REGIONAL HYDROLOGIC CONSEQUENCES OF INCREASES IN ATMOSPHERIC CO_2 AND OTHER TRACE GASES

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Abstract. Concern over changes in global climate caused by growing atmospheric concentrations of carbon dioxide and other trace gases has increased in recent years as our understanding of atmospheric dynamics and global climate systems has improved. Yet despite a growing understanding of climatic processes, many of the effects of human-induced climatic changes are still poorly understood. Major alterations in regional hydrologic cycles and subsequent changes in regional water availability may be the most important effects of such climatic changes. Unfortunately, these are among the least well-understood impact.

Water-balance modeling techniques – modified for assessing climatic impacts – were developed and tested for a major watershed in northern California using climate-change scenarios from both state-of-the-art general circulation models and from a series of hypothetical scenarios. Results of this research suggest strongly that plausible changes in temperature and precipitation caused by increases in atmospheric trace-gas concentrations could have major impacts on both the timing and magnitude of runoff and soil moisture in important agricultural areas. Of particular importance are predicted patterns of summer soil-moisture drying that are consistent across the entire range of tested scenarios. The decreases in summer soil moisture range from 8 to 44%. In addition, consistent changes were observed in the timing of runoff – specifically dramatic increases in winter runoff and decreases in summer runoff. These hydrologic results raise the possibility of major environmental and socioeconomic difficulties and they will have significant implications for future water-resource planning and management.

1. Introduction

As fossil-fuel use and industrial development have grown over the last century, the atmospheric concentration of carbon dioxide and other radiatively-active trace gases has also increased. Despite recent improvements in our understanding of atmospheric dynamics and large-scale climatic processes, however, the climatic effects of these concentrations of gases are still only partially understood. One of the most important – and yet least well-understood – consequences of future changes in climate may be alterations in regional hydrologic cycles and subsequent changes in the quantity and quality of regional water resources.

By using hydrologic modeling techniques – particularly modified water-balance methods – it is possible to begin to draw some conclusions about the sensitivity of regional watersheds to future climatic changes. The research results described here for a major hydrologic basin in the United States suggest that important changes in the timing and magnitude of critical hydrologic variables –

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specifically runoff and available soil moisture – may result from changes in precipitation and temperature associated with plausible anthropogenic climatic changes. Of particular concern are large decreases in summer soil moisture that are robust across a wide range of climate-change scenarios. At the same time, consistent increases in runoff during winter months observed in the model runs may lead to increased flooding. Associated with these hydrologic effects will be a wide range of economic, environmental, and societal impacts.

Climatic conditions affect the supply of food and water, the need for shelter, the accessibility of mineral resources, the distribution of flora and fauna, and so on. As a result, even short-term variations in current climatic conditions, such as those seen recently in central Africa, Bangladesh, and the southeastern United States, are often responsible for enormous human suffering, misery, and economic hardship. The possibility that global climate itself may be altered permanently by human activities must be cause for substantial international concern, and, perhaps, alarm.

The problem is that, at present, while there are diverse ways in which global climate may be affected by human actions, we are unable to see clearly either the direction of changes in climate or the nature of the societal impacts of such changes. Because we are unable to 'do the experiment' directly, we must attempt to model climate and climatic changes – an imprecise alternative because of the complexity of the global climate system. Much of the effort of trying to understand the climate system has focused on the development of large-scale computer models of the many intricate and intertwined phenomena that make up the climate. The most complex of these models – typically referred to as 'general circulation models' or 'global climate models' (GCMs) – are detailed, time-dependent, three-dimensional numerical simulations that include atmospheric motions, heat exchanges, and important land-ocean-ice interactions (Manabe, 1969a, b; Schlesinger and Gates, 1980; Manabe and Stouffer, 1980; Wetherald and Manabe, 1981; Ramanathan, 1981; Manabe *et al.*, 1981; Hansen *et al.*, 1983, 1984; Washington and Meehl, 1983, 1984).

GCMs permit us to begin to evaluate the implications for global climatic patterns of increasing concentrations of radiatively-active atmospheric gases. While great uncertainties remain, a consensus is now beginning to form about both the direction and magnitude of certain impacts, such as increases in global-average temperatures and changes in the intensity and distribution of the global hydrologic cycle.

Unfortunately, state-of-the-art general circulation models – though much improved over early versions – are large and expensive to operate. Furthermore, while GCMs are invaluable for identifying some climatic sensitivities and changes in global climatic characteristics, they have two particular limitations that reduce their value to researchers interested in more detailed assessments of water resources: (i) they are unable to provide much detail on regional or local climate impacts, and (ii) they are unable to provide much detail on small-scale surface hydrology, such as regional soil moisture and runoff (Manabe and Stouffer 1980, Dickinson 1984). Until these limitations are eliminated, new methods must be used to evaluate important regional hydrologic impacts of climatic changes.

2. Methods for Regional Hydrologic Studies of Climatic Change

Recently there have been some serious efforts to evaluate the regional hydrologic implications of climatic changes (Schwarz, 1977; Stockton and Boggess, 1979; Němec and Schaake, 1982; Revelle and Waggoner, 1983; Flaschka, 1984, U.S. Environmental Protection Agency, 1984). These early works provided the first tentative evidence that relatively small changes in regional precipitation and evapotranspiration patterns might result in large changes in regional water availability.

If realistic estimates of actual changes in regional water availability are to be calculated, however, a number of improvements over these earlier works need to be made. In order to be valuable to water-resource planners, regional hydrologic assessments should include (i) a focus on short time-scales such as months and seasons, rather than annual averages; (ii) the ability to incorporate both hypothetical climatic changes and the increasingly-detailed assessments of regional changes produced by GCMs; (iii) the ability to produce information on hydrologically-important variables, such as changes in runoff and available soil moisture, rather than just changes in temperature and precipitation; and (iv) the ability to incorporate snowfall and snowmelt, topography, soil characteristics, natural and artificial storage, and other regional complexities.

One of the most promising methods for assessing the regional hydrologic effects of global climatic changes is the use of water-balance models modified for use under conditions of changing climate (Gleick, 1986b). Water-balance modeling was first developed in the 1940s and 1950s by C. W. Thornthwaite and J. R. Mather as a way of estimating evapotranspiration and of evaluating the importance of different hydrologic parameters under a variety of hydrometeorological conditions (Thornthwaite, 1948; Thornthwaite and Mather, 1955, 1957). The spatial resolution of water balances can range all the way from global assessments of the hydrologic cycle of the earth to microscale assessments of water balances on the surfaces of foliage or even animals. The temporal resolutions studied are equally large – from annual (or longer) balances to instantaneous, continuous-time, analyses. Almost all water-balance models evaluate the fate of specified water inputs – such as precipitation – as those inputs are utilized, stored, or changed.

