THE POTENTIAL WATER RESOURCE IMPACTS OF CLIMATE CHANGE

One of the most dramatic impacts resulting from global climatic change could be alteration in regional hydrologic conditions and subsequent changes in regional water availability, water quality, flood hazard, and other elements of water resources. Studies undertaken during the past decade to evaluate regional hydrologic implications of climatic change tend to indicate a high degree of sensitivity of regional hydrology to even small changes in precipitation and evapotranspiration. This section examines some of these recent studies, paying particular attention to their methods and their implications for water resource management.

Assessing Hydrologic Impacts of Climate Change

As in most areas of climate impact assessment (see, for example, Kates et al., 1985; and Riebsame, 1988a), evaluations of the potential water resource impacts of global warming rely on empirical and projective studies. Empirical studies of past climate fluctuations, especially dry spells, give the resource manager an idea of the climate sensitivity exhibited by a particular basin or water management system (Russell, Arey, and Kates, 1970). Most empirical studies examine system function under extreme events (floods and droughts) and not climate change per se, but the results of these studies can be re-examined for the insight they offer on how systems might handle cumulative change.

Projective studies involve translating the climate scenarios described earlier into water resource impacts by using extrapolation or modeling techniques (Schwartz, 1977; Beran, 1986). The studies described below take both empirical and modeling approaches.

Recent Studies

Nemec and Schaake (1982) used arbitrary increments (namely, temperature changes of ±1°C and +3°C and precipitation variations of ±10% and 25%) to study impacts of climatic fluctuations on selected watersheds. In addition to calculating subsequent changes in hydrologic characteristics, they also determined the reservoir sizes necessary to achieve a certain level of water supply reliability under different climatic changes. Their results for the arid Pease River basin in the southwestern U.S. (Figure 10), show that a 10% decrease in precipitation led to 150% to 200% increases in storage required to yield 20% of the mean annual runoff at a fixed level of reliability.

Revelle and Waggoner (1983) used the well-known Langbein relationships of mean annual runoff, precipitation, and temperature (Figure 11) to estimate the impacts of a 2°C warming and 10% precipitation decrease in the western U.S. Their results suggest marked decreases in runoff. For example, a 10% reduction in precipitation resulted in decreases in runoff ranging from 12% to 50%, depending on the change in temperature and original mean precipitation. However, Karl and Riebsame (in press) conducted an empirical analysis of relative climate and runoff fluctuations in the U.S. and found evidence that the Langbein nomogram overstates the effect of temperature changes on runoff,

