Global Warming in the Southwest: Impacts on Adaptive Management of the Colorado River Below Glen Canyon Dam

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ABSTRACT

Global warming is already documented and certain to continue. It will reduce precipitation and increase temperatures over the globe, but already-arid areas like the American Southwest will bear the most significant consequences. The Lower Colorado River Basin's population and industry depend almost solely on the assumption that 7.5 million acre-feet (maf) of water will flow through Glen Canyon Dam every year, but global warming will certainly reduce this amount in a relatively short time (50 to 100 years). Glen Canyon Dam has also had significant negative impacts on the biological and geological resources below it, and water is needed to restore these features. With cities, farms, animals and plants depending on ever-declining water from one river, tradeoffs will be made in the near future as global warming worsens. This paper first analyzes impacts of climate change on the dependents of the Colorado River below Glen Canyon Dam and then examines what recourse will be available in the future, given reduced runoff levels. Biological restoration below the dam is feasible, but methods will have to creatively use very little available water. Complete restoration is not possible, but saving a few well-selected species is a feasible goal. With reduced runoff inevitable, the only sustainable long-term options are policy change, agricultural reform and controlling growth in the Southwest.

INTRODUCTION

Climate warming in the next hundred years is certain given current trends and CO_2 emissions. The uncertainty is the magnitude of warming and how our fundamental resources, such as water, will be affected. This is crucial when river systems like the Colorado are already in a tenuous balance of supply and demand. Before problems with human water demand, the geology and ecosystems of the Colorado River once commanded all of the flow. Damming the river has forever changed the hydrology of the river system from a warm, muddy, highly variable stream to a cold, clear, flat-line flow (Patten et al 2001). Recent studies on the river system show that to restore even semi-"natural" states of flora, fauna and flow, high-magnitude, flashy floods must be allowed—these were seasonal and common in the basin's history. This is part of the Grand Canyon "Adaptive Management Program" (AMP), charged with rehabilitating pre-dam communities and processes by modifying dam operations. The AMP's erroneous assumption, however, is that sufficient water will be available to perform the adaptive management recommendations in the future. This paper draws together climate modeling, biology and politics of the Colorado River below Glen Canyon Dam to make predictions about long-term feasibility of current operations, and what changes could be made to improve sustainability of the system.

OVERVIEW OF CLIMATE CHANGE MODELING

General Circulation Models (GCMs) predict the magnitude of future climate warming by combining known weather patterns (from a historic observational period of several decades, such as 1961-1990) with human influences such as CO_2 emissions and deforestation. Adding the projected atmospheric warming to normal weather patterns produces an estimate of future climate (IPCC 2001). Atmospheric temperature change is modeled at the global level, then down-scaled to extrapolate impacts on regions as small as the Colorado River basin. Downscaling to regional impacts is done with coupled climate models, which couple models with smaller spatial resolution to large-scale GCMs of atmospheric temperature, giving estimates of regional attributes (Figure 1). For instance, variable infiltration capacity (VIC) (Liang et al 1994) of soils, with 1/8° (13km) resolution, and ocean-surface temperature, with 2/3° (70km) resolution (IPCC 2001) are coupled to a GCM with 2.8° (300km) resolution to estimate regional effects of climate warming. Downscaled predictions are tested against historical data to re-predict past events related to climate (e.g. fires, floods). The downscaled models are usually accurate: The VIC's model of the Green River's historic flows was accurate within 1-3 percent (Christensen et al 2004), while a future fire-risk model correctly predicted most major fires of the last 40 years (PNRS 2004). While regional models are increasing their accuracy as they include more variables, they are still less accurate than global models (Washington et al 2000). A coupled model will only be as accurate as the largest cell size in its component models—which could be as large as a 300 km square. However, all models predict significant warming.

The two most useful models for impacts of climate change on the Colorado Basin are the Parallel Climate Model (PCM; Department of Energy) and the Canadian Centre for Climate Modeling's General Circulation Model (CCC-GCM) because they are both downscaled to the southwest United States or the Colorado River basin, and both model into the next century (Washington et al 2000, Christensen et al 2004).