Water-balance models incorporate soil-moisture characteristics of regions, permit month-to-month, seasonal, and annual estimates of hydrologic parameters, and use readily-available data on meteorological phenomena and soil and vegetation characteristics. They can provide accurate estimates of surface runoff when compared to measured runoff, reliable evapotranspiration estimates under many climatic regimes, and estimates of groundwater discharge and recharge rates. Typical data requirements are monthly-average temperature and precipitation and information on the soil and vegetative characteristics of a region – often the only long-term hydroclimatological data that are available. Snowmelt – a major source of runoff in many watersheds – can also be incorporated into such a model.

Since its introduction, the water-balance approach has become one of the most versatile and widely-used tools for environmental and hydrologic analysis. Moreover, numerous modifications and extensions to the original water-balance formulations have been developed and used in hydrologic research (see, for example, Sokolov and Chapman, 1974; Miller, 1977; Mather, 1978; U.S. Army Corps of Engineers, 1980). These modifications permit the systematic evaluation of flooding and drought probabilities, agricultural water demands, groundwater recharge rates, the distribution of soils and vegetative cover, and a wide variety of other water-resource issues. Examples of the diverse applications of the water-balance approach include the reconstruction of the hydrology of small, forested watersheds (Haan, 1972), estimations of Pleistocene-era climatic conditions and lake levels (Snyder and Langbein, 1962), and evaluations of the seasonal and geographical patterns of water supply and irrigation demand in a 785 000 km^2 basin in Northern Africa (Al-Khashab, 1958).

For climatic impact assessments, the flexibility of water balances is an additional advantage: by integrating hydrologic advances with existing water-balance techniques, new insights into hydrologic processes and environmental impacts can be gained. Furthermore, water-balance models are well suited to the current generation of micro-computer software and hardware.

Once a region has been characterized by water balances, the effects of climatic changes can be evaluated in three ways. First, after verifying model accuracy using long-term historical data, it is possible to use historical data to evaluate the effects of past fluctuations in precipitation and temperature on runoff and soil moisture. Second, by determining the sensitivity of runoff and soil moisture to hypothetical changes in the magnitude and temporal distribution of precipitation and temperature, it is possible to assess the hydrologic effects of a wide range of climatic changes. Third, by incorporating even rough regionally-disaggregated changes in temperature and precipitation predicted by general circulation models of global climate, an estimate of the impacts of predicted climatic changes on regional hydrology can be made.

All three approaches have advantages. In the first case, historical variations in temperature and precipitation can be used to determine the sensitivity of runoff and soil moisture in any given watershed. For example, an extended period of higher-than-average temperature may be accompanied by distinct reductions in runoff. Similarly, extended periods of high precipitation may change the timing of soil-moisture saturation and increase the vulnerability of watersheds to flooding. Second, the use of hypothetical data to test the sensitivity of watersheds to climatological variations offers the opportunity to evaluate possible transient climatic responses. While existing general circulation models are limited almost entirely to equilibrium response models, Schneider and Thompson (1981) have pointed out that the transient responses of the climate may be quite different. Despite the importance of this observation, there have been few attempts to incorporate non-equilibrium climatic states in climate impact assessments.

The third approach, linking regional models with general circulation model output, also has distinct advantages. Even in the absence of a consensus about the precise nature of changes in many hydrologic variables, regional models can be used both to evaluate the quality of regional information from GCMs and to begin to estimate realistic regional climate impacts. While the present quality of the regional information provided by GCMs is low, improvements in hydrologic parameterizations and grid resolution of these models over the next several years will improve the quality of regional climate evaluations. Moreover, when information from non-equilibrium climate models becomes available, it can be used to investigate the transient responses of climate to anthropogenic perturbations. In the meantime, by linking GCM output with more accurate regional hydrologic models, regional evaluations may provide important insights.

3. A Water-Balance Model for Climatic Impact Assessment

A model was developed to evaluate the advantages and limitations of water-balance methods for the regional hydrologic assessment of climatic changes. Details of model formulation, testing, and validation are provided in Gleick (1986a, 1987). This model was then used to evaluate the hydrologic impacts of plausible changes in climate in the Sacramento Basin – the most important hydrologic basin in California and one of the most important basins in the United States (see Figure 1).

The Sacramento Basin provides over 30% of the total runoff for the State of California, including almost all of the water used for agriculture in the Central Valley – one of the most productive agricultural regions of the world. Since the water resources of this basin are already heavily committed, any climatic change that decreases total water availability or alters the timing of soil moisture and runoff would have major effects on the social and physical environment of the region. Details of the development of the model, the modifications of the model for use under scenarios of changing climate, and the calibration and statistical verification of the model using long-term historical data are presented in Gleick (1986, 1987).

In order to determine the effects of changing climate on the water resources of this region, a series of climate-change scenarios (involving changes in temperature and precipitation) were developed and used to drive the water-

Fig. 1. The Sacramento Basin hydrologic study area, California.

balance model. Both purely hypothetical climate-change scenarios and scenarios developed from general circulation model output were chosen for analysis. The hypothetical scenarios of temperature and precipitation changes were chosen after reviewing state-of-the-art estimates of future changes in climatic conditions. The GCM precipitation and temperature scenarios were developed after discussions with leading climate modelers in the United States and after a review of model capabilities and design. These scenarios can be summarized as follows:

(i) Ten hypothetical scenarios involving combinations of plus 2 and plus 4 deg Celsius (C) and plus and minus 0, 10, and 20% precipitation; and

(ii) Eight scenarios of temperature and precipitation changes predicted for this region by three state-of-the-art general circulation models: the Geophysical

Fluid Dynamics Laboratory (GFDL) model (Manabe and Stouffer, 1980; Manabe *et al.*, 1981), the Goddard Institute for Space Studies (GISS) model (Hansen *et al.*, 1983, 1984), and the National Center for Atmospheric Research Community Climate Model (NCAR CCM) (Washington and Meehl, 1983, 1984).

None of these eighteen scenarios includes decreases in average-monthly temperatures because of the consensus in the climate community that increasing concentrations of atmospheric trace gases will lead to increases in surface air temperatures on both a global and a regional scale. This consensus has been expressed as a 95% probability that an 'equivalent doubling' of atmospheric carbon dioxide – the injection into the atmosphere of CO_2 and other trace gases such that the effect of the combined gases on the radiative balance of the atmosphere is equivalent to the effect of a doubled concentration of CO_2 alone – will result in an average global warming of between 1.5 and 4.5 °C, with a most likely temperature increase of approximately 3.0 °C. Current GCM results suggest that in many areas, particularly northern latitudes, broad temperature increases will exceed these values. Annual-average temperature increases of two and four degrees C are reasonable expectations in the region of the United States under consideration.

Wide regional variations in precipitation are expected, with evidence for both increases and decreases in different regions. For the purposes of this study, five precipitation scenarios were evaluated: no change in monthly-average precipitation, increases in monthly-average precipitation of 10 and 20%, and decreases in monthly-average precipitation of 10 and 20%. These scenarios compare well with precipitation changes generated from general circulation model data and are similar to precipitation assumptions made by previous hydrologic assessments (Stockton and Boggess, 1979; Nemec and Schaake, 1982, Revelle and Waggoner, 1983; Flaschka, 1984). Combining the two temperature scenarios with the five precipitation scenarios produces the 10 hypothetical scenarios listed in Table I.

