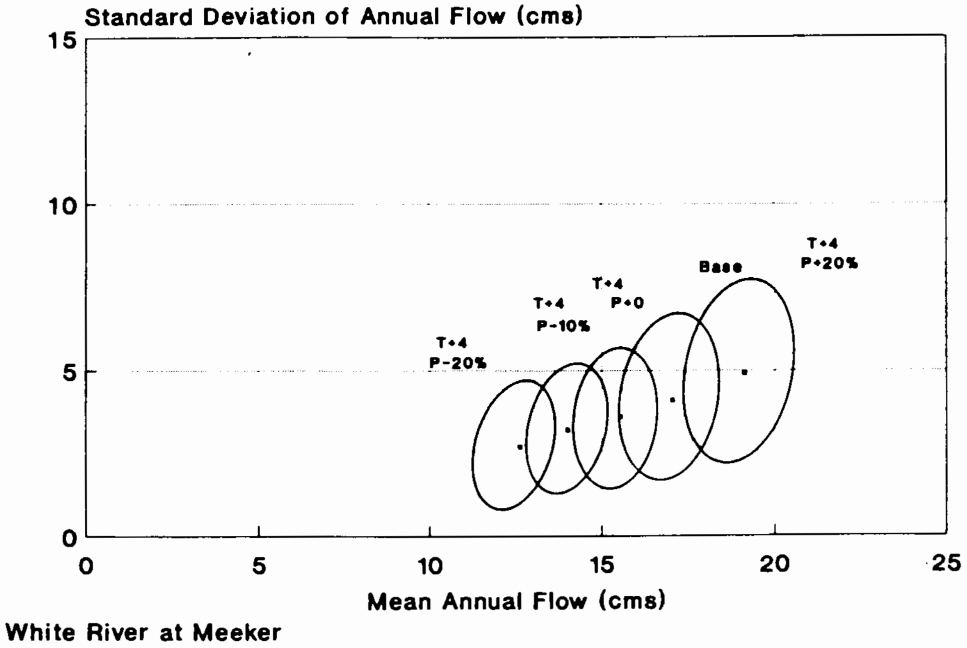


Fig. 2. Point estimates of annual flow (mean and standard deviation) for the White River and approximate 90% confidence regions for the base case and selected scenarios.

generated from a log-normal distribution defined by μ and σ. The mean and standard deviation of each 35-year series were then plotted (σ versus μ), and the 90% confidence region was defined to be the ellipse that contained 90% of these points (Figs. 2–4).

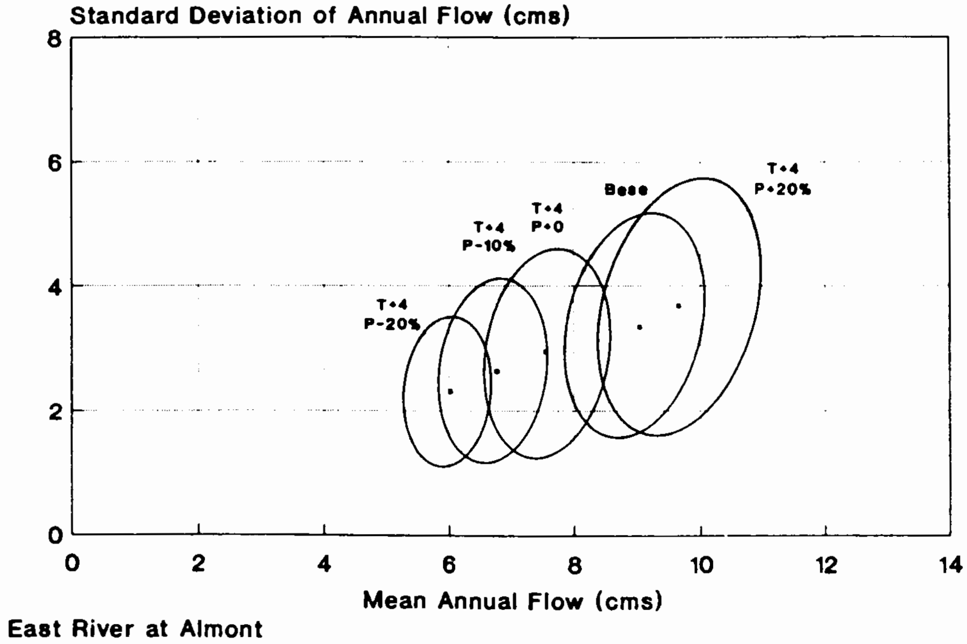


Fig. 3. Point estimates of annual flow (mean and standard deviation) for the East River and approximate 90% confidence regions for the base case and selected scenarios.