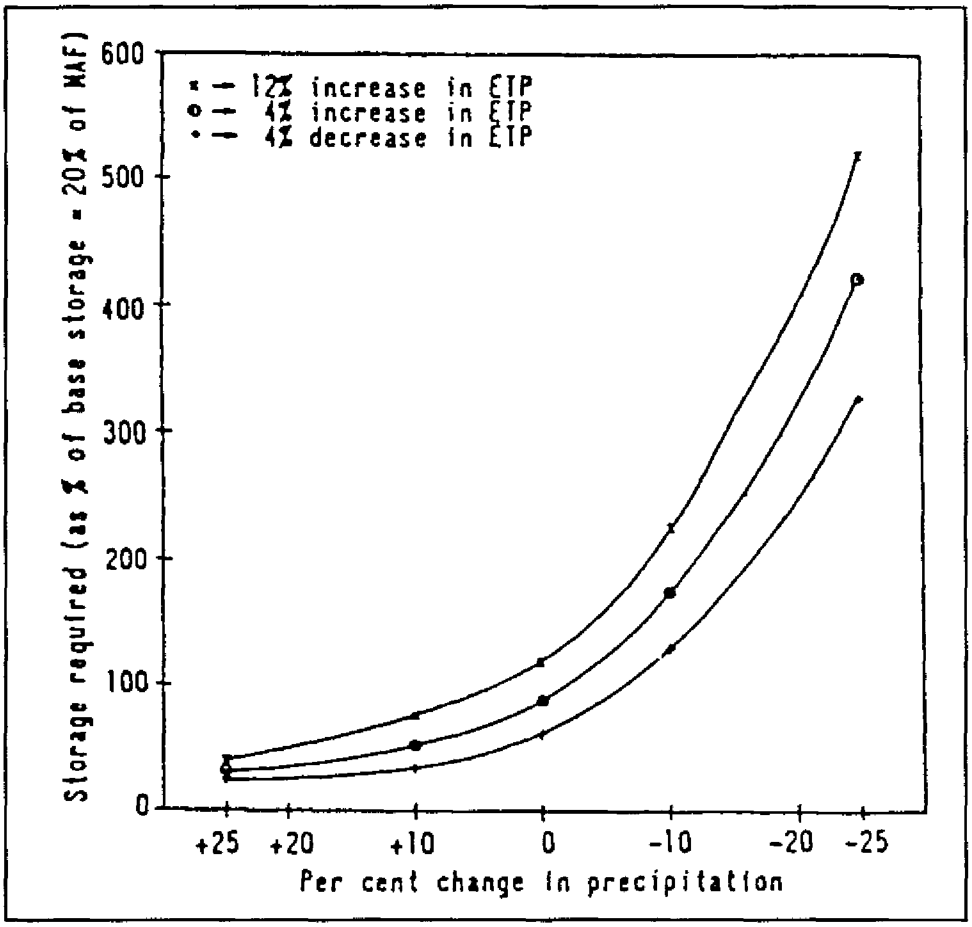

FIGURE 10

CHANGES IN RESERVOIR STORAGE NECESSARY TO PRODUCE A GUARANTEED YIELD AT A CONSTANT RELIABILITY AS A FUNCTION OF CHANGES IN PRECIPITATION AND POTENTIAL EVAPOTRANSPIRATION

Source: Nemec and Schaake, 1982

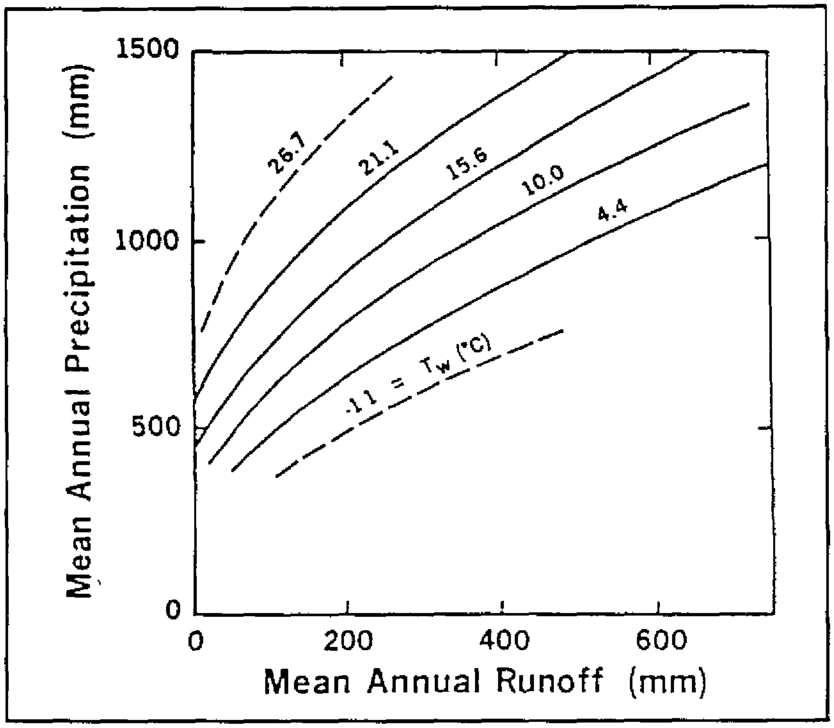

FIGURE 11

RELATIONSHIP BETWEEN MEAN ANNUAL PRECIPITATION AND RUNOFF AS A FUNCTION OF WEIGHTED MEAN TEMPERATURE (T_w)

Source: After Langbein, 1949

as illustrated by their version of the nomogram (Figure 12; see also, Wigley and Jones, 1985).

