# GLOBAL CHANGE AND WATER RESOURCES IN THE SOUTHWEST

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*All that lies between the cradle and the grave is uncertain. - Seneca*

## INTRODUCTION

Some things in life are certain; others are not. Perhaps the only certainty upon which we could reach agreement without any dissent would be death and taxes. One certainly cannot predict how people will react to the challenges of meeting long-term needs for water. A January 11, 1998, editorial in the *Washington Post* pointed out that about 10 percent of the U. S. population depended on the Colorado River for its water in whole or in part. Early allocations of Colorado River water, made on the basis of hydrologic studies for a period of record that we now know was a "wet" time compared to the long term normal, led to over-allocations. Still some regions are not now using their allocations and some are using more than their allocations. A day of reckoning will occur.

Regardless of allocations, states that do not use their allocated water will likely lose it, perhaps through a market transfer process. Tucson is an interesting case study. Totally dependent on a declining ground water supply, the Central Arizona Project (CAP) was to bring surface water from the Colorado River to this Sonoran Desert city. But when the Colorado water (of lower quality than the traditional ground water supply) was introduced into the city distribution system the users revolted. The water with a different chemistry dislodged rust from pipelines and temporarily resulted in murky tap water. This was no doubt correctable, since millions function well with Colorado River water as their sole supply. But politics entered the scene. Some, using scare tactics about the water not being safe instead of using good science and engineering, persuaded the majority of voters in a referendum to direct that no more Colorado River water be directly used in the water supply. It was to be used in recharge systems that do not now exist.

The notion of using the water for recharge is good. But to ignore the potential of directly addressing the problem now using science and technology is bad. In the long haul, Tucson stands to possibly lose a portion of a surface water supply that will be badly needed in the future, and for which the infrastructure costs have been very great and largely provided for by the U.S. taxpayers. A sane and long-term water policy is needed in this city that has done so much in the past to use water wisely. Tucson is a leader in many water conservation practices such as xerophytic landscaping. It looks nice and I for one haven't regretted not having to mow a lawn for the last ten years.

But I've said enough on Tucson. Let's look at the larger picture in the Southwest, of which Tucson is a part. The focus of this paper is largely on the potential effect of global change on the water supply in the highly politicized Colorado River Basin.

It is virtually certain that total agreement will not be reached on the impact of global change on water resources. In fact, total agreement on whether global change is occurring -- or will occur -- as a result of the buildup of the greenhouse gases in the atmosphere is not likely.

Because the climate is subject to natural variability, we cannot prove without a doubt that change is occurring. El Nino's are probably not a development of the last few decades, but we now better understand the cause with satellite measurements of ocean temperatures. Is it part of the natural cycle of events in the world, or is it an ominous change in the climate? My guess it that it is part of a natural cycle that may be intensified by global change.

When studying the climate, a record of years or decades is not enough. It takes a long time to "prove" that the variations that we see are not simply a part of the natural variability of the climate.

During the extraordinarily hot summers of 1989 and 1990 with the widespread droughts of the time, some newspaper articles suggested that greenhouse gas-induced warming had begun. In those two years Tucson did have

165 and 178 days, respectively, with temperatures over 90 degrees F, compared to the normal 141 days. The maximum temperature in 1990 reached a scorching 117 degrees F, an all time record. Perhaps greenhouse warming has begun. However, no professional climatologist would make such an unqualified statement, based on limited observations. Although the temperature extremes we were observing in the late 1980s "fit in" with the global change scenario, good science is not the result of "feelings." Good science requires careful and patient analysis of vast amounts of data. Then, hopefully, the truth will emerge. Although the data supporting most aspects of climate change are mounting, there is still much uncertainty regarding climate change and its potential effects on water resources.

In this paper I provide a brief overview on some issues related to the buildup of carbon dioxide and other greenhouse gases. While global warming is the most apparent global change that will occur, there will be many others. Very important among these are changes in the hydrologic cycle. I will focus on the water supply of the southwestern United States since water is the lifeblood of this region. The hydrology of the region is complex and greenhouse gas buildup and global warming could significantly alter it. I doubt that any area of the United States is more at risk in terms of its critical water supply than this desert Southwest. Therefore, in this paper I concentrate on the localized hydrology changes in the Southwest.