The eight remaining scenarios were developed from data generated by three general circulation models – the Princeton Geophysical Fluid Dynamics Laboratory model, the Goddard Institute for Space Studies model, and the National Center for Atmospheric Research Community Climate Model. State-of-the-art GCMs provide us with one of our only direct insights into the behavior of global climate at hundreds of different points around the globe. As such, precipitation and temperature data from individual grid points can be used to develop additional climate scenarios to evaluate the hydrologic response of regional watersheds to climate changes. Individual grid-point data, made available by the three modeling groups, do *not* represent realistic predictions of the expected climate at points on the earth. Current GCMs do not permit detailed regional estimates of climatic changes because of limitations on computer time and speed, model resolution, major physical parameterizations, and existing

TABLE I: Climate-change scenarios

Change in monthly temperature	Change in monthly precipitation
Hypothetical climate-change scenarios	
T plus 2 °C	No change
T plus 2 °C	−10%
T plus 2 °C	−20%
T plus 2 °C	+10%
T plus 2 °C	+20%
T plus 4 °C	No change
T plus 4 °C	−10%
T plus 4 °C	−20%
T plus 4 °C	+10%
T plus 4 °C	+20%
General circulation model climate-change scenarios	
Geophysical Fluid Dynamics Laboratory (Princeton, New Jersey)	
Temperature changes only	
Temperature and relative precipitation changes	
Temperature and absolute precipitation changes	
Goddard Institute for Space Studies (New York, New York)	
Temperature changes only	
Temperature and relative precipitation changes	
Temperature and absolute precipitation changes	
National Center for Atmospheric Research (Boulder, Colorado)	
Temperature changes only	
Temperature and absolute precipitation changes	

data sets. Climate modelers understand and emphasize these limitations (and it is important that researchers interested in regional impact assessments understand them as well). But these additional data provide a sense of 'realism' that cannot be matched by even a wide range of hypothetical scenarios. In addition, as GCMs continue to improve their spatial resolution and hydrologic parameterizations, the quality of regional detail will improve. These improvements in regional output can then be used to drive water-balance evaluations of hydrologic areas of special interest and concern.

Despite the limitations on spatial resolution and hydrologic parameterizations of GCMs, the modelers at the three climate centers agreed to provide grid-point data for several reasons: (i) to evaluate the strengths and weaknesses of the hydrologic mechanisms used by general circulation models; (ii) to help gain a better understanding of the differences and similarities among GCMs; (iii) to study the sensitivity of regional hydrologic systems to changes in climatic variables; and (iv) to help identify the advantages and limitations of coupling GCM output with smaller regional impact models. Thus, while the scenarios developed by the GCMs should not necessarily be treated as more likely descriptions of the future than the hypothetical scenarios described above, they do offer additional insights into both the capabilities of GCMs and their hydrologic responses.

All three GCMs produced precipitation and temperature data for a control or a 'one-times-CO_2' ($1 \times CO_2$) scenario and for a 'two-times-CO_2' ($2 \times CO_2$) scenario. The differences in model formulations, parameterizations, grid scales, and geographical resolutions among the three GCMs result in differences in estimates of the effect of a doubled concentration of carbon dioxide on precipitation and temperature. In particular, there were wide variations among the three models – both positive and negative – in the monthly and seasonal precipitation responses. Differences in the control runs – the attempts to reproduce existing climate – introduce further variations in the temperature and precipitation results.

These differences have some advantages. First of all, they reemphasize the limitations of GCM grid-point estimates and GCM model resolution. Second, by evaluating different *predicted* temperature and precipitation scenarios, a wider range of climatic changes – including seasonally and monthly-varying anomalies – can be evaluated. Third, by including GCM-derived scenarios in the hydrologic evaluation of a region, it may be possible to identify areas in which consistent changes in soil moisture or runoff occur *despite* widely-varying precipitation and temperature inputs. Such robust results would indicate important hydrologic sensitivities.

The data from the three models were used to produce three different climate-change scenarios: predicted temperature changes alone; temperature changes together with the relative (percent) change in precipitation between the $2 \times CO_2$ runs and the control runs; and temperature changes together with the absolute change in precipitation between the $2 \times CO_2$ runs and the control runs. For reasons described in Gleick (1986a), the relative precipitation runs from the NCAR model were not included in the analysis. The remaining eight scenarios developed from the GCM temperature and precipitation data are summarized in Table I.

All eighteen temperature and precipitation scenarios were then used to drive the water-balance model of the Sacramento Basin, and the effects on monthly-average soil moisture and monthly-average runoff were evaluated. For each scenario, a 50-yr record of monthly-average temperature and precipitation was created by applying the changes to the 50-year historical record of monthly-average temperature and precipitation in the Sacramento Basin. These data were used to drive the water-balance model, producing a 600-month (50-yr) record of predicted monthly runoff and available soil moisture. The monthly runoff and soil moisture data were then averaged to produce long-term average values.

4. Model Results

Major changes in runoff and soil moisture can be observed in all eighteen scenarios, including certain changes that are consistent in their direction in every scenario despite wide differences in the original precipitation and temperature inputs. The most important changes are persistent decreases in summer soil moisture, decreases in the magnitude of summer runoff, and increases in the magnitude of winter runoff. These results suggest important hydrologic sensitivities.

Both seasonal and monthly impacts were studied because short-term hydrologic changes are often of greater interest and value to water-resource planners than annual-average changes. Two 'seasons' were evaluated – winter (assumed to be December, January, and February) and summer (assumed to be June, July, and August). These assumptions are consistent with most GCM analyses of seasonal climatic variables. They also correspond well to actual seasonal conditions in the Sacramento Basin, which receives much of its precipitation during winter months and is dry during the summer months.

4.1. *Changes in Runoff: Hypothetical Scenarios*

Dramatic changes in runoff patterns are observed in all ten hypothetical scenarios. Summer (June, July, and August) runoff for all ten hypothetical scenarios is reduced compared to base summer runoff (i.e. compared to model