The PCM is driven by historical sea, atmosphere and land data from 1950 to 1999. It models four scenarios: control, assuming static 1995 CO2 levels; and "business as usual" (BAU) emissions rates for three time periods: 2010-2039, 2040-2069 and 2070-2098 (Washington et al 2000, Christensen et al 2004). Treating the next century as three separate periods allows natural climate periodicity like the Pacific Decadal Oscillation to show up in the model. The PCM predicts average annual temperatures to increase 1.7 degrees C in the next 50-60 years and 2.4 degrees C in the next 100 years (Christensen et al 2004).

The CCC-GCM predicts mean annual temperatures as well as July and January averages; this exposes the disproportionate winter temperature increases that most models predict (Washington et al 2000). Another difference between the two models used in this paper is that CCC-GCM uses double CO_2 as input while the PCM uses defined time intervals. It may take more or less than 100 years for CO_2 to double, so the CCC-GCM eliminates the assumption of constant emission rates by using double CO_2, while the PCM uses an assumed, constant rate.

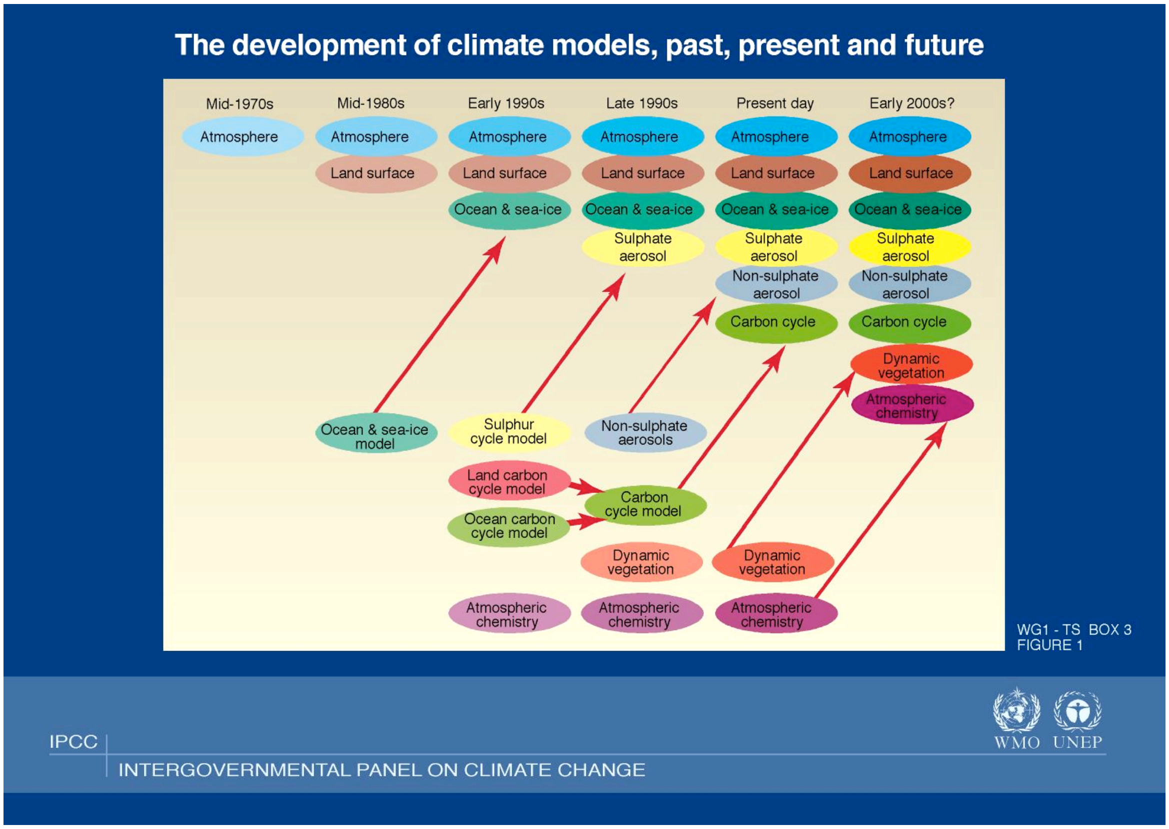


Figure 1. Coupled climate models illustrated.