## HISTORY OF GLOBAL CHANGE AND BACKGROUND

Historic climate variability which shows some interesting swings in temperatures over the last million years has been reported (Hecht, 1981). For example, in the last 100 years in the Northern Hemisphere, temperatures increased from the 1890s until the 1940s, then decreased until the mid-1960s, and have leveled off since then. Variations in the last 1000 years suggest a range of temperatures of nearly 1.5 degrees C during that time. The warm period from 900 to 1200 AD is referred to as the Medieval Warm Period. By contrast, the period from 1450 to 1850 was significantly cooler and is known as the Little Ice Age. Thus climatic events, which we believe to be extreme in the short-term climatology sense, have occurred many times in the past.

We learn from examining the last million years that there have been several ice ages. We know that the solar radiation the Earth receives is affected by its orbit which tilts the poles toward and away from the sun with frequencies of about 21,000, 41,000, and 90,000 years. Yugoslav astronomer M. Milankovitch in 1941 proposed this widely accepted theory which explains glacial periods (Rosenberg, 1987). Since the last major ice age occurred about 18,000 years ago, one could speculate that we might experience another glacial period in about 3000 years. However, the rate of temperature change due to variations in the earth's orbit according to Milankovitch's theory is very, very slow compared to that resulting from the build up of the greenhouse gases, which has been very rapid since the beginning of the industrial revolution.

Past climate changes have been on a geologic time scale. But instead of thinking in geologic time, we tend to focus on what will happen in our lifetime -- or perhaps the lifetimes of our children and grandchildren -- and their children and grandchildren.

## SOME INTERESTING HISTORICAL DATA

The world population total grew from 3.0 billion in 1960 to 5.2 billion in 1989 and according to United Nations estimates is likely to grow to 8.2 billion in 2025. The dominant contributors to this growth are projected to be China and other developing nations that have historically had low rates of energy consumption. The current high levels of per capita energy consumption in the U. S. and Europe could decrease if optimistic projections regarding energy conservation are realized. However, considering the projected increase in the per capita energy use rate for China and the third world, and their expected population growth, the prospect for dramatically reducing greenhouse gas emissions worldwide is not bright. These developing countries assert they should not be deprived of the opportunity to develop their economies and benefit as the highly developed world has. As a result, the developing nations are projected to be the dominant source of carbon emissions by 2010 and beyond, although their collective contribution presently is relatively small, given the large populations involved (Flavin, 1990).

Greenhouse gases in the atmosphere were not regularly measured until continuous observations were started in 1958 as part of the International Geophysical Year. The increase in atmospheric carbon dioxide from 280 ppm in 1870 at the beginning of the industrial revolution to 316 ppm in 1958 and about 345 ppm now is striking (Rosenberg, 1988). Methane is another important greenhouse gas and it has grown from 1.51 ppm in 1977 to over 1.65 ppm now. Other greenhouse gases accumulating in the atmosphere include the chlorofluorocarbons (CFCs) and nitrous oxide. The combined effect of these trace gases in the atmosphere is to trap the sun's energy and alter the heat balance of the Earth. The gases are relatively transparent to the short wave radiation of the sun, but they are relatively opaque to the longer wave outward radiation from the Earth and this causes warming.

The argument that the greenhouse effect will cause temperature rises of unprecedented rates has its critics. Some contend that compensating effects will essentially negate the predicted warming (Kerr, 1989). These compensating effects include increased cloudiness, an altered albedo of the Earth reflecting more of the sun's energy, and greater carbon fixing through enhanced photosynthesis of plants in a $CO_2$ enriched atmosphere. Although some argue that we do not have "proof" of change, I hope we don't put our heads in the sand and say it's not happening. The evidence that I have seen convinces me that the global change problem is real.