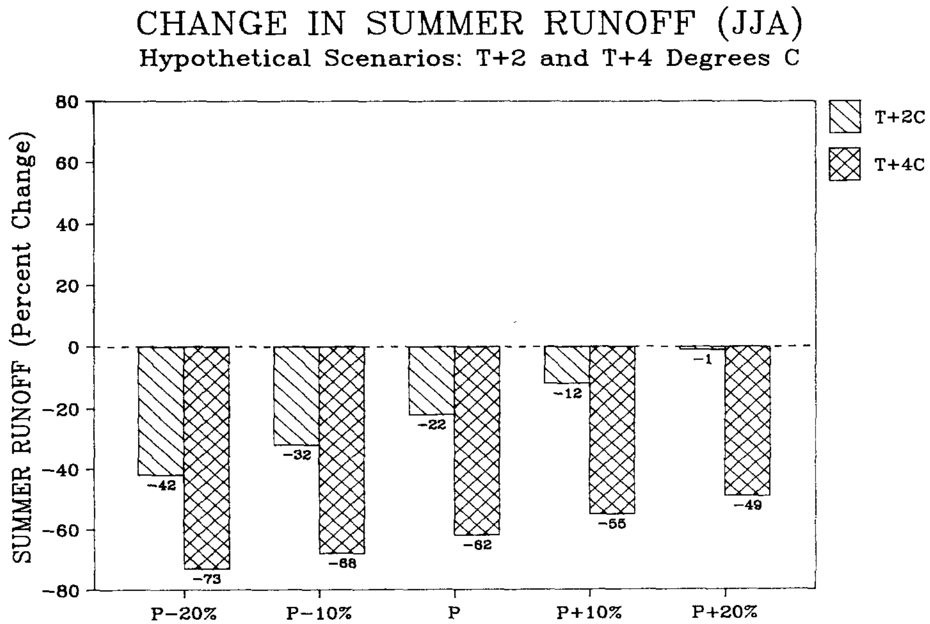

Fig. 2. Percent change in summer (June, July, and August) runoff between the base case and the hypothetical scenarios with an increase in average-monthly temperature of 2 and 4 °C ($T+2$ °C, $T+4$ °C) and precipitation changes of zero and plus and minus 10 and 20%. Note that all these scenarios show decreases in summer runoff.

runoff generated from the long-term historical data). Figure 2 plots the percent changes in average summer runoff for the ten hypothetical scenarios. The reduction in runoff is most pronounced in those runs where monthly-average temperature is increased and monthly-average precipitation is reduced, although reductions in summer runoff occur even with large increases in monthly-average precipitation. The most dramatic example of this is a reduction in summer runoff of nearly 50% when monthly-average temperature increases 4 °C and monthly-average precipitation increases 20%.

Winter runoff increases over the base case in seven of the ten hypothetical scenarios. The percent changes in average winter runoff are plotted in Figure 3. Increases in temperature alone cause increases in average winter runoff due to an increase in the proportion of rain to snow and hence a decrease in the storage of water in the snowpack during the winter months. For the $T+2$ °C run with no change in precipitation, winter runoff increases eight percent; for the $T+4$ °C run with no change in precipitation, winter runoff – which is already high in this watershed – increases dramatically by 34%. When precipitation changes are imposed on the temperature increases, winter runoff results become mixed – for $T+2$ °C runs, increases in precipitation cause increases in winter runoff, and decreases in precipitation cause decreases in winter runoff. For the $T+4$ °C runs, the winter runoff changes are mostly positive: winter runoff increases for all the runs except a 20% decrease in precipitation imposed on top of an increase of 4 °C.

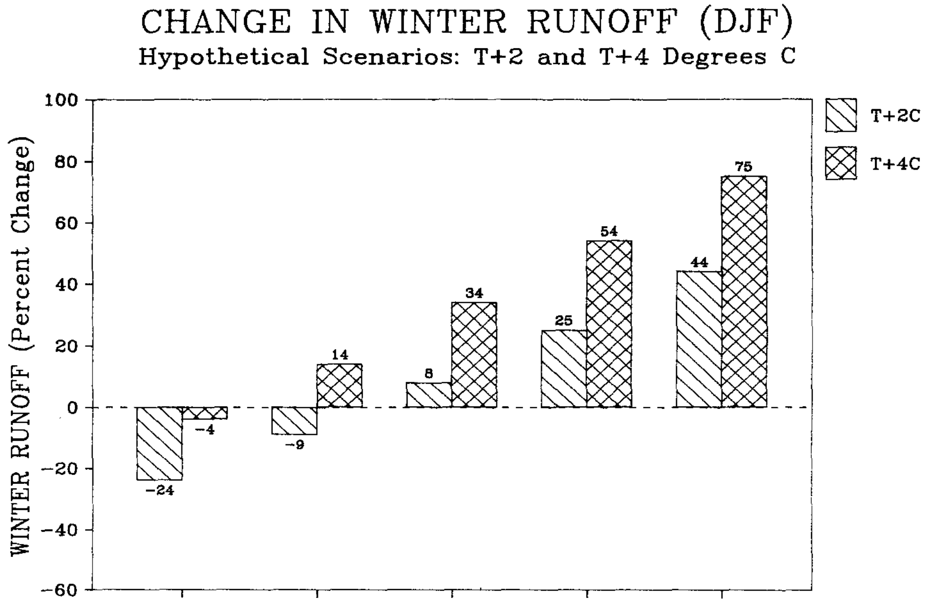

Fig. 3. Percent change in winter (December, January, and February) runoff between the base case and the hypothetical scenarios with an increase in average-monthly temperature of 2 and 4 °C ($T+2$ °C, $T+4$ °C) and precipitation changes of zero and plus and minus 10 and 20%.

Some of the changes in average winter runoff are extremely large, particularly in the runs with increases in precipitation. Increases in monthly precipitation of only 20% lead to increases in average winter runoff of between 40 and 80% for the $T + 2$ °C and the $T + 4$ °C runs. Such dramatic increases in runoff must raise concerns about flooding possibilities, especially in basins with flood-control systems designed for different hydrologic conditions, or in basins without major reservoirs.

Additional information of interest to water-supply planners is obtained by looking at the effect of changes in temperature and precipitation on the standard deviation of winter and summer runoff (see Tables II and III). For the hypothetical scenarios, the standard deviation of summer runoff is consistently reduced, whether average precipitation increases or decreases. The decrease in standard deviation is insignificant only in the case of the low temperature increase ($T + 2$ °C) and the maximum precipitation increase (plus 20%). In all of the $T + 4$ °C runs, the standard deviation of summer runoff is reduced substantially – by between 50 and 75%. The variability of winter runoff, on the other hand, increases by between 20 and 50% when monthly-average precipitation increases. Temperature increases alone increase the variability of runoff during the winter months by increasing the proportion of rain to snow and thus increasing the amount of prompt runoff.

The full consequences for runoff can be seen when average-monthly runoff –

TABLE II: Effect of hypothetical temperature and precipitation scenarios on the standard deviation of summer (JJA) runoff

(Percent change over base run)

Precipitation change	−20%	−10%	0	+10%	+20%
Temperature change					
$T + 2$ °C	−35	−26	−18	−9	−1
$T + 4$ °C	−72	−67	−62	−57	−53

TABLE III: Effect of hypothetical temperature and precipitation scenarios on the standard deviation of winter (DJF) runoff

(Percent change over base run)

Precipitation change	−20%	−10%	0	+10%	+20%
Temperature change					
$T + 2$ °C	−27	−11	+6	+22	+39
$T + 4$ °C	−21	−4	+14	+32	+50

rather than annual or even seasonal runoff – is studied. Here we see the importance of looking at temporal changes of hydrologic variables on a scale shorter than an average-annual cycle. When looking only at the average-annual figures, the decrease in runoff from a four °C increase in average temperature is only seven percent. When individual monthly changes are evaluated, however, the same increase in temperature leads to an increase in average January runoff of 39% and a decrease in average June and July runoff of nearly 70%.