CONSEQUENCES OF CLIMATE WARMING

Global

Models show that CO_2 concentrations alone will increase temperature at the poles at least four times more than in mid-latitudes (Washington 2000, Collier and Webb 2002). This will melt arctic ice, which will increase ocean surface temperatures. Oceans have the greatest influence on climate, so increased surface temperature further alters weather patterns after air temperatures are already increased by CO_2 (PNWRS 2004). High-temperature anomalies in the southeastern Pacific are associated with El Niño events, which control seasonal flood-drought cycles in the American West (Reynolds et al. 1997, Collier and Webb 2002). El Niño and La Niña (warm-phase and cool-phase) events are of similar spatial and temperature scale as are predicted changes in future climate. These anomalous events are, therefore, good models for conditions that may become normal under global warming (Reynolds et al 1997).

Southwestern U.S.

Downscaled models have predicted consequences for the southwestern U.S. much like a persistent La Nina. The Future Arctic Case model (FARC; Sewall and Sloan 2004) predicts that warmer sea-surface temperatures will lead to more extreme El Niños and La Niñas, significantly reduced winter precipitation and more intense, earlier spring precipitation (Sewall and Sloan 2002). The winter and spring of 1995-1996 was a good window into the possible future climate of the southwest. It was one of the driest periods on record, with less than 2" of precipitation and temperatures up to 6 degrees F higher than normal. Much of the southwest experienced "extreme drought conditions" (according to the Palmer Drought Index) (. These dry conditions were brought on by factors which are also predicted in future climate change: a strong La Nina and cool-phase North Atlantic Oscillation, which displaced winter storms to the north (NOAA, June 1996).

Researchers disagree on the amount and timing of precipitation. Overall, however, evaporation minus precipitation (E-P, a common measure of precipitation regime) over Western North America will increase by up to half (Sewall and Sloan 2004). Precipitation is difficult to model with certainty because it is not solely tied to temperature change—it is dependent on other variables such as ocean temperatures, which are in turn tied to temperature change. Evaporation rate, however, is physically tied to temperature and can be modeled more accurately. For every unit increased temperature, air's ability to hold water doubles. Combining best estimates of decreasing precipitation with more certain physical models of evaporation still has significant results: these two factors will most likely "have the net effect [of reducing] runoff from 8 to 20 percent" (Christensen et al 2004).

Increased temperatures will also shift pressure gradients that influence storms. The 500 millibar geopotential height influences the location of the jetstream, which steers storms across North America. Shifts in this cause shifts in storm tracks which, in turn, dictate the frequency of winter storms in any location (Sewall & Sloan 2004). Storms will move northward in western North America as temperatures increase. In the FARC model, shifting storms lead to an annual decrease in cumulative precipitation in the American West up to 30 percent (Sewall & Sloan 2004). Note that even though the Southwest is projected to experience more frequent and severe El Niños and La Niñas, if El Nino storms track more northward even “wet” years will be drier.

Colorado River Basin

The CCC-GCM predicts a 3 to 4 ºC increase in the Arizona-Colorado area in July and up to a 6 to 7 ºC increase in January (Mohseni et al 1999). This is a significant increase in temperature and is likely to have a major influence on the hydrologic cycle and associated ecosystems.

Model predictions consistently indicate that the timing of runoff is likely to shift within the Colorado Basin. Wolock & McCabe (1999) find that more precipitation will fall as rain than snow, which will cause earlier, faster snowmelt and more winter runoff, and decreased summer runoff. This should not be confused with precipitation changes; precipitation is simply what falls from the sky, while runoff is what reaches the river basin from snowmelt and upstream precipitation. Westmacott and Burn (1997) find that timing of hydrologic events—more than magnitude—is tied to temperature change. Higher temperatures will almost certainly cause earlier spring melt, regardless of precipitation magnitude.

The runoff that reaches the river basin will also be warmer due to two influences: runoff will be lower, meaning less water will have to be warmed per unit time, resulting in warmer temperatures. Air-water convective warming will also increase stream temperatures because air will simply be warmer in the next century. For the double-CO2 case, mean annual stream temperatures should increase 2 to 5 ºC. However, the impact of warming due to increases in air temperatures will be different depending on the time of year. During the summer, evaporative cooling of water reduces the impact of high air temperatures on water (Mohseni et al 1999). This is particularly significant when air temperatures rise above 20 C. In contrast, when air temperature is below 20 C, evaporation has less of an impact on cooling. Water temperature more directly reflects ambient air temperatures under these conditions. Thus overall warming is likely to have greater impact on water temperature in the Canyon during late fall through early spring, when air temperatures will continue to be low, albeit higher than under historic conditions. Mohseni's (1999) new projected annual average minimum for the Colorado River Basin is 12-14 °C, and the new projected maximum is 24-26 °C.

