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Desertification of the American Southwest

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Desertification of the American Southwest:
An analysis of Population, Climate, and Water Management.

The Interactive Qualifying Project Report
Submitted to the faculty
Of the
Worcester Polytechnic Institute
In partial fulfillment of the requirement for the
Interactive Qualifying Project

By Kyle Forward, Ryan Blair and Nick Souviney
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Advised by Professor Theodore C. Crusberg
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Abstract

This report investigates current conditions and trends in the American Southwest that are contributing to an increasingly dire situation in the Colorado River Basin. The effects of climate change, global warming, population growth, and increased demand for water have created a need for regional management of water resources and the scarcity of current water and future predictions.
Introduction

Global warming is getting worldwide recognition as a problem that is already affecting the environment we live in. This problem is of a huge concern to the Colorado River Basin. The Colorado River Basin, as seen in Figure 1, encompasses climate zones ranging from alpine to arid desert. Precipitation in this area of the United States is already scarce and increasing temperatures due to global warming are causing changes in the hydrological cycle of the Colorado River. These changes are presenting interesting problems for water managers who are trying to figure out a solution to decreasing water supply in the region. Higher temperatures cause fluctuations in the timing of the hydrological cycle as well as increases in evapotranspiration. Both of these things result in a smaller water supply for an area that is experiencing astronomical population growth.

Jobs across the northern United States have been migrating out of the country in search of cheaper labor for several decades. The combination of jobs leaving the north and the appearance of technological jobs in the southwest has created an exponential growth in the region. The region houses some of the densest cities in the country and lays claim to some of the highest per capita water use in the country (Chourre, 1997). The extreme heats and dry conditions in the southwest cause the per capita water use to be abnormally high. The region currently has been able to reduce its water use, per capita, to twice that of the national average. Utah, alone, has been in the top 5 states for daily per capita water use over the past two decades, reaching an astounding 575 gallons per day per person (USGS, United States Geological Service). In order to prevent the region from running out of water some restrictions must be put in place.
Water rights and water management has become a recent focus in the American Southwest due to the increasing problems with drought, salinity, population, temperature, and demand. This myriad of factors has put a strain on current water resources and many organizations and bureaus have come together to determine a proper course of action to both mitigate and rectify these causes. The increased demand by the agricultural sector has led to increased runoff into rivers, skyrocketing prices for water purification and the reduction of salinity for downstream consumption (Water Use Trends in the Southwestern United States 1950-1990). Earlier snowmelts have caused earlier center-of-volume dates, affecting snowmelts and available water during the warm months. The allocation of water rights and management between the states and federal governments
has become a focus once again as demand in the Lower Basin has begun to exceed its allocated volume and it has become necessary to use excess Upper Basin resources. These complementing problems have created a large strain on resources in the area and future predictions are dire for the region if no measures are implemented. The combined effects of climate change, population increase, and increasingly variable water availability have created a need for evaluation and action on the current situation of the American Southwest.
Population Growth

There are a few geographical principles that need to be considered when analysing the total population and the population density of an area. The size of a county has a large impact in determining the population density, while it has little effect on the actual population. A telling example is to compare Clark County NM and Bernalillo County NM through the 1980s. Las Vegas and Albuquerque are to be found in these counties, respectively. Even though Las Vegas is much larger than Albuquerque in total population, Bernalillo County has a greater population density since the actual geographical size is smaller than that of Clark County. The county of San Francisco is example of a county with a total area of 46 square miles but with a high population, 723,959 people in 1993 giving it a density of 15,660.85 people per square mile.

Population and population density maps by county tend not to give a whole lot of information. Los Angeles, CA metropolitan area makes up the vast majority of the total population of the San Bernardino County and is very densely populated. As seen later in Fig. 1, a density map of a region by county would show San Bernardino as a very low density county since its total area is 20,339.4 square miles. Although the density has remained “low” since 1900, when it was 1.37 people per square mile, it has grown exponentially to recently reach 69.74 people per square mile in 1993. To prevent having counties be misrepresented, some new borders have been drawn to better show divisions of the land so that the government can track how each section of land is used and can be improved. (Chourre, 1997)