Cohen (1986) used output from two different GCMs--the GISS and GFDL models--to estimate future changes in water supply in the Great Lakes basin resulting from greenhouse-induced climate change. Runoff from the catchment area was computed for current and doubled CO_2 conditions. Changes in hydrologic parameters were calculated using the Canadian Climate Centre's version of the Thornthwaite water balance model. This empirical model

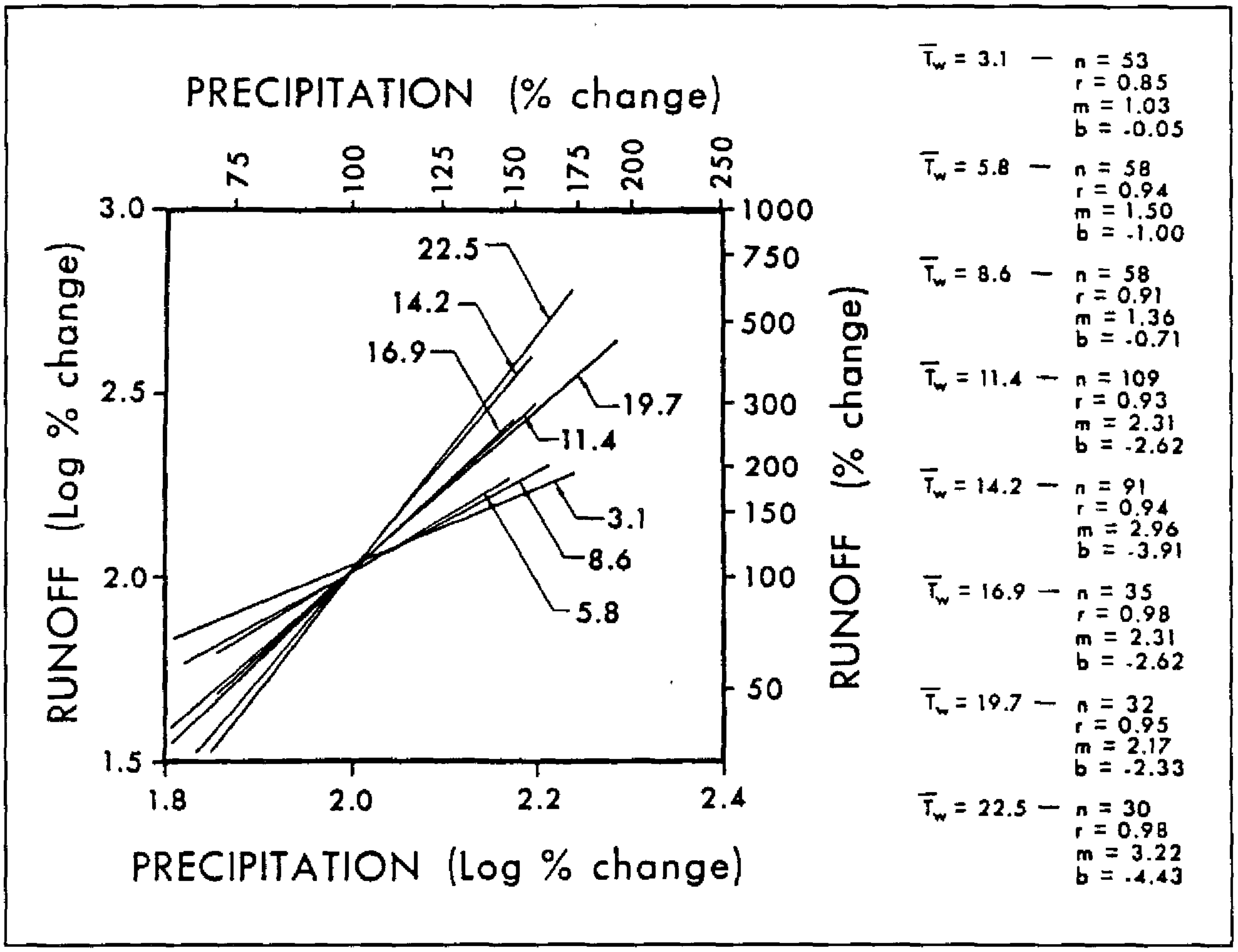

FIGURE 12

RELATIONSHIP BETWEEN EPOCH-TO-EPOCH CHANGES OF PRECIPITATION $(P_2/P_1)\%$ AND RUNOFF $(R_2/R_1)\%$ AS A FUNCTION OF T_w.

Source: Karl and Riebsame, in press

computes monthly mean evaporation based on latitude (a surrogate for insolation) and temperature.

Because 32% of the catchment area consists of lake surface, open water evaporation, which is greatly affected by wind speed, was of great importance. Consequently, a number of different scenarios (five) were used, matching the two model temperature patterns to alternative wind scenarios. Cohen cautions, however, that the large uncertainty regarding possible future wind characteristics over the lakes allows for only generalized conclusions about water resource impacts.