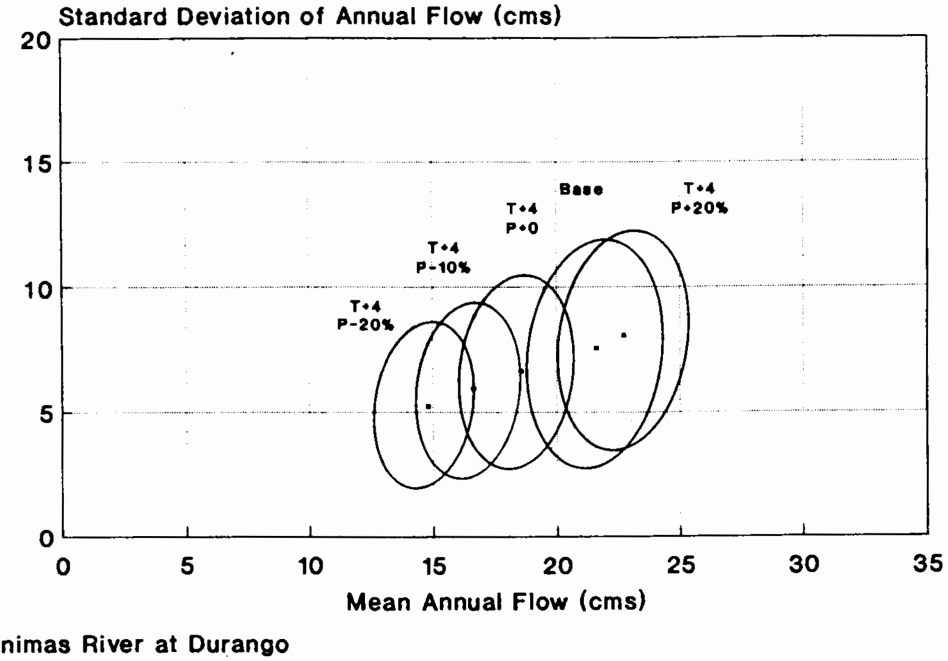


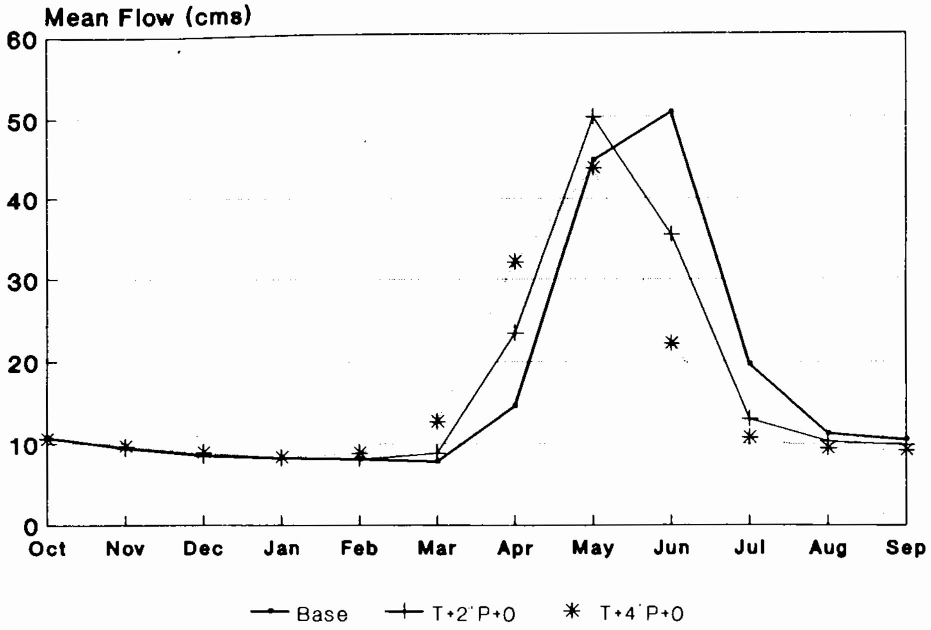
Fig. 4. Point estimates of annual flow (mean and standard deviation) for the Animas River and approximate 90% confidence regions for the base case and selected scenarios.