Biological Communities

Fish

With average stream temperatures increasing 2 to 5 °C, the fish assemblages able to live and reproduce in the canyon will change (Figure 2). Some fish will not feed or breed above a threshold temperature (Haden 1992; Mohseni et al 1999; Scheller et al 1999). Warmer water will clearly favor several natives including the Humpback Chub (*Gila cypha*). However, warm water will also likely encourage upstream colonization of warm-water nonnatives from Lake Mead and increases in already-established populations (Haden 1992). Assuming that other impediments to natives (daily fluctuating flows, little seasonal variation) do not change, nonnatives will continue to outcompete natives even with higher stream temperatures.

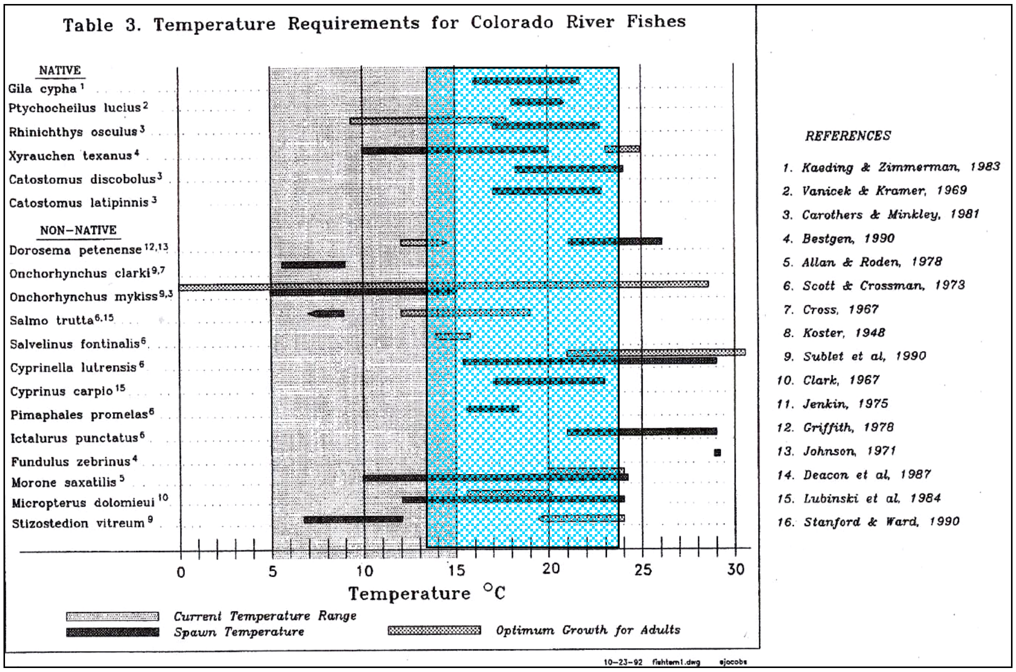


Figure 2. Temperature requirements for Colorado River fishes (Haden 1992). Blue overlay roughly shows Mohseni's (1999) projected new Colorado River

Basin temperature range with doubled CO_2. Stream temperatures are averaged over the Basin (Note that most tributaries are warmer than the mainstem).

Vertebrates

Generalizations can be made about how diversity of major taxa is likely to change with increased temperatures because diversity has been shown to be correlated with temperature on a global scale (Figure 3). However, the assemblages present in any given ecosystem are influenced by more than climate—the predictions here are generalizations that do not take into account microclimates (common in the Canyon), competition and habitat morphology.

Bird species richness is strongly correlated with temperature—diversity decreases with increased temperature (Currie 2001). Therefore, bird species richness in the Colorado Basin should decrease in the future. At least one species, the California condor (*Gymnoygyps californianus*), has recently left the Canyon due to climate change (Brown et al 1987). In the long run, the Canyon will become less hospitable even to arid-adapted species, driving bird richness down in general.