Cohen's results indicate a decrease in net basin supply under all five scenarios, as illustrated in Table 1. The differences between the two basic model scenarios are quite small; however, significant differences exist between the wind scenarios. GCMs predict greater warming at the poles than the equator, which would result in a decreased pole-equator temperature gradient and consequent decreases in pressure gradients and wind speeds. Hence, decreased wind speeds over the region are a plausible outcome of global warming, and Cohen postulated future speeds at 80% of current normals. This markedly reduced the water supply loss in a warmer climate (see Table 1).

TABLE 1

PRELIMINARY ESTIMATES OF NET BASIN SUPPLY (CMS)[2]

Source: Cohen, 1986

	Land based runoff +	Lake precip. –	Lake evap. =	NBS	Δ%
Normal[b]	5845	6224	4657	7412	--
GISS[b]	5368	6701	6199	5870	–20.8
GISS 80% winds[b]	5368	6701	4958	7111	– 4.1
GFDL[b]	5200	6168	5321	6047	–18.4
GFDL· 80% winds[b]	5200	6168	4256	7112	– 4.0
GFDL, GFDL winds[b]	5200	6168	5105	6264	–15.5
Cornwall (1959–1982)	–		–	7190	-

[a] Numbers may not add due to rounding errors

[b] Consumptive use not included

Cohen also suggested an integrated framework (Figure 13) for modeling the cascading impacts of climate variation on a region's water supply. Such a framework illustrates the vast array of components which need to be considered in comprehensive research on this topic; it can serve as a guide to other comprehensive basin studies.