Using the above method, only three scenarios were significant for all basins at the 90% confidence level: T + 4°C, P – 20%, T + 4°C, P – 10%; and T + 2°C, P – 20%. For the White River, one additional scenario, T + 2°C and P + 20%, was also significant. None of the GCM scenarios were significant at the 90% level. The statistically significant scenarios correspond to a minimum change in mean annual flow of 18% on the White River, 25% on the East River, and 22% on the Animas River.

Annual average flows are normally distributed on the East River and approximately log-normally distributed on the White River and Animas River. Temperature increases strongly skew these distributions towards high-flow years for the Animas River and East River, indicating a greater frequency of occurrence of low-flow years. This shift is also evident for the White River but is not nearly so pronounced. In all cases, the climate change scenarios result in distributions of annual flow that are approximately log-normal. As expected, percentage changes in runoff are significantly greater for low-flow years, whereas absolute effects are greater for high-flow years.

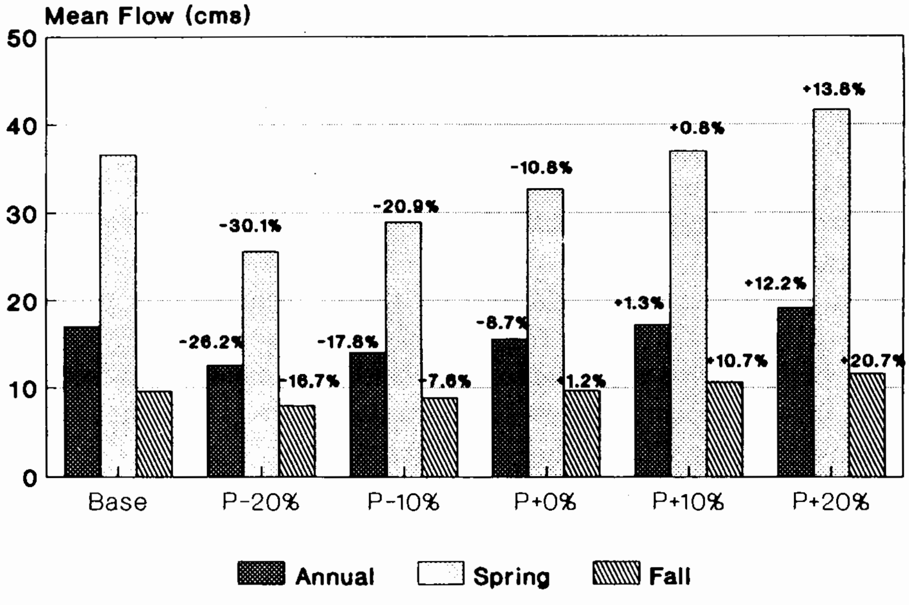
Seasonal flow

Temperature increases cause peak runoff to occur earlier in the year. A temperature increase of 2°C shifts peak runoff from June to May for the White River and Animas River. For the East River, peak runoff still occurs in June, although it is not nearly so exaggerated. For all three basins, the 2°C rise