In 1900 Arapahoe County, in Colorado, had a high population of 153,017 people. Taking a better look at the density within the county showed that the majority of
Arapahoe County’s citizens lived in a small area surrounding Denver. Denver County, Colorado has been listed as having an above average population density since the early 1900s despite never being listed as having an above average population by the United States Census Bureau. In an attempt to attract more people to the region and level off the population density growth of the region, Denver County officials began to annex surrounding towns in an increasing manner. From 1920 to 1930 the size of Denver County expanded from 60.8 square miles to 61.1 square miles and from 70.7 square miles to 97.2 square miles from the 1950s to the 1960s. (Chourre, 1997) The acquisition of 27 square miles during the 1950s finally achieved the goal of slowing, and even decreasing the population density of Denver County through annexation. Post 1970 the local population began to move to the suburbs outside of Denver County, in what appeared to be an attempt to distance themselves from the increasing tourist population.
Population changes have a multitude of causes. The northeast was once known for its paper industries. There were paper mills on nearly every major river in New England. As jobs migrate out of the north east, so do the taxes the companies used to pay to their city and state. The loss of tax money deeply impacts the educational system and local infrastructure. As jobs in the northern United States began to dissipate and educational systems decreased in effectiveness, technological jobs started to appear across the southwestern United States.
The exponential population growth of southern California, demonstrated in Fig 3, is alarming when coupled with the abnormally high water consumption per capita in the southwest.
Per Capita Water Use

High per capita water use is not only a problem for the areas realizing population decreases; it also impacts the areas with population booms. Natural resources are in a limited supply and can only be stretched so far. The major issue in the southwest, currently, is population growth that will put the region far beyond the bounds of the limit to the amount of water in the area. Not only is the population increasing but amount of water used per capita there far exceeds that of the rest of the United States. Fig. 4 shows the US average water use per capita has remained fairly consistent from 1970 to 1990, approximately 190 gallons per day (Marella, 1995). Over that 20 year period one state that has remained ranked in the top five highest states in per capita water consumption, decreasing from 473 gallons to 344, is Utah. In 1980 the water consumption in Utah sky rocketed to 575 gallons per day per capita. (Marella, 1995)

![Figure 4 - Trends of Per Capita Water Use in the United States (Marella, 1995)](http://www.pepps.fsu.edu/safe/pdf/sc1.pdf)
Henderson, Las Vegas and North Las Vegas, Nevada all draw water from Lake Mead (Fig 5).

![Map of Las Vegas, NV, 2008](image)

Figure 5- A map of the area surrounding Lake Mead (Map of Las Vegas, NV, 2008)

The University of Nebraska-Lincoln compiled data from these three major cities to determine exactly how all the water was being used daily as presented in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Irrigation: 47%</th>
<th>Water Waste: 23%</th>
<th>Toilet: 8%</th>
<th>Laundry: 6%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other Indoor Use: 6%</td>
<td>Faucet: 5%</td>
<td>Shower: 5%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1-The Daily Water Use Distribution of Water from Lake Mead in Henderson, Las Vegas and North Las Vegas. (Nebraska-Lincoln)

The drought and increasing population is driving the levels of Lake Mead very low. The depth decreased 70 feet in 3 years from 1998 to 2003, from 1210 feet to 1140 feet respectively. (Nebraska-Lincoln) The heat and dry weather in the southwest is cause for an increase of the per capita water consumption used for irrigation (Fig. 6), but there are many other factors to consider. Something must be done to reduce the amount of water being consumed per capita before the resource is severely depleted.
Influences in Water Demand

Of all the causes listed in Fig. 7 that affect the demand of water, there are only a few sections of the chart that can be controlled. The demographic of a region can not be controlled by the government. All the government can do creating sections of a town that
are solely for commerce or industrial buildings, while other parts of town are devoted to residential or farm land. These restrictions can impact a town that is supplied water from an underground pocket but the restrictions will not change the amount of water taken out of the Colorado River each year.

The economics of a region cannot be directly controlled. States like Florida will see a huge rise in per capita (based on permanent population) consumption during tourist season. The economics of water, can however, be controlled through demand pricing. Raising the price per gallon of water during a tourist season would cause people to be more cautious about how it is put to use. Increasing the price of water to a large enough degree may drive people to buy appliances that use less water, such as washing machines and dishwashers. This will also make people more aware of turning off a sink while brushing their teeth or taking quicker showers.

The average family may not have the largest impact on the water supply but the changing economics on the value of water will have the largest impact on the family. Not only will the price of their running water increase but so will the price of all their purchased crops and goods. For farmers to continue making a profit selling their goods they must increase the price of their product as the price of the water they are using to irrigate with goes up. The same holds true for any industry that uses water to either create or transfer heat to their final product. Paper mills owned by Huhtamaki Packing Company, for example, use vacuum dyes to draw paper out of a mixture of paper pulp and water before placing the paper filled dye against a source of heat to mold paper plates. The tanks of pulp are continually filled automatically as the level drains. Without active leak detection and repair thousands of gallons of water could be wasted daily from a single broken machine without anybody knowing. A union worker is much less likely to
notice a leak of this nature and react to it than a farmer. A union worker has job security based on the number of days spent doing a particular job while the farmer requires all of his crops to make it to market to make his living. A broken irrigation machine would mean thousands of dead crops and many wasted hours of planting. Restrictions placed on industries and farms would yield greater amounts of water being saved as apposed to restrictions on residential housing.