Mammal richness varies with temperature and precipitation similarly to bird richness, so mammal diversity is also expected to decrease (Currie 2001).

Reptiles and amphibians thrive as temperatures increase. Highest diversity of both groups occurs in areas with highest mean July temperatures. Reptile diversity is therefore expected to increase significantly as temperatures in the southwest rise (Currie 2001). Amphibians are dependent on water for reproduction, however, so amphibians will increase most in areas where precipitation will not decrease as air temperatures increase. This means amphibian diversity is more likely to increase in higher altitudes and latitudes than the Grand Canyon, where it will probably decrease as summer precipitation decreases.

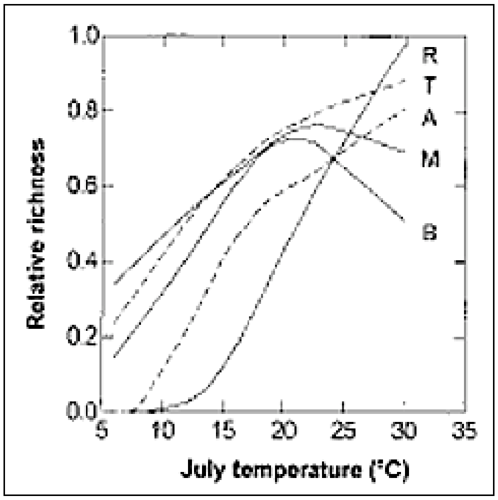


Figure 3. Richness of reptiles (R), trees (T), amphibians (A), mammals (M), and birds (B) related to mean July temperature (Currie 2001).

Vegetation

The Mapped Atmosphere-Plant-Soil System (MAPSS) uses climate, soils and existing vegetation to map “potential” vegetation (without considering human modification of landscape such as agriculture) (PNWRS 2004). The MAPSS predicts that the southwest will undergo significant vegetation changes with increased CO2 levels: in the next century, the now-arid southwest will be dominated by grasslands, woodlands and even some conifer forest.

Increased evapotranspiration rates will play a part in changing the Grand Canyon’s flora. As air temperature increases, its ability to hold water will increase twofold. This will not only speed up evaporation but also transpiration—plants will move water faster through their vessels and out into the air. The present Tamarisk (*Tamarix ramosissima)* problem shows what can happen when plants with high active transpiration rates invade. Due to Tamarisk’s high transpiration rate, it takes up water faster than other species and has higher salt concentrations in its tissues and surrounding soil. The high salinity is unpalatable to several herbivores (Purdy 2005) and the surrounding soils are too salty for native plants, such as Cottonwood (*Populus tremuloides*), to establish (King 2005). The result is, increasingly, monocultures of Tamarisk in the Canyon (Stevens et al 2001). Increased air temperatures will cause passive evapotranspiration rates to increase in all plants, which should further increase salinization of soils. All evidence points to the Canyon's becoming more hospitable to Tamarisk in the future.

Agriculture

The Colorado River supplies about 6.4 maf to 3 million acres of farmland in the Lower Basin (Kelly 2002). Increases in air temperature increase rates of evapotranspiration in crops, which more quickly depletes soil moisture and increases demand for irrigation water (Hanson 1997). Soil will require increasing amounts of water to keep up with the rate at which plants leach it out, and more of the Colorado will be diverted due to this principle of physics.

Reservoirs

Northward-shifting storms mean reduced precipitation caught in the Colorado River basin. The Colorado River basin depends on mountain precipitation for at least 70 percent of its annual flow (Christensen et al 2004). The PCM simulation shows a 3-6% reduction in precipitation in the basin itself (Christensen et al 2004). This reduced precipitation coupled with increased evaporation leads to a 14 – 18% decrease in runoff by the year 2098. Modest changes in stream flow result in much larger changes in reservoir storage because demand is now approximately equal to runoff. In the future, a much higher percentage of demand will have to be met with reservoir storage alone. Christensen et al (2004) show that a 10 – 20% reduction in runoff leads to a 30 – 60% decrease in storage. Storage will decrease more steadily, causing more frequent failures. For business-as-usual (BAU) emissions, Lake Powell and Lake Mead both are predicted to reach failure, or "inactive capacity" levels at least three times in the next century. For Christensen's three test periods between 2010 and 2098, average storage is 15-20%, equivalent to "dead pool" (below penstocks) for Lake Mead. This is significant given that Lakes Powell and Mead are now very low—34% and 57%, respectively (NOAA 2005).