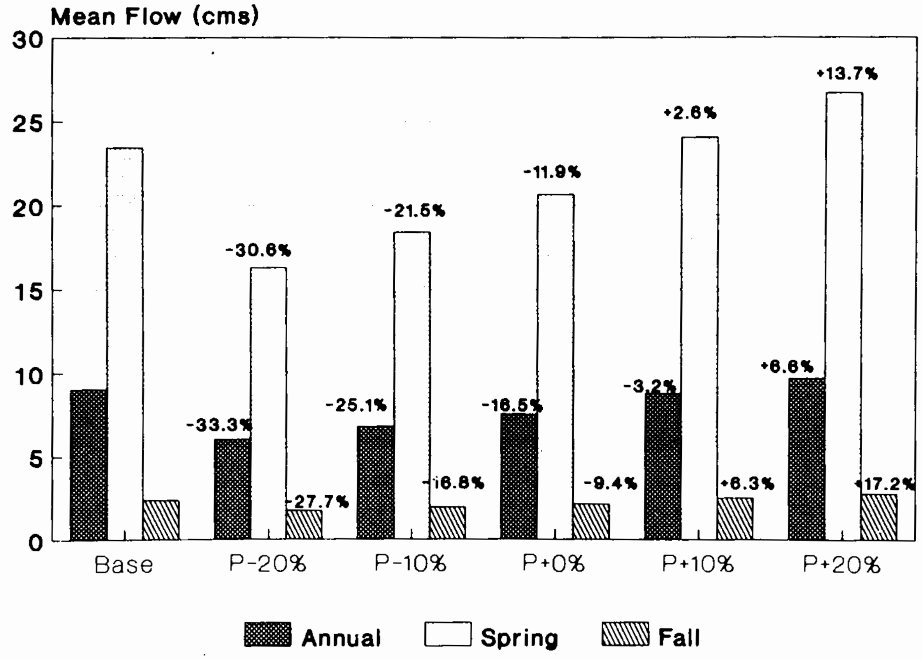
White River at Meeker

Fig. 5. Mean monthly flow of the White River. The plots represent the base case and scenarios of 2 and 4°C temperature increases with no change in precipitation. Under scenarios of increased temperature, peak runoff occurs earlier in the year.



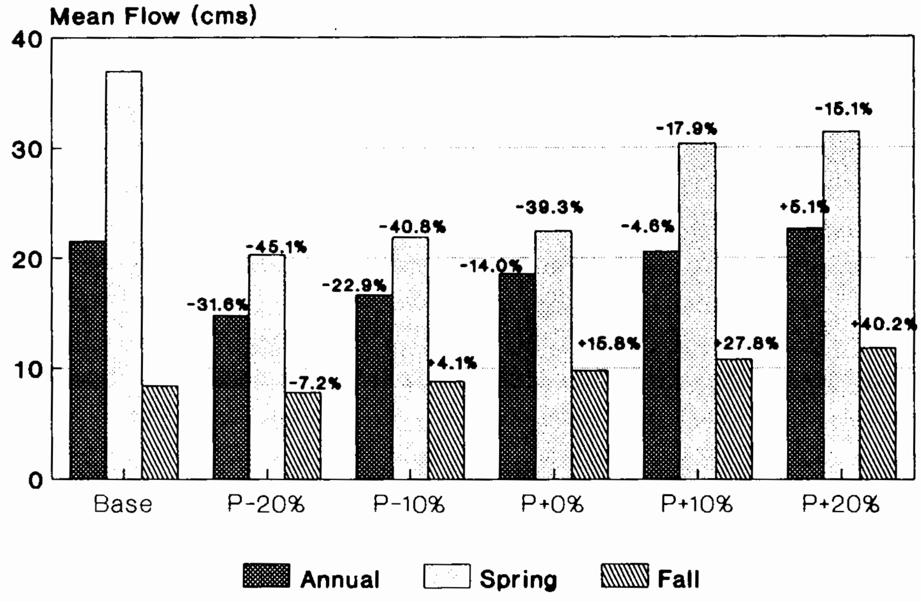
White River at Meeker: T+4°C Scenarios

Fig. 6. Mean annual flow, mean spring (April–June) flow, and mean fall (October–December) flow for the White River. The base case and the *T* + 4°C scenarios are shown. Percentage numbers indicate the change in flow compared with the base case.



East River at Almont: T+4°C Scenarios

Fig. 7. Mean annual flow, mean spring (April–June) flow, and mean fall (October–December) flow for the East River. The base case and the $T + 4°C$ scenarios are shown. Percentage numbers indicate the change in flow compared with the base case.



Animas River at Durango: T+4°C Scenarios

Fig. 8. Mean annual flow, mean spring (April–June) flow, and mean fall (October–December) flow for the Animas River. The base case and the $T + 4°C$ scenarios are shown. Percentage numbers indicate the change in flow compared with the base case.

creates a double peak, with runoff in May and June being nearly equal. When temperature is increased by 4°C, the East River also undergoes a distinct shift in the timing of peak runoff, from June to May. The UKMO scenario for the Animas River and White River shifts peak runoff from June to April, which reflects the 6.8°C temperature rise. Figure 5 illustrates the general effect of temperature on the timing of peak runoff for the White River.

Figures 6–8 illustrate mean flow as it varies between high- and low-flow seasons. Spring flow is averaged over the three highest flow months (April–June) and fall flow over the three lowest flow months (October–December). These results suggest less-extreme seasonal flows as a result of climate change in most cases. In the Animas River model, climate scenarios tend to diminish the differences between spring and fall flows; spring flows decrease in all scenarios. In the White River and East River models, climate scenarios do not decrease spring flows as dramatically, and scenarios that incorporate precipitation increases of 20% augment spring flow substantially. Because spring flows are already very high, significant increases in runoff would result in more flooding.