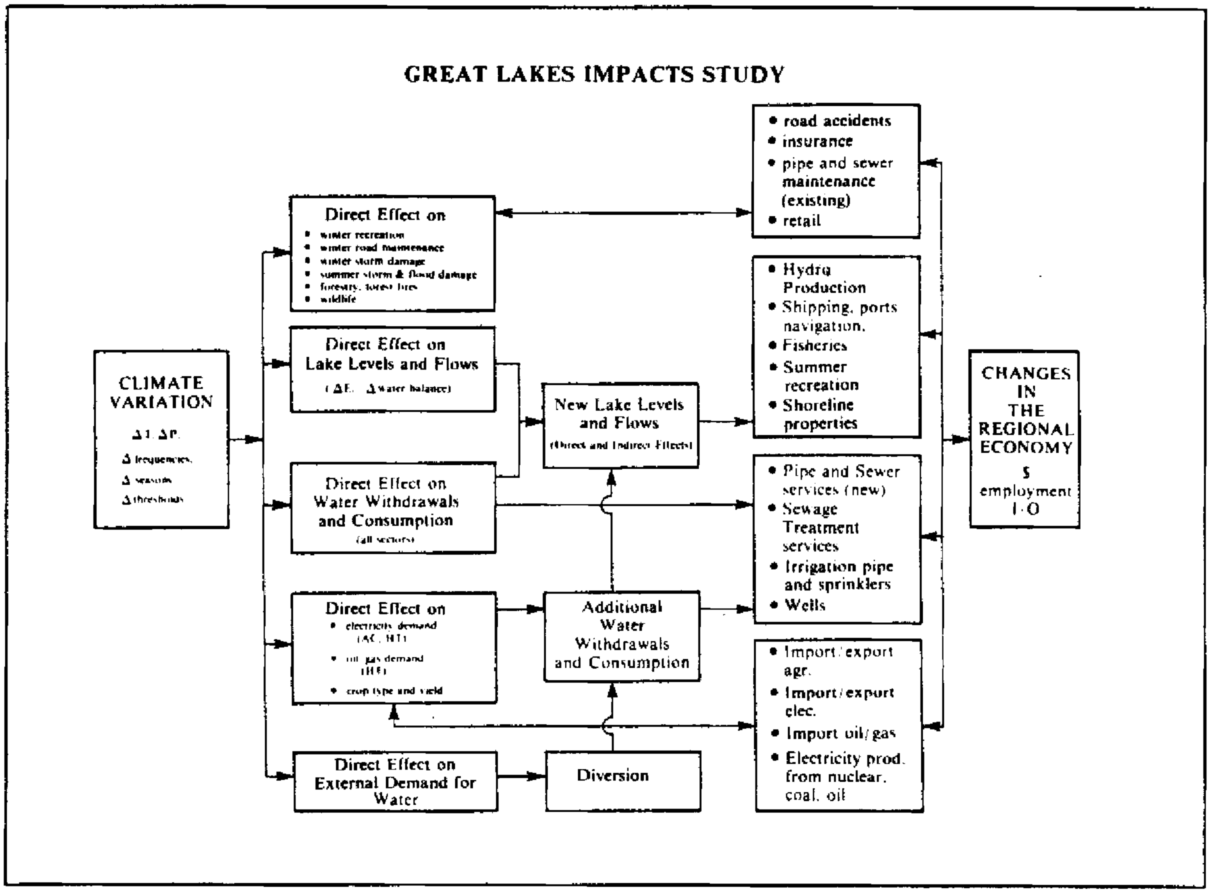

FIGURE 13

FLOW CHART OF THE COMPONENTS OF CLIMATE IMPACTS AND RESPONSES IN THE GREAT LAKES REGION OF NORTH AMERICA

Source: Cohen, 1986

Gleick (1987a, 1987b) evaluated the impacts of climate change on the hydrological characteristics of California's Sacramento River basin. This basin was selected because of the importance of its runoff to agriculture and industry, as well as the good quality and quantity of available hydrologic data. However, even with this relative wealth of pertinent data, Gleick cautions that hydrologic impacts of climatic change cannot be predicted with certainty sufficient to change current management operations.

Gleick used both GCM data and arbitrary increments to provide input to a modified version of the Sacramento water-balance model (modified, that is, for use under conditions of changing climate). Eighteen different climatic scenarios were created: ten hypothetical scenarios involving combinations of +2°C and +4°C, and ±0%, 10%, and 20% precipitation; and eight scenarios of GCM-predicted temperature and precipitation changes from the GFDL, GISS, and NCAR models. Output from the GCMs was in the form of temperature and precipitation data for current and doubled CO_2.