## SOME IMPACTS OF GLOBAL CHANGE BESIDES WATER

What is the relative impact of some of the local changes that might occur as a result of climate change from greenhouse warming? Some of the effects will be positive. For example, a $CO_2$ enriched atmosphere will lead to a more productive agriculture, other things being equal, because the photosynthesis process will be more efficient. This is because less carbon rich air must diffuse through the leaf stomata for the same biomass production. At the same time the water use efficiency of the plants should increase very slightly. This is all on the positive side.

Regarding negative impacts of global change, sea level rise will be one. The many coastal cities of the world will be more subject to flooding and coastal erosion. If the sea were to rise by one meter, to say nothing of the two or three meters which some have speculated could be possible, then sea levels would seriously encroach on many areas of the world (Jacobson, 1990). The current flooding problems of Venice resulting from subsidence would become worse and other areas might have more impact. More salt-water encroachment into the ground water would occur along the coastline, fouling many water supply aquifers in those coastal regions. Low lying rice production areas of Southeast Asia could be flooded with seawater and become worthless for production.

What about the direct impact of warming? Many areas of the world will benefit. Canada will potentially experience improvements in its agricultural production as will some northern areas of the former Soviet Union with large areas marginally acceptable because of the short growing season perhaps becoming another grain belt. The U. S. corn belt could move northward and up into Canada. The southern pine forests could shift northward into the Northeast. If the water supplies are not adversely affected, the agricultural productivity of the world could be significantly enhanced.

Perhaps one of the most serious things about the buildup of greenhouse gases, and the CFCs in particular, is the potential effect on the ozone layer. The recently observed hole in the ozone layer in the Southern Hemisphere, and even more recent thinning of the layer in the Northern Hemisphere, should be adequate cause for concern. In Arizona we are particularly sensitive to the potential adverse skin cancer effect of poorly filtered solar radiation beating down on us. While it is too early to accurately predict the long-term effects of greenhouse gases on the ozone layer, we must be concerned.

## THE HYDROLOGIC CYCLE -- THE PATHWAYS OF THE EARTH'S WATER

Laws of nature can describe every single process that occurs in the atmosphere. That includes everything -- the global circulation patterns, the formation and movement of the weather fronts which transfer large air masses across continents, the large hurricanes, the small but devastating tornadoes, and the isolated showers drifting across the City of Tucson, as well as the tiny (in a relative sense) dust devils in the Sonoran Desert. These are just a few examples.

The hydrologic cycle is very complicated. Like the global circulating models, which are even more complex, the hydrologic processes also can be mathematically modeled to provide useful estimates of future conditions. However, hydrologic processes are very sensitive to local conditions. This is particularly true in desert areas interlaced with mountains such as we see in Arizona and in the Southwest.

What about the projected change in soil moisture and changes in runoff resulting from any increase in precipitation? Soil moisture is crucial for agricultural production. Increased soil moisture will accompany those areas with precipitation increases. The five major global circulation models all predict an increase in average worldwide precipitation (Geophysical Fluid Dynamics Laboratory at Princeton, Goddard Institute for Space Studies, National Center for Atmospheric Research, Oregon State University Model, and United Kingdom Meteorological Office). This is to be expected because there will be more evaporation from the earth's water surfaces due to higher temperatures. However, the precipitation increase is not projected to be uniform across the world (White, 1990). In fact, some regions are projected to have decreases in precipitation and lowered soil moisture at least in some seasons. If one analyzes the results of recognized global circulation models, it is quite apparent that many inconsistencies exist and the ability of the models to predict changes in soil moisture is not perfect by any means.

The models tend to agree that the interior of the U. S. is likely to be drier in the summer. This could be very serious for the interior wheat belt of the Great Plains and corn belt of the north central states. There is far too much uncertainty to speculate on whether Arizona will be drier or wetter. However, it is certain that any drying in the desert Southwest will have extremely adverse effects since even a slight decrease in the rainfall will seriously affect the water supply in this desert region.