DISCUSSION

In the first study to analyze the impacts of climatic change on the Colorado River, Stockton and Boggess (1979) used Langbein's relationships (Langbein et al., 1949) to estimate the effects of a 2°C temperature rise and a 10% decrease in precipitation. They found that streamflow in the Upper Basin would decline by about 44%. Following up on that work, Revelle and Waggoner (1983) developed a linear regression model of runoff, using precipitation and temperature as independent variables. Their results indicated that a 2°C temperature increase would decrease mean annual flow by 29%, whereas a 10% decrease in precipitation would decrease runoff by about 11%. In combination, these changes would result in a 40% decrease in runoff, in close agreement with Stockton and Boggess' earlier result.

In contrast, our studies with a conceptual model suggest less severe (but still important) impacts on runoff and a greater sensitivity of annual runoff to precipitation rather than temperature changes. A 2°C temperature rise (which incorporates an 8% increase in potential evapotranspiration) decreases mean annual runoff by less than 10% in the three sub-basins studied. When combined with a 10% decrease in precipitation, runoff decreases are of the order of 20%. These results are comparable to other studies of arid and semi-arid basins that have used conceptual hydrologic models (e.g. Gleick, 1987b; Flaschka et al., 1987), supporting Karl and Riebsame's (1989) conclusion that the Langbein relationships overstate the role of evaporation. In a recent study, Schaake (1990) modeled the Animas River and found that a 9% decrease in mean annual flow resulted when a 2°C temperature rise was combined with a 10% increase in potential evapotranspiration. Similarly, our results show a 7% decrease in mean annual runoff for a temperature rise of 2°C and an 8% increase in potential evapotranspiration. For the range of scenarios presented here, mean annual runoff changes nearly linearly with precipitation, although this relationship begins to break down as precipitation increases by 20%, at which point runoff begins to increase relatively fast. Results from Schaake indicate that, in the absence of temperature and potential evapotranspiration increases, this non-linearity occurs for a precipitation increase of only 10%, which causes a corresponding increase in runoff of 19%.

The results derived from GCM scenarios are well within the range established by the hypothetical scenarios. Of the three GCMs, the GFDL model (T + 4.9°C, P + 0) results in the most extreme decreases in runoff for all basins. The least extreme effects are generated by either the UKMO 1 or the GISS 2 grid point, which incorporate respective increases in precipitation of 30% and 20%.

Temperature increases had a much smaller effect on mean annual runoff in the White River than in the other basins, which is probably due to the higher elevation of the White River Basin. The NWSRFS model reduces evapotranspiration when snow is on the ground by an amount proportional to the areal snow cover. This effect may be mitigated to some extent by increased snowmelt; however, in basins that experience little or no year-round snow cover, increased melting will have only a minor effect on mean annual runoff, although it will still have a substantial impact on seasonal runoff. Thus, for the basins modeled in this study, mean annual runoff should show less sensitivity to temperature increases as elevation increases.

The statistical significance of changes in mean annual flow cannot be assessed in a straightforward or definitive manner. On the one hand, because data generated by the sensitivity runs are highly correlated with data generated by the base runs, sensitivity estimates of changes in the mean and standard deviation would be expected to be reasonably accurate and statistically significant with respect to one another. At the same time, however, the streamflows generated by the scenarios may not be significantly different from values compatible with the historical flow series. Using the method of Klemes (1985, appendix B), our analysis suggests that precipitation changes of more than 10% would be necessary before changes in runoff would be significantly different from the historical flow series, even if the steamflow distribution was to remain stationary. Moreover, temperature changes of 4°C would not produce a statistically significant impact on runoff, unless accompanied by precipitation decreases. This is consistent with the finding of Klemes (1985, appendix B) that precipitation changes of 15–20% would be required to generate statistically significant changes in runoff in the Pease River (Texas) and Leaf River (Missouri). This conclusion does not imply that the impacts of climatic change are insignificant but does suggest the difficulty inherent in detecting the impacts of climatic change given a relatively short and variable streamflow record.

Although all the scenarios studied alter the annual and monthly distribution of flows, annual variability is not strongly affected. In addition, the differential effect of the scenarios on high- and low-flow years is relatively moderate. Although the percentage change in annual flow is higher for low-flow years than it is for high-flow years, in all cases these differences are within 10%. Of potentially greater concern is the increased frequency of extreme years.

The analysis of seasonal impacts is constrained by the fact that changes in temperature and precipitation were applied uniformly to all daily data. In fact, these annual changes would be distributed unevenly throughout the year. Although GCM results provide some insights into seasonal changes, they are not definitive. The GISS and UKMO models suggest that absolute temperature increases in the Colorado Basin are greater in winter, whereas the GFDL model indicates that temperature increases are greatest in the summer and fall months. All three GCMs suggest that percentage increases in precipitation are greater in the winter and spring.