For all ten hypothetical scenarios evaluated, major shifts in the timing of monthly runoff can be seen. While the increase in average temperature is a principal driving force for these shifts, the changes in precipitation contribute to and amplify the effects. Even in those cases where overall precipitation decreases, the distribution of runoff over the year changes so that spring and summer runoff decrease while runoff during the winter months increases. Figures 4 and 5 show the long-term average-monthly runoff for four of the ten hypothetical scenarios.

The changes in the timing of runoff occur primarily because of the increase in average temperatures, which has two effects: (i) a large decrease in the proportion of winter precipitation that falls as snow, and (ii) an earlier, faster, and shorter spring snowmelt. The first effect causes greater winter rainfall and winter runoff and less overall precipitation to be stored in the snowpack and held over until spring snowmelt. The second effect intensifies the magnitude of peak flows in spring and shortens the duration of spring runoff, which leads to decreases in summer runoff levels and depressed soil-moisture levels throughout the spring and summer. The effect of increased temperatures on evapotranspiration is most pronounced in the spring and summer months and has a great impact on soil moisture. This effect is discussed later.

4.2. *Changes in Runoff: GCM Scenarios*

The significant changes in seasonal runoff observed in the hypothetical runs described above are also observed in all eight of the GCM scenarios. Despite differences in GCM resolutions, formulations, and parameterizations, the values of summer runoff predicted by the water-balance runs using GCM data all change in the same direction and by similar magnitudes; winter runoff shows similar effects in the opposite direction. Specifically, average summer runoff decreases for all eight scenarios while average winter runoff increases in all eight scenarios. These runoff changes are plotted in Figures 6 and 7. When only the GCM temperature changes are evaluated, average summer runoff values decrease dramatically by between 40 and 68%. These decreases persist when the precipitation changes are included, even under the large spring and summer precipitation increases of the GISS model. The average winter runoff increases range from 16 to 81%. The greatest increases appear in the model runs using the GISS data, which had the greatest overall increases in precipitation. The large

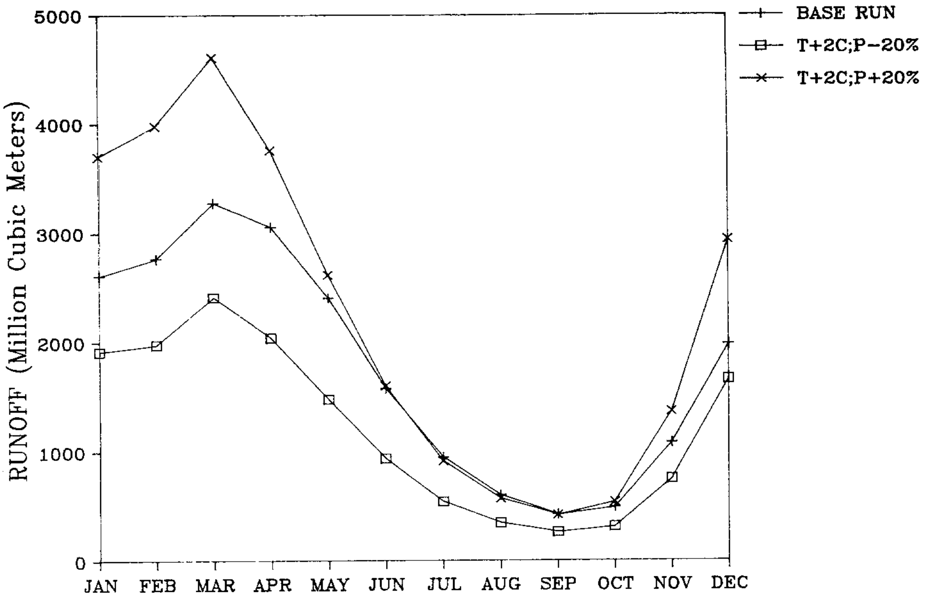

Fig. 4. Average-monthly runoff (model and base run) for the $T+2$ °C; $P+20\%$, and the $T+2$ °C; $P-20\%$ scenarios.

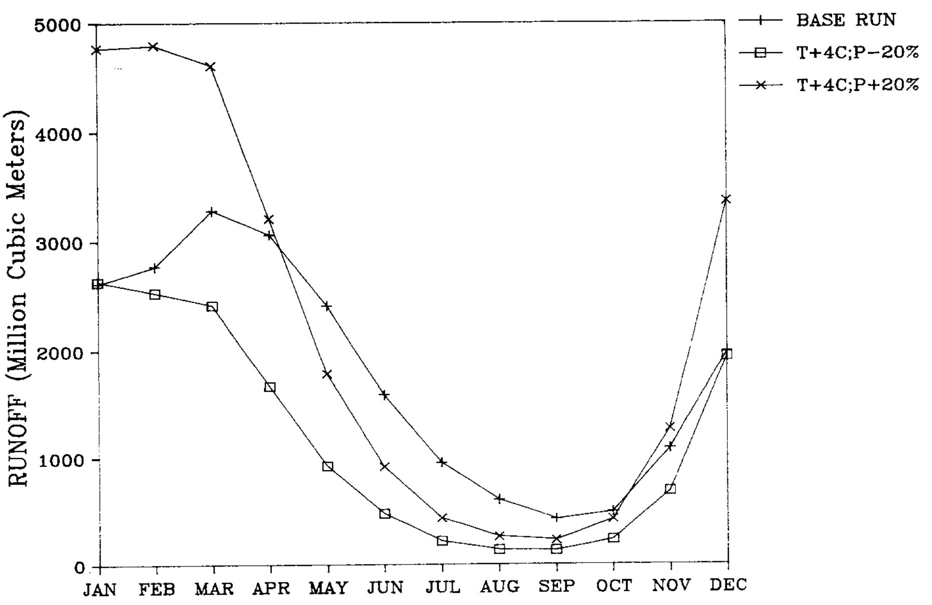

Fig. 5. Average-monthly runoff (model and base run) for the $T+4$ °C; $P+20\%$, and the $T+4$ °C; $P-20\%$ scenarios.