The most important changes noted by Gleick in this study were: 1) persistent decreases in summer soil moisture, 2) decreases in the magnitude of summer runoff, and 3) increases in the magnitude of winter or early spring runoff. Because of the region's Mediterranean climatic regime (i.e., most of the precipitation occurs in the winter months, followed by a summer drought), water resource managers are strongly dependent on spring runoff, much of it from snowmelt, to fill reservoirs in order to meet high summer demand. Thus, more peaked spring runoff would logically require more storage capacity even with no change in total runoff.

Gleick created a "two-basin model" in order to better estimate the magnitude and timing of runoff in the Sacramento basin because of the heterogeneity of the basin's physical character. He split the basin roughly into two hydrologic areas: the lowlands of the Central Valley and the mountains of the Sierra Nevada. A large percentage of runoff in this basin is from snowmelt and a "one-basin model" cannot accurately show how the timing of snowmelt might change in response to climate change. In comparison with the one-basin model, the two-basin model more accurately reproduced both timing and magnitude of monthly runoff conditions. As a result, the model shows promise for the evaluation of the impact of climatic changes on regional hydrologic characteristics. However, changes in initial climate conditions may necessitate changes in how the model is divided, in turn affecting its accuracy.

The U.S. Environmental Protection Agency's national assessment of climate change impacts (at this writing the full report to Congress is still in draft form; see Smith and Tirpack, in press) includes hydrological aspects chiefly in the California and Great Lakes case studies. The California study will be discussed here.

Lettenmaier and Gan (1988) studied the potential hydrologic impacts of global climate change on four catchments in California's Sacramento-San Joaquin Basin. The four basins were chosen on the basis of geographic and hydrologic diversity, the absence of upstream flow regulation, and the availability of long-term hydrological and meteorological data.

Two different hydrologic models--one for prediction of snow accumulation and ablation, another for soil moisture accounting--were used to simulate daily outflows from each of the four watersheds. The models were used to simulate hydrologic conditions under seven different climatic scenarios.

The warming associated with all the climatic scenarios resulted in a consensus among the models on a dramatic shift in the snow accumulation pattern in each of the basins:

> under the warmer conditions predicted by the GCMs, snow would occur only rarely at lower elevations, and the snow accumulation would be reduced at the higher elevations.

The models also indicated a shift of the maximum mean runoff from the spring to winter. As in Gleick's study of the entire Sacramento Basin, winter runoff increased, while spring and summer runoff (and, consequently, soil moisture) were greatly reduced. A shift in maximum evapotranspiration to earlier in the season was also noted. Simulated changes in annual runoff totals were minor and generally regarded as inconsequential. As the authors stated,

> From a hydrologic perspective, GCM-predicted changes in precipitation, for which there is less consensus than temperature, would be less important than the predicted temperature changes.

Sheer (1988) used a water balance model (developed by Water Resources Management Inc. for use by the Metropolitan Water District of Southern California) to simulate the effects of possible future climate change on deliveries of California's two largest water systems--the federal Central Valley Project (CVP) and the California State Water Project (SWP).

The GISS, GFDL, and OSU models were used to create doubled CO_2 climate scenarios, in addition to base runs (representative of current climate), that were then used as input to the water balance simulations. Although outputs of the GCMs differed (the run using the OSU model showed a smaller change from the base run than the other two GCMs, for instance), impacts of the three scenarios were roughly similar. Increased temperatures in all three doubled CO_2 runs resulted in more winter precipitation falling as rain, thus reducing the winter snowpack. Higher temperatures also lead to earlier winter snowmelt. Thus, instead of the snowpack acting as storage for use in the irrigation season, much of it would melt earlier and run "unused" to the sea. This would represent a decrease in water which could be reliably supplied by either the Central Valley Project (CVP) or the State Water Project (SWP).