Our results suggest that an increase in temperature will shift the seasonality of runoff, with peak runoff occurring in May rather than in June. This change reflects the fact that under higher temperature conditions more precipitation falls as rain than as snow, and snowmelt runoff occurs earlier in the year. This result has been seen in several other regional studies (e.g. Gleick, 1986; Bultot et al., 1988). Because this seasonal result is induced by changes in temperature, rather than the less reliable changes in precipitation, we believe it is fairly robust.

The interpretation of model results in this study must be tempered by several caveats. Firstly, the climate scenarios used to generate results suffer from significant limitations. Hypothetical scenarios provide insight into basin sensitivity but may not be internally consistent. GCM scenarios, on the other hand, are internally consistent but have a very limited ability to predict regional climatic changes. GCM predictions of precipitation are particularly problematic in this respect because precipitation patterns are strongly influenced by localized orographic effects that are not taken into account. In addition, future changes in evapotranspiration are essentially unknown. Finally, all scenarios were applied on an annual basis; this again may be a reasonable approximation for temperature increases but undoubtedly skews precipitation patterns, which are likely to change dramatically under conditions of altered climate.

Secondly, the NWSRFS model has several limitations. Because the model incorporates many parameters, other combinations of parameter values may exist that provide equally good calibration fits but which have different effects on output sensitivity. In addition, as the model has not been properly validated for simulation purposes, the good calibration fit obtained for the model may be illusory. Parameter uncertainty is an inevitable problem in conceptual modeling, which can only be overcome through a rigorous validation procedure that breaks down the model into its component parts. Futhermore, the ability of the model to assess changes in streamflow under a CO_2-altered climate is not known. These problems were discussed by Klemes (1985) in his critique of climate-impact modeling of hydrologic phenomena. Arid basins, such as the Colorado, are particularly difficult to model accurately. Finally, the historical record was limited to 35 years, which is too short to allow a substantive analysis of natural (non-greenhouse) variation.

CONCLUSIONS

Hydrologic modeling of the Colorado River suggests that variations in mean annual runoff of 30% as a result of climatic change are not unrealistic, with even greater changes possible in the most arid sub-basins. The relationship between changes in precipitation and changes in annual runoff are nearly linear for the scenarios and basins modeled. A 10% decrease in precipitation causes a decrease in runoff of approximately 10%, assuming increases in temperature and evapotranspiration described above. In the absence of any change in potential evapotranspiration, runoff would be much more sensitive to increases in precipitation and less sensitive to decreases. Changes in temperature alone (of up to 4°C) may not generate statistically significant impacts on annual runoff, given the brevity of the historical record. In this study, a rise in temperature of 2°C corresponds to a decrease in mean annual runoff of 4% on the White River, 9% on the East River, and 7% on the Animas River. Thus, for these rivers and scenarios, precipitation changes were more significant than temperature changes. The magnitude of annual effects was similar for the East River and Animas River, whereas the White River was less affected by the increases in temperature owing to its higher elevation. These changes in annual flow could be aggravated or mitigated by changes in seasonal flow. Should precipitation increase in some regions, spring flooding is a possible consequence. Decreases in mean annual runoff may, however, decrease seasonal variability. Overall, seasonal changes in runoff patterns are likely to be greater than annual changes and may be a more sensitive indicator of climatic change.

In general, conceptual models of arid and semi-arid basins suggest that streamflow is less sensitive to climatic change than previous statistical models have indicated. At the same time, however, our results suggest that changes in runoff of up to 20 or 30% are plausible given state-of-the-art estimates of future climatic changes. Impacts of this magnitude on the Colorado Basin could have enormous economic, social, and political repercussions. This study also points out the difficulty of observing climatic impacts. Most hydrologic records are quite short and have been subject to other complicating effects (e.g. dams, diversions, changes in vegetative water use).

The robustness of the results presented here is constrained by the reliability of the model. Although providing more detailed information than simple statistical relationships, current hydrologic models have substantial limitations, and their applicability under altered climatic conditions has not been established. Future research in this area would benefit from the collection of additional hydrologic data, the development and testing of regional hydrologic models specifically for climate-impact studies, and the standardization of statistical techniques for evaluating simulation data.

ACKNOWLEDGMENT

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