The five global climate models for which results are available assume a doubling of the atmospheric carbon dioxide levels. While such an increase could not occur until well into the next century, we can gain insight by looking at what changes might occur. Temperature increases range from 2.8 degrees C to 5.2 degrees C with an average of 3.9degrees C (Abelson, 1989). However, averages mean very little since the temperature increases will be greatest at the poles and quite small at the equator. Projected precipitation increases range from 7.1% to 15.8% with the average being 10.1%. The precipitation patterns are not so orderly and the confidence of these predictions is much less than for temperature.

## RAINFALL-RUNOFF RELATIONSHIPS AND WATER SUPPLY

I believe the potential effects of global change on water supplies may be more serious than the temperature changes. This is particularly true in regions where surface water supplies come from snowpack-stored water in the mountains. That is the case for the Southwest U.S. where the Colorado River is a major source of water for densely populated cities in the deserts of southern California and Arizona. In these regions even if the total precipitation stays the same in a future warmer world, we will face a decreasing water supply available for human use.

Much of the desert Southwest (Arizona, Nevada and Southern California) has an average annual precipitation of less than 10 inches. For this region, the future supply significantly comes from the Colorado mountains via the Colorado River and associated distribution projects. There is little dependable runoff in most of the West except for the mountainous regions. However, in the Colorado Rocky Mountains, for example, there is over 20 inches of runoff in some areas. That is the water supply that ultimately will be used in Southern Nevada and in Arizona and Southern California, because this Southwestern U.S. area is projected to experience shortages in water supply (Postel, 1990). Ground water overdraft already is serious in these areas. The extended California drought of the late 1980s and early 1990s has brought the seriousness of the water supply problem into focus, although the recent El Nino may cause the layman to think of floods, not droughts.

It is worth noting that we have an insatiable thirst for water. In the U.S., the population grew from about 150 million in 1950 to nearly 250 million in 1980, an increase of 53%. Yet, the total offstream water withdrawal increased from about 180 billion gallons per day (bgd) in 1950 to 450 bgd in 1980 -- a 150% increase. Much of that increase was due to irrigation expansion (Postel, 1989).

The Colorado River is the key surface water supply for the desert Southwest U.S. just as throughout history the Nile has quenched the thirst of its region. The Colorado Basin covers Southwestern Wyoming, Western Colorado, Eastern Utah, all of Arizona, and small pieces of Southern Nevada, Northwestern New Mexico and Southeastern California. The Colorado water supply comes largely from the mountains in the upper basin. Much of the water falls as snow and is captured and stored as snowpack on the mountain slopes. The water waits there, without the need for reservoirs to hold it back, for the spring and summer thaw to release it in an orderly fashion at the time when crops need it, and people in the searing heat of the lower basin thirst for it.

This thaw-driven flow into Lake Powell on the Colorado River is near the annual average from January to April, then rises slowly until June when it increases rapidly just as the water-use need of the lower-basin users starts to reach its peak. Keeping the water in the mountains until needed is a nice benefit of nature that the Bureau of Reclamation engineers has utilized. Still, to complement the natural snowpack storage, several reservoirs have been constructed on the Colorado River to provide storage lakes and flood control. Managing these reservoirs is complex because one cannot maximize storage to guard against a future drought and maximize flood protection at the same time. This is further complicated by the fact that releases into the Grand Canyon are now geared to helping maintain a proper regime in the channel and maintain sandbars for campsites for river rafters. So a compromise has to be reached -- one that will surely be criticized by some group when an event at either end of the drought or flood extremes occurs.

**REEMPHASIZING THE UNCERTAINTY REGARDING FUTURE PRECIPITATION**

I do not know whether the Southwestern U.S. will have more or less rainfall at the time in the next century when the greenhouse gases have doubled in the atmosphere. What I can say is that either way we will almost certainly see some significant changes in our water supply because of the global warming. Let me explain.