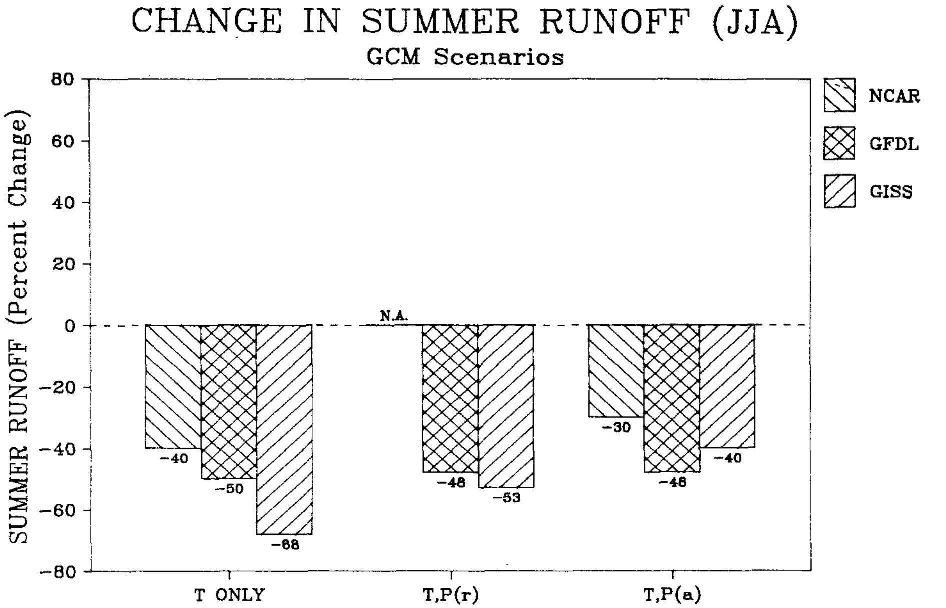

Fig. 6. Percent change in average summer (June, July, and August) runoff between the base case and the eight GCM-derived scenarios: the National Center for Atmospheric Research (NCAR), the Geophysical Fluid Dynamics Laboratory (GFDL), and the Goddard Institute for Space Studies (GISS). Note that summer runoff decreases in all eight runs. Key: (*T* only) Temperature change only. (*T*, *P* (*a*)) Temperature and absolute precipitation. (*T*, *P* (*r*)) Temperature and relative precipitation. (N.A.) Not included. See text for details.

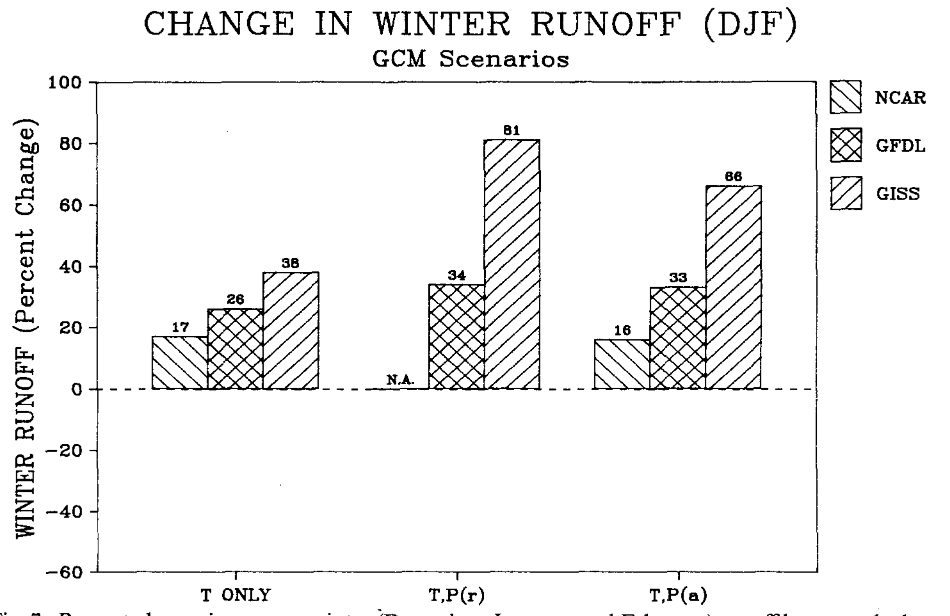

Fig. 7. Percent change in average winter (December, January, and February) runoff between the base case and the eight GCM-derived scenarios: the National Center for Atmospheric Research (NCAR), the Geophysical Fluid Dynamics Laboratory (GFDL), and the Goddard Institute for Space Studies (GISS). Note that winter runoff increases for all eight scenarios. Key: (*T* only) Temperature change only. (*T*, *P* (*a*)) Temperature and absolute precipitation. (*T*, *P* (*r*)) Temperature and relative precipitation. (N.A.) Not included. See text for details.

increases in average winter runoff raise the distinct possibility of significant flooding and water-management problems.

The variability of seasonal runoff in the GCM scenarios also shows dramatic changes: winter runoff standard deviations increase by between 8 and 45%, with the largest increases associated with the largest increases in precipitation. The standard deviation of summer runoff shows decreases that are even more severe – from 30 to 67%. Table IV and V summarize the percentage changes in the standard deviation of summer and winter runoff for the eight GCM scenarios.

The consistency of these changes despite the variations in the GCM assumptions and outputs is the result of two factors: first, the temperature increases in the models are driving significant changes in the timing of snowmelt runoff during the winter and spring; and, second, although the precipitation changes make important contributions to the changes in the magnitude of runoff, they are of less importance in determining the timing of that runoff than are the changes in temperature. This result was also observed above for the hypothetical scenarios.

TABLE IV: Effect of GCM temperature and precipitation scenarios on the standard deviation of summer (JJA) runoff

(Percent change over base run)

GCM[a]	*T* only	*T* and relative *P*	*T* and absolute *P*
NCAR	–30	n.a.	–31
GFDL	–48	–38	–42
GISS	–67	–56	–61

[a] The three general circulation model data sets are: temperature only; temperature and relative precipitation; and temperature and absolute precipitation. The differences among the three runs are discussed in the text.
n.a. Not included here; see Gleick (1986a, Appendix C).

TABLE V: Effect of GCM temperature and precipitation scenarios on the standard deviation of winter (DJF) runoff

(Percent change over base run)

GCM[a]	*T* only	*T* and relative *P*	*T* and absolute *P*
NCAR	+8	n.a.	+28
GFDL	+13	+21	+16
GISS	+12	+45	+22

[a] The three general circulation model data sets are: temperature only; temperature and relative precipitation; and temperature and absolute precipitation. The differences among the three runs are discussed in the text.
n.a. Not included here; see Gleick (1986a, Appendix C).

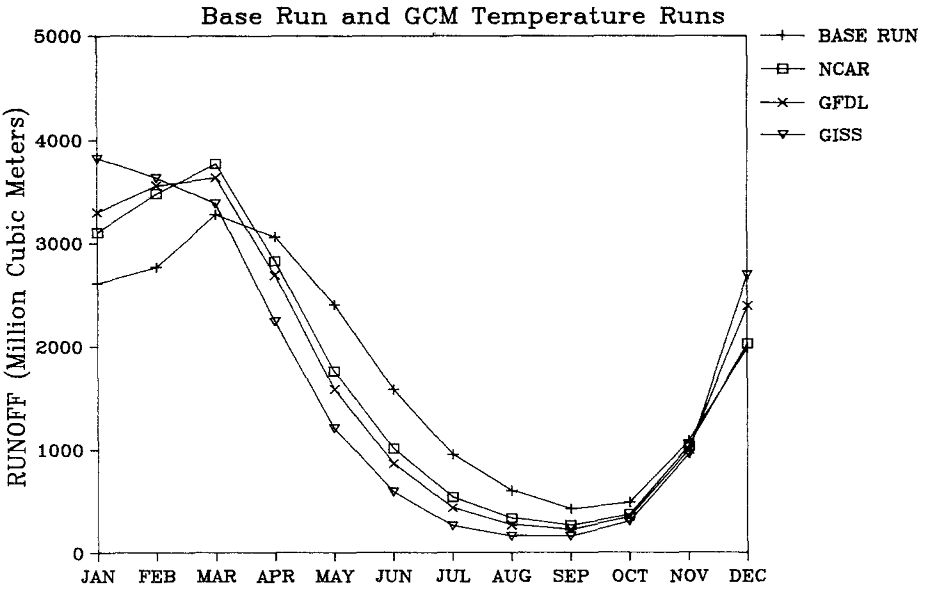

Fig. 8. Average-monthly model runoff for the base run and the three GCM temperature runs (assuming no change in precipitation): the National Center for Atmospheric Research (NCAR), the Geophysical Fluid Dynamics Laboratory (GFDL), and the Goddard Institute for Space Studies (GISS). Note that for all three GCM runs, runoff is higher in the winter and lower in the summer than base runoff.