All models showed little change in reservoir storage at the end of March, i.e., the end of the shortened runoff season (only the levels of Oroville Reservoir, the largest storage facility of the SWP, were modeled), because reservoir levels are limited by the need to preserve free volume for flood control. However, <u>all</u>

three models concur that reservoir storage at the end of May would be substantially lower, because of the quicker snowpack melt in the spring brought on by warmer temperatures.

Although the models predict a change in runoff seasonality (i.e., more runoff in the winter months but less in the summer), they also show an increase in total annual outflow. Such an increase may partially offset the "loss" of runoff resulting from earlier snowmelt (runoff which cannot be stored). However, from a water management perspective, the change in runoff seasonality is the more significant factor and would overshadow small changes in annual totals. These results indicate that even climatic shifts that increase moisture may cause serious water management problems in finely tuned systems like California's SWP and CVP.

Climate Change and Water Resource Systems

Most water projects are designed for both flood and supply management, and involve planning horizons of several decades, within the time frame of potentially large global warming effects (Schwartz 1977; Cohen 1986). Water project planning is predicated on expected hydrological conditions based on data from the past 30 to 100 years. Thus potential global warming raises the question of how well water projects based on historical conditions will handle future climate change. Fortunately, most projects incorporate substantial buffering capacity. Hanchey et al. (1988) argued that project planners had

> over the course of fifty years of application and refinement [developed] a large body of empirical and theoretical procedures and decision rules that have yielded what are generally considered to be fairly

> robust and resilient project designs. . . . This empirical approach, emphasizing as it does extremes of climate variability over the past 100 years, encompasses a significant proportion of the anticipated [climate] changes, at least for large scale water management. (p. 399)

The fact remains, however: climate change is, by definition, a change in the statistical properties of climatic elements on which project designs are based, and, depending on the size of safety margins, it will change the frequency of conditions that approach or surpass failure thresholds. Assuming that planners have achieved socially acceptable project reliability, then any climate change larger than the uncertainty inherent to hydroclimatological analysis violates explicit and implicit planning criteria.

Without project sensitivity analyses linked to climate change projections, we cannot know how significant this violation may be. Assumed climate stability is a potentially dangerous "blind spot" in water project design, given the threat of global warming (Lettenmaier and Burgess, 1978; Changnon, 1984). Assessments of the vulnerability of water projects to climate change are rare, and beyond a reassuring sense that such systems have been designed in a conservative manner, the capacity of most existing projects to accommodate climate change is unknown.

Water projects can be adjusted to climate change by altering project goals (for example, accepting lower reliability), operations, or physical facilities. Goal and operational changes are common in a project's lifetime, but such changes tend to be made only when droughts or floods cause near or actual system failure (Glantz, 1982; Rhodes et al., 1984; Phillips and Jordan, 1986; Riebsame, 1988b). Physical facility changes due to altered environmental conditions are much less common, though precedents are being set where postconstruction studies have revealed geological risks to dams and other control structures.

In summary, it appears that even relatively small changes, such as those that might occur in the next one to two decades, can disrupt water systems. Further climate change, now projected to occur at rates unprecedented in human history, can only exacerbate the problem. The problem for the water resource planner is to decide when and how to respond to the threat, given its potential consequences and great uncertainties. The long lead times associated with water resources planning, and the assumption in most hydrological analyses that climate characteristics are stationary over time, exacerbate this decision-making problem. While it may not yet be time to act, it is clearly time to assess sensitivities and canvass possible responses.

CONCLUSIONS

The material presented here shows both strengths and weaknesses in our understanding of climate change. The general effect of growing greenhouse gas concentrations in the atmosphere is well understood and accepted almost universally: there will be a warmer global climate. But the specifics of timing, rate, and regional magnitude and character of likely climate changes are not yet within our grasp. Nevertheless, the growing credibility of global warming predictions, and growing public and policy maker awareness, means, simply, that water resource managers will come under increasing pressure to respond in <u>anticipation</u> of climate change, even before the uncertainties are significantly reduced. How they respond to this pressure is another issue.