Experts use mathematical models to estimate what changes in runoff may occur with the temperature increasing and have done so for cases where the precipitation is projected to either increase or decrease. Notable among those researchers has been Charles Stockton of the University of Arizona's Tree Ring Laboratory. Among the river basins that have been analyzed by scientists are the Colorado River and other rivers in the Great Basin (the region from Arizona northward), the Sacramento River Basin in California and the Pease River in Texas.

Remember that when basins extend into mountain areas, and the winter temperatures are warmer, more of the precipitation is in the form of rain instead of snow. Rain soaks into the ground where it falls or runs off at the time. The massive storage potential of mountain snowpacks is lessened. That is not a trivial matter as regards the water supply, which would have been stored as snow and upon melting used later for human purposes.

To illustrate, consider a basin reaching into snowcapped mountains where the temperature has risen due to global change. Even if the precipitation amount doesn't change, the total runoff and usable water supply will decrease. Naturally, for a basin where the precipitation decreases, the runoff and available supply will decrease even more. Let me give you some results of analyses by various investigators. Remember that the models used cannot possibly describe all of the complex hydrologic processes. However, they provide a good guide regarding what we might expect under various global change scenarios.

**EFFECTS OF GLOBAL WARMING ON RUNOFF**

For the moment let us accept the fact that there will be temperature increases as a result of the greenhouse gas buildup. Scientists have great confidence in this prediction as opposed to a no temperature change scenario (White, 1990). They are also confident that global average precipitation will increase. But we cannot be sure whether there will be increases or decreases in any given location. So we should look at all possibilities. We can expect a greater portion of the precipitation to be as rain instead of snow because of the warmer temperatures -- a very important factor in basins which have snowpack accumulation.

Two approaches have been used. One is to study basins with periods of several years when the rainfall was abnormally high or low compared to the long-term averages. We can then compare the runoff response during these periods. The Illinois River Basin provides a recent example (Singh, 1990).

In northern Illinois precipitation was 9 to 14% higher in the 20 years prior to the mid 1990's compared to the previous 60 years. The Illinois River flow during this period was 20 to 25% higher than normal. In this case, the runoff increase was about double the precipitation increase. In the spring flood season, during that 20-year wet period, the precipitation was 8 to 23% over normal, but the flood peaks increased much more, 46 to 56%. Similar studies show that during periods of low rainfall, the percentage runoff decreases exceeded the precipitation decreases. In both cases we see the streamflow change is greater than the precipitation change.

A second method used for estimating the changes in runoff and water supply when precipitation changes is to use a mathematical model. This model is more useful in estimating the effects of global change on water supply. Projections of runoff changes for various reasonable climate change scenarios have been made for several basins using a volume balance model. Examples from four basins, all in the relatively arid West or Southwest are given.

The first example is for the Colorado River Basin. The study assumed a 2 degree C temperature rise and calculations were made for precipitation decreases of 10% and also for increases of 10%. Stockton and Boggess analyzed the runoff changes in the upper basin and the lower basin separately (Stockton and Boggess, 1979). In a similar study, Revelle and Waggoner looked at the entire basin as a unit (Revelle and Waggoner, 1983).

An analysis of the upper basin in particular is important because that portion has higher annual precipitation, much of it as snow. It turns out that even when precipitation increased, the annual runoff is projected to decrease. To understand the reasons, remember with higher temperatures, the ground is not frozen (and impermeable) for so long. The winter rain can soak in at the spot, as opposed to being stored as snow until runoff begins during the spring thaw. These data suggest that the water supply of the Colorado River will be adversely affected by any temperature rise even if the annual precipitation increases. These studies both considered a 2 degree C temperature rise and changes in precipitation of both plus and minus 10%.

A second case comes from the work of Peter Gleick on the Sacramento River Basin in California (Glieck, 1987). The upper watershed where most of the runoff occurs is snow-covered in the winter. Gleick looks at winter (December, January and February) runoff separately from the summer (June, July and August). He also looks at the annual total to see the overall changes. Moreover, he analyzed +2 degree C and +4 degree C temperature changes and precipitation changes of plus or minus 10 and 20% as well as no change.