When monthly-average results are studied, all eight GCM scenarios lead to increases in runoff during each of the winter months. Greater winter runoff then slowly gives way to decreases in runoff during the spring and summer months with runoff minimums in late summer and early fall. The predicted temperature increases alone produce very large decreases in runoff during the summer months and large increases in runoff during January and February. Figure 8 plots the average-monthly model runoff produced for the three GCM temperature scenarios plotted against the average-monthly runoff for the base run. The change in timing of runoff can be seen clearly in these figures, particularly the increase in winter runoff and decrease in summer runoff.

Changes in both the timing and magnitude of runoff are extremely important for water availability. Yet changes in runoff alone do not tell us all there is to know about the vulnerability of a region to changes in water-resources – changes in other variables must also be evaluated. Perhaps the most important of these is the change in the soil moisture available to crops and other plant communities. Soil moisture is one of the most valuable measures of water availability for agricultural development and productivity, and it is a principal determinant of vegetative types and extent. Among the most consistent results obtained in this study are decreases in soil-moisture availability during critical parts of the year.

The next two sections describe in detail the seasonal and monthly soil-moisture changes in the lower Sacramento Basin (the 'lower basin') that result from using the hypothetical and GCM-derived temperature and precipitation scenarios to drive the water-balance model.

4.3. *Changes in Soil Moisture: Hypothetical Scenarios*

Average summer soil-moisture values in the agricultural portion of the Sacramento Basin show large, consistent decreases from the base case for all ten hypothetical scenarios. Percent changes in average summer soil moisture are shown in Figure 9 for the ten hypothetical temperature and precipitation scenarios. These decreases range from eight percent to 44%. The minimum decrease of 8% results from a temperature increase of 2 °C combined with the maximum increase in average precipitation of 20%. The maximum decrease in average summer soil moisture of 44% results from a 4 °C increase in temperature combined with a 20% decrease in average precipitation.

Winter soil-moisture values also show decreases in the basin – seven of the ten scenarios resulted in reduced average winter soil moisture. These reductions are not nearly as large as the reductions in summer soil moisture, but the winter reductions offer some additional insights into the sensitivity of watershed to

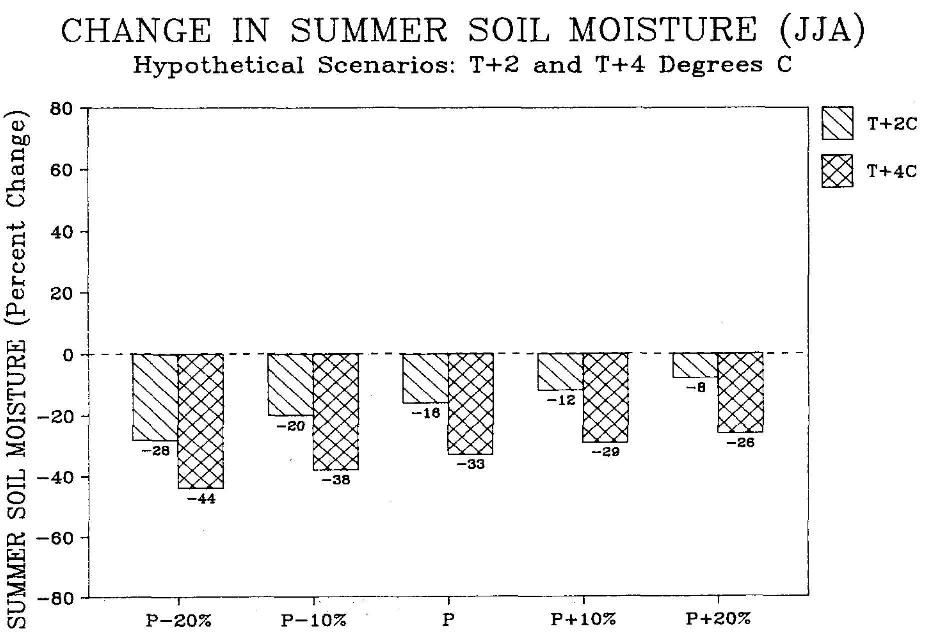

Fig. 9. Percent change in average summer (June, July, and August) soil moisture between the base case and the hypothetical scenarios with an increase in average-monthly temperature of 2 and 4 °C ($T+2$ °C and $T+4$ °C) and precipitation changes of zero and plus and minus 10 and 20%. Note that all these scenarios show decreases in summer soil moisture.

changes in climate. Temperature increases alone reduced winter soil moisture by 4 and 9% (for 2 and 4 °C increases, respectively) as a result of increased evapotranspiration rates. Of greater interest is the fact that the *increases* in soil-moisture for the three remaining scenarios were relatively small – soil moisture even decreased slightly when the temperature increased 4 °C and precipitation increased ten percent. In this particular run, the increase in precipitation was not sufficient to overcome the effect of increased evapotranspiration in the lower basin. It should be noted that the change in soil moisture noted for this run is extremely small – statistically insignificant.

During the winter months, percentage increases in precipitation have a larger effect on absolute precipitation than the same percentage increase in summer months simply because overall precipitation levels are higher. Yet these increases in precipitation do not manifest themselves as proportional increases in winter soil moisture. During winter months, soils tend to be near or at saturation and surplus moisture that falls as rain tends to run off, while the rest falls as snow and is stored in the snowpack. Thus greater winter precipitation tends to result in either more prompt storm runoff (and hence, total surface runoff) or an increase in the snowpack. Decreases in precipitation have the opposite effect, which can be seen by the larger proportional decreases in average winter soil-moisture values. Table VI shows the percent changes in average winter soil-moisture values for the ten runs using hypothetical inputs.

Monthly soil-moisture availability in the Sacramento Basin using the hypothetical temperature and precipitation scenarios was also reduced consistently from its base level, with the greatest percentage reductions occurring during the summer months. For seven of the ten hypothetical cases, soil-moisture values were reduced in every month of the year. For the other three runs, which involve increases in monthly precipitation, only small increases in the soil moisture during winter months were observed.