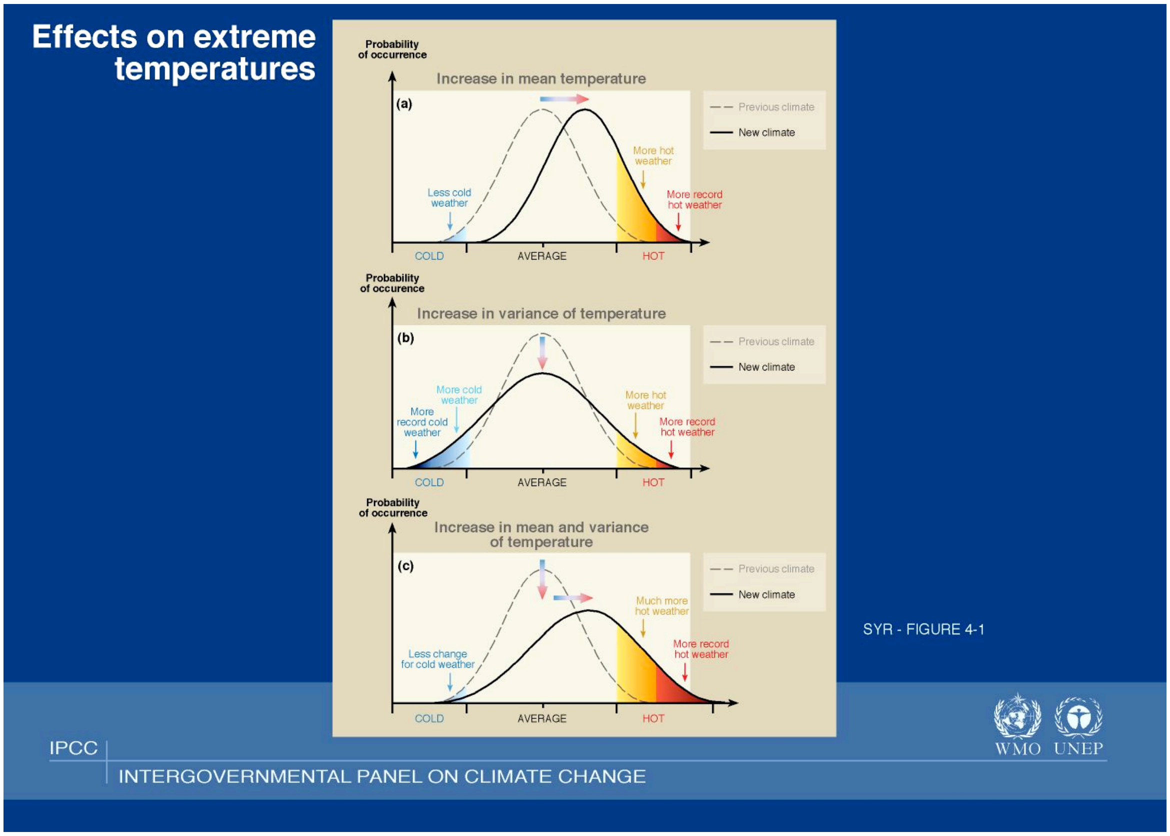
Increased evaporation will have a significant impact on reservoirs. Reservoirs like Lakes Mead and Powell with thousands of acres of exposed surface area will lose water at much higher rates in the next century. Currently, about 1.6 maf of water is lost to evaporation from Lake Powell, at a rate of 80 inches per year (Christensen et al 2004). With a 4 degree increase in temperature, this could cause a significant evaporative loss of 96-112 inches per year.

Caveats

Climate oscillates naturally

The predicted temperature increase under global warming is no larger than what Earth has experienced in the past. However, it has happened faster than past climate changes and tracks inline with rates of CO_2 emission—it is obviously anthropogenic (Collier 2002). In other words, it appears to be a permanent increase in global mean temperature rather than a normal oscillation. The Southwest will continue its normal cycle between wet and dry years, with the Southern Oscillation continuing to bring El Nino and La Nina events. In the future, though, global warming will exacerbate these natural oscillations (Cook et al. 2004).