Winter runoff is not reduced nearly as much as summer runoff in the model. This is very important because the winter runoff occurs when the water cannot be used for irrigation and other summer uses unless it is stored in reservoirs. To provide the same dependable supply for California users, including the Southern Californians who receive the water through canals of the California Water Project, would require more costly reservoir facilities. In general, the patterns of runoff change for the Sacramento River are similar to those for the Colorado River.

The last example is for several sub-basins in the Great Basin (most of Nevada and Western Utah)and for the Pease River in Texas (Flaschka, Stockton, and Boggess, 1987), (Nemec and Schaake, 1982). Here we see the effects of precipitation changes magnified in terms of runoff changes. These basins do not have the dominant effects of snowpack on the watersheds, so winter versus summer seasonal considerations do not dominate. These results are quite similar to the case from the actual records from the Illinois River Basin. Note that in the case of the Pease River the investigators assumed that a 1degree C or 3 degree C temperature rise corresponded to a 4% and 12% increase in evapotranspiration (ET) on the watershed.

## WHAT DOES IT ALL MEAN IN TERMS OF WATER SUPPLY?

A recent summary on climate change effects on the water resource systems of the U.S. comes from a report of the American Association for the Advancement of Science Panel on Climatic Variability, Climate Change and the Planning and Management of U.S. Water Resources (Waggoner, 1990). The summary and conclusions of Chapter 8 in that report by John Schaake entitled "From Climate to Flow" clearly illustrate the importance of potential climate change to arid regions. That summary follows:

"Stream flow is sensitive to climate change. Elasticity's range from less than 1.0 to as high as 10 for different locations and climate and stream flow measures. Low flows will be more affected than high. Dry climates will be more affected than humid. Elasticity to precipitation change is greater than elasticity to potential evapotranspiration which means that warming of the atmosphere alone will decrease stream flow far less than warming plus a simultaneous decrease in precipitation. Reservoir yields will be affected, but the elasticity of reservoir yield is less than the elasticity of the mean flow. Because water quality problems tend to be coupled with low flow conditions, water quality effects of climate change may prove to be among the most significant, especially in arid areas" (Schaake, 1990).

While not certain, the data strongly suggest that the water supplies of Arizona and Southern California will be reduced by the temperature rises due to global change. These conclusions are not based on idle speculation. Granted, the science and models we use are not perfect. It is good science, nonetheless.

Research on localized hydrology will improve our understanding of the climate and hydrologic systems of Earth. Some of that research will be conducted at the University of Arizona as a part of the large Earth Observing Satellite research program of NASA. One of the most serious problems of climate change will be change in the water supply. Through good research we will learn how to more accurately predict those effects.

## IMPLICATIONS FOR NATIONAL WATER POLICY

The experience in Tucson, where a short-sighted voter decision has been made not to use available CAP water and instead continue to draw on the depleting ground water supply, seems to indicate that the voters still do not appreciate the ground water limits. The attitude seems to be that, through some means, water will be available in the future when it is needed. The fact that desert aquifers can become so depleted that they cannot support the demand of the current population, let alone a larger one, seems to be lost in the heat of the discussion. While no one would suggest that the concerns of citizens about the safety of the water be minimized, policy makers must more carefully look at the opportunities to use science and engineering in solving these water problems. Moreover, water administrators must make certain that a sound water information dissemination plan is in place to allay the fear of voters. The age-old problem of distrust and lack of effective communication has plagued Tucson in this recent decision regarding CAP water use.

If global change is occurring, and I believe it is, decision makers on water in the Southwest had better take note. The research reported on in this paper clearly shows that there is almost certain to be a negative effect on the water supply in the Colorado River Basin. And that effect is much greater than the direct effects of temperature change. If the statement in the *Washington Post* editorial in 1998 that 10 percent of the U. S. population depends in whole or in part on Colorado River water, is close to correct, it is hard to over-estimate the water policy implications of global change in the Southwest. Engineers and hydrologists must become more directly involved in water policy issues. They must become more proactive and not leave the water policy issues to the non-technical water policy experts alone.

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