4.4. *Changes in Soil Moisture: GCM Scenarios*

Water-balance model results using all eight GCM scenarios show large reductions from the base case summer soil-moisture values in the lower basin despite

TABLE VI: Effect of hypothetical temperature and precipitation scenarios on the average winter (DJF) soil moisture (Lower basin)

(Percent change over base run)

Precipitation change	−20%	−10%	0	+10%	+20%
Temperature change					
$T+2$ °C	−20	−11	−4	+2	+6
$T+4$ °C	−25	−16	−9	−3	+3

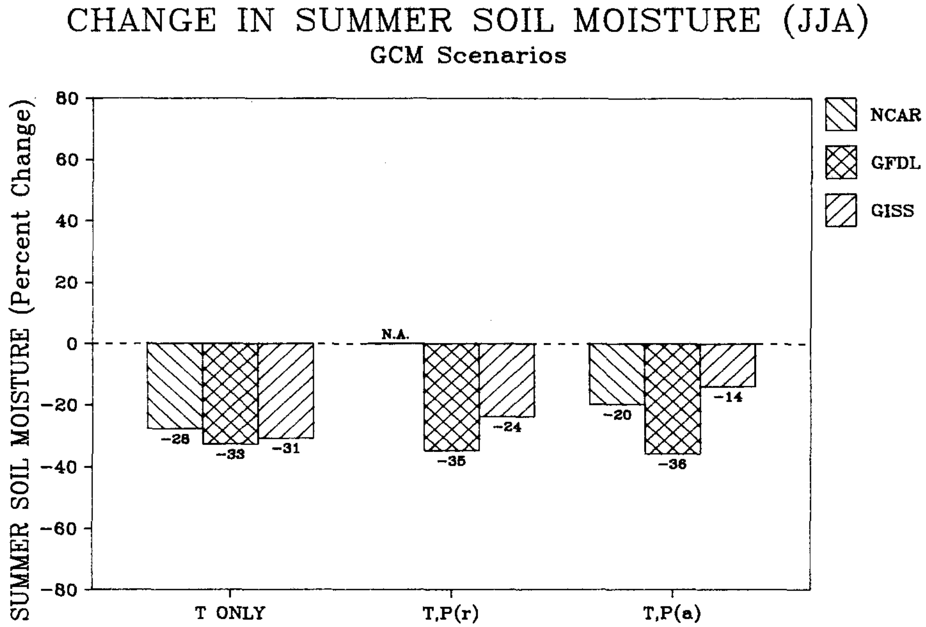

Fig. 10. Percent change in average summer (June, July, and August) soil moisture between the base case and the eight GCM-derived scenarios. Note that all eight scenarios show decreases in summer soil moisture. Key: (*T* only) Temperature change only. (*T*, *P* (*a*)) Temperature and absolute precipitation. (*T*, *P* (*r*)) Temperature and relative precipitation. (N.A.) Not included. See text for details.

the widely varying precipitation inputs. These reductions range from 14 to 36%. Average winter soil-moisture results show modest changes in all eight GCM scenarios. Figure 10 presents the changes in average summer soil moisture based on the GCM climate-change scenarios; Table VII presents the changes in average winter soil moisture.

The decreases in average summer soil moisture in the Sacramentio Basin are remarkably consistent regardless of which GCM scenario is used to drive the water-balance model. The magnitude and the consistency of the average summer soil-moisture drying signify a major hydrologic impact, especially given that these results are consistent with the summer soil-moisture results from the ten hypothetical temperature and precipitation scenarios discussed earlier: *all 18 climate-change scenarios lead to decreases in summer soil moisture.*

In addition to the seasonal results described above, there is a consistent monthly depression of soil-moisture availability for the GCM runs; the only increases occur during some winter months for the highest precipitation scenarios of the GISS model. The water-balance model results using six of the eight GCM scenarios show decreases in monthly soil moisture after March continuing through December. The other two scenarios – using the GISS relative and absolute precipitation data – show increases in soil moisture beginning again in November.

TABLE VII: Effect of GCM temperature and precipitation scenarios on the average winter (DJF) soil moisture
(Lower basin)

(Percent change over base run)

GCM[a]	T only	T and relative P	T and absolute P
NCAR	−2	n.a.	−3
GFDL	−5	−4	−3
GISS	−10	+4	+3

[a] The three general circulation model data sets are: temperature only; temperature and relative precipitation; and temperature and absolute precipitation. The differences among the three runs are discussed in the text.
n.a. Not included here; see Gleick (1986a, Appendix C).

5. Result Summary and Discussion

The research presented above evaluates one of the most important regional impacts that may result from changes in global climate – changes in water availability. Eighteen widely-varying climate-change scenarios were used to drive a water-balance model designed to evaluate the impacts of global climatic changes on runoff and soil moisture in a major watershed – the Sacramento Basin in California. The scenarios studied include ten scenarios with hypothetical temperature and precipitation changes, and eight scenarios with changes in precipitation and temperature generated using data from three state-of-the-art general circulation models of global climate.

Despite the uncertainties that surround the nature and timing of future climatic changes and their subsequent impacts, the research presented here raises serious concerns about regional water availability. In particular, observed decreases in summer soil moisture and runoff and increases in winter runoff are robust and consistent across widely-varying scenarios. This consistency suggests strongly that hydrologic vulnerabilities will make the impacts of climatic changes on water resources an issue of major concern in many regions of the world.

Four particularly important and consistent changes were observed:

(1) Large decreases in summer soil-moisture levels for *all* 18 climate-change scenarios.

(2) Decreases in summer runoff volumes for *all* 18 climate-change scenarios.

(3) Major shifts in the timing of average-monthly runoff throughout the year.

(4) Large increases in winter runoff volumes for fifteen of the 18 climate-change scenarios, including all 8 GCM cases. The other three scenarios – all of which involved 10 or 20% decreases in precipitation – showed small or moderate decreases in winter runoff.

Several of the results described here support recent suggestions that mid-latitude summer soil-moisture reductions may occur in many regions of the world (Manabe *et al.*, 1981; Mitchell, 1983; Manabe and Wetherald, 1986). The principal physical mechanisms involved – the decrease in snow as a proportion of total winter precipitation, an earlier and faster disappearance of winter snow-pack due to higher average temperatures, and a more severe evapotranspiration demand during the warmer summer months – are both physically plausible and consistent with the hydrologic mechanisms that lead to summer soil-moisture drying in the GCMs. While other, countervailing hydrometeorologic features may well exist – such as cloud cover/evapotranspiration feedbacks – the consistency of the soil moisture and runoff results observed here must be considered a first warning of possible important changes in regional water availability. As more information on these other factors develops, it can be incorporated into water-balance models to provide more detailed regional assessments.

The hydrologic changes described above will, if they materialize, have serious implications for many aspects of water resources, including agricultural water supply, flooding and drought probabilities, groundwater use and recharge rates, the price and quality of water, and reservoir design and operation – to mention only a few. Yet information on these changes, by itself, is unlikely to lead to major policy responses. Only by looking at the specific characteristics of water-resource problems – and their vulnerability to the types of changes in runoff and soil moisture identified above – can details of future societal impacts be evaluated. Such evaluations must begin now in diverse hydrologic basins so that policies for mitigating or preventing the most serious hydrologic impacts of climatic changes can be developed and implemented.

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