The western United States has undergone severe, long-term droughts in the past. A relatively recent, significant drought from AD 900 to 1300 is implicated in the disappearance of the Anasazi from Canyon (Collier & Webb 2002, Cook et al. 2004). Droughts like this will happen again in the future, but global warming will increase their length and severity. The increased global temperature will serve as a new mean from which all future oscillations will deviate (Cook et al. 2004). While the Southwest will continue to have some wet and some dry years, high temperatures and droughts will become more frequent and more extreme because both mean temperature and variability are projected to increase (Figure 4; IPCC 2001).



Effects on extreme temperatures

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IPCC | INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

Figure 4. Effects of increased mean and increased variability on extreme temperatures. IPCC 2001.

Groundwater: a buffer to decreased runoff?

The southwest is not entirely dependent on runoff for its water supply. About 250,000 acre-feet are supplied by aquifers that feed into the Colorado and Gila rivers (Montgomery & Harshbarger 1992). However, groundwater is already overtapped. In Arizona alone, groundwater is overdrawn by 1.24 maf per year. This has caused severe surface subsidence in areas of the Southwest with the worst groundwater overdraw (Unruh 1997). Groundwater will certainly not provide a "buffer" for future runoff shortages.

EFFECTS OF CLIMATE CHANGE ON ADAPTIVE MANAGEMENT

Controlled floods are part of the Adaptive Management plan to restore biological and physical processes in the Grand Canyon (Pennisi 2004). Research shows that to mitigate many problems in the watershed—eroding sandbars, armoring of debris flows, invasive species—floods must be of very high magnitude for short periods rather than long, lower-magnitude floods (Webb et al 1999, Patten et al 2001). Long-duration, medium floods cannot accomplish the same reworking of debris flows or invasive species control, for instance, as a high-magnitude flash flood can (Webb et al 1999, Stevens et al 2001). While the 1996 and 2004 floods were large—above hydropower levels—they were still not as large or flashy as would be ideal. Scientists have difficulty convincing the Dam operators to release over-hydropower floods now, but it will be nearly physically impossible in the future: "Due to lower inflow volume and greater storage space available, the system is less likely to have uncontrolled spills (releases that do not generate hydropower) in the future" (Christensen et al 2004). Hydroelectric flows are 32,000 cfs. If hydroelectric flows will become near impossible—Christensen predicts only 2 to 7 percent of future years will allow it—the fairly-effective "trout perturbation" flows of 20,000 cfs will soon be impossible as well. The strongest flows possible by the end of the next century will be largely impotent for any serious habitat building or maintenance. The system will be solely dependent on precipitation in the basin, which may or may not be more common in the future—models can only say for certain that overall flow will be lower and earlier.

A novel suggestion for dam management, aimed at encouraging native plants and animals, is to have low-magnitude seasonal fluctuating flows rather than high-magnitude (Campos 2005). This would add the seasonal variability that some species need, without requiring unfeasible changes in dam flow. This will certainly be possible in the future because flow is projected to be much lower in late summer and higher in spring. The barrier to this method, of course, is human needs. Slowing flow to an extremely low level in summer would be feasible and beneficial to the ecosystem, but the Lower Basin has used its entire yearly 7.5 maf allotment since 1990. Slowing flow to the level required for restoration would probably not fulfill the Colorado River Compact's obligation to the Lower Basin. Therefore, policy changes would need to precede most changes in dam operation.

FULFILLING WATER COMPACTS

There will simply not be enough water to fulfill the Colorado Compact, Central Arizona Project or Metropolitan Water District agreements. In the future, reduced runoff coupled with increased evaporation, increased consumption and population growth will regularly stop deliveries short of the Compact, Central Arizona Project and Metropolitan Water District. In fact, Christensen et al (2004) show that the Compact will be violated in 30 to 40 percent of years in the next century, CAP will be violated 80 to 99 percent of the time, and the MWD will be violated in at least 50 percent of coming years. High rates of violation for CAP and the MWD are not surprising, however, given their purpose. They were both designed to use up "extra" Colorado River water that California and Arizona felt entitled to. Most of these models also hold demand constant, which is an obvious oversimplification given population growth rates in the Southwest (Chourre 1997). Population tends to grow to match available infrastructure. Why not keep building subdivisions if you "have" 7.5 million acre feet of water every year?

CONCLUSIONS

How can Colorado River management accommodate climate change?

The Colorado River is changed—it is a different river post-dam and must be managed as such. While adaptive management techniques such as controlled floods show promise for restoring some pre-dam features, many of these techniques will not be feasible in the coming century. Incoming water will be so significantly reduced that officials and agencies will soon have to choose between restoration and appeasing millions of people who are promised water from Glen Canyon Dam. The dam is a fact of the region—removing it is not an option logistically or diplomatically, given that it supplies a fundamental resource for entire cities and farms of the Southwest. The only available recourse is to reduce human water use through policy, agricultural and growth reform.

Biological restoration is an option, but restorers should not equate "historic" with "natural" restoration. Due to climate change and population growth, the amount of water flowing through the Colorado will never again be what it was historically. Given a chance, however, native communities will evolve around the changes in flow and temperature and reach a new "equilibrium", or natural state. If flow changes are too drastic and nonnatives continue to occupy natives' niches, however, natives will fail. Therefore, biological management should focus on controlling nonnatives. Focusing on conserving a few particular natives is feasible as well, but they should be chosen wisely based on endemism, rarity and existence of other viable populations. Policies can help by reducing the likelihood of a sudden disappearance of water—conservation and growth control can help ease the transition to inevitable lower flows from Glen Canyon Dam.

Water allowances are too high now to allow for decreased runoff in the future. The original Colorado River Compact was based on an unusually high flow, so even at present the river is almost fully allocated every year (Ingram et al. 1990). The only reason the system does not routinely fail is that the Upper Basin never uses their full allotment (Christensen et al. 2004). As of 1992, 9.3 maf of water from the Colorado was consumed by cities, agriculture and evaporation per year (Montgomery & Harshbarger 1992). With current flows averaging 12 maf, this leaves a 2.7 maf surplus to supply future growth. In light of evidence for decreased runoff and increased evaporation, however, a 2.7 maf surplus should be seen as a safety net for the existing users—not justification for more growth. Without reworking water laws, cities will grow to the capacity that water rights allow. When the Colorado's supply inevitably dwindles in the next century, a population made possible by 16 maf of promised water will have less than half that. With Level 1 or 2 shortages imposed almost every year beginning in the middle of the century (Christensen et al 2004), citizens and policymakers will have to face serious questions of water needs versus wants – sanitation versus lawns.

Agriculture, which consumes 85 percent of the Lower Basin's water allotment, is wasteful of water because farmers grow non-water-efficient crops in extremely arid climates like Arizona, Nevada and California's Imperial Valley (Kelly 2002). In the future, increased evapotranspiration will cause already poorly-adapted crops like alfalfa to use more water less efficiently, further decreasing available water for cities or, much less, habitat restoration. Increased air temperatures will also evaporate much of the sprinkler irrigation water before it hits the ground. Marc Reisner writes in Cadillac Desert (1993) that "...whether irrigation on the southern plains ends in...seven, or even in fifty years does not matter; the fact is, it will mostly end." Conservation is possible, however, and effective. Morrison et al. (1996) show that several basic changes in

Southwest agriculture can result in significant water savings. They calculate that fallowing unproductive fields, converting inefficient, low-value crops like alfalfa to high-value ones such as citrus, and installing drip irrigation, the Lower Basin could save about 1.2 maf per year. This would account for all most its current groundwater overdraw.

Another recent piece of encouraging evidence is offered in Gleick's December 2004 article: in California, water consumption is not unbridled and constantly increasing with population. As California's GDP has increased to 275% of its 1975 level, water consumption has stayed almost static (Gleick 2004). Conservation is not a lost cause; it must be spread outside of California to states like Arizona that are simultaneously the biggest Colorado River consumers and the most likely to experience growth in the next century (Chourre 1997).

Simple changes in public policy could cause significant improvements in Southwest water use in all sectors. As well as changing agriculture, mandating environmentally-sound landscaping and efficient appliances would save water in the consumer sector. Conservation policies like these have already met with success in Las Vegas, saving 30 percent in one year after policies were changed (Ackerman 2004). Being humans themselves, policymakers and Glen Canyon Dam operators would be more likely to allocate water for ecological restoration if all human needs—that is, legitimate ones—are met first.

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