Educating the public about the lack of water may linger in a few peoples heads but tends to be forgotten by the greater public. In 1990 the Australian Water Utilities promoted a propaganda piece declaring the amount of water that could be saved by changing to newer, more efficient appliances. The propaganda had predictions of the current water consumption verses the water consumption of the new technology along with the estimated number of households that would have the new technology installed by the year 2034. An actual review of Australia’s utilities from the year 1990 to 2003 showed no reduction in the demand of water (Beatty, 2003). The reduction in household sizes and the increasing population densities have caused the amount of water consumed to increase. Australian water utilities even tried propaganda concerning appliances in order to lower water use (Fig. 8).
There is no way to control rainfall, temperature, evaporation or climate changes. There are however ways to help prevent drastic changes in the climate, though global warming. Hower temperatures mean more evaporation, less rainfall and, in turn, more of a drought.
Climate: Effects on the Hydrology of the Colorado River Basin

Climate

The Colorado River has a drainage base that covers over 244,000 square miles and travels through Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming while having a length of over 1,440 miles. Because of its size the Colorado River Basin contains climate zones ranging from alpine to desert and exhibits significant climate variability throughout the basin. This variability is influenced by both the latitudinal location and the topographical position of the land. Precipitation increases with elevation, while temperature decreases with elevation and latitude (Wagner & Baron, 1998). These variations have important implications for the hydrology of the Colorado River Basin. Very little precipitation is experienced in the desert climate zones while a lot of precipitation, particularly in the winter, is experienced in the alpine regions. This alpine precipitation is the main source of water for the Colorado River as 40% of the precipitation in the basin falls in the highest 20% of basin. Research on the Colorado River Basin’s climate and hydrologic systems has included long-term studies of climate and river hydrology as well as reviews of statistics associated with temperature and precipitation extremes (Smerdon, 2007).

Another important factor in the climate variability in the Colorado River Basin is the El Niño Southern Oscillation (ENSO) phenomenon. This phenomenon is created through the varying relationship of sea surface temperature and pressure over the tropical Pacific Ocean. (Lewis Jr, 2003) The warm phase of ENSO, known as El Niño or negative Southern Oscillation, typically brings wet and cool winters to the Southwest. The opposite cool phase of ENSO, La Niña or positive Southern Oscillation, has been reliably
associated with dry and warm winters (MacDonald, Rian, & Hidalgo, 2005). During the
El Niño phase of the ENSO precipitation levels are typically anomalously high while
during the cold ENSO events known as La Niña precipitation in the region is generally
anomalously low. In both the winter and the spring the likelihood of high precipitation is
significantly greater than normal in El Niño years, while the risk of substantial dry
conditions is significantly increased during La Niña years (Lewis Jr, 2003). The
temperature changes associated with these climatic fluctuations can be seen below in Fig.
9. This graph is known as the Southern Oscillation Index and is a measurement based on
the pressure difference measured at Darwin and at Tahiti. When there is a positive
number, we have a La-Niña (ocean cooling), but when the number is negative we have an
El-Niño (ocean warming) (Daly, 2008).

![Southern Oscillation Index](image)

**Figure 9 - Southern Oscillation Index**  (Daly, 2008)

The El-Niño Southern Oscillation is the result of a cyclic warming and cooling of
the surface ocean of the central and eastern Pacific that are carried by the strong trade
winds (Daly, 2008). The ENSO cycle occurs irregularly at intervals of 2-7 years and is an
important contributor to the inter-annual climate variation found in the Colorado River
Basin. Its pattern is marked by variations in stream flow, particularly in extreme high and low stream flow (Smerdon, 2007)

Recently, changes in the climate of the region have began to dramatically affect the hydrological processes of the basin such as precipitation, snowpack accumulation and its subsequent melting, evapotranspiration, annual runoff, stream flow timing, and the recharge of subsurface aquifers (Smerdon, 2007). These climatic changes are the result of changing atmospheric conditions that are directly linked to increasing greenhouse gas emissions and a steadily increasing global mean surface temperature. These changes are resulting in less and less available water for human consumption and use as well as unpredictability in seasonal stream flow and changes in the ESNO cycle (Smerdon, 2007). Although the region is used to annual variability in its climate, increases in temperature in the region have lead to conflicts with water storage, water re-use, and have resulted in a drought that is currently taking place in the Southwestern United States. The magnitude of this drought can be seen below in Fig. 10 (U.S. Drought Monitor, 2008). Another indication of the severity of this drought can be seen in the water levels of Lake Mead from 1935 to present (Fig. 11) As we can see since 2000 that water level at Lake Mead has dropped over 100 feet in elevation due to increases in temperature which have resulted in more evaporation and less precipitation storage (Hoerling & Eischeid, 2006).
Figure 10 - U. S. Drought Monitor  
(http://www.drought.unl.edu/DM/DM_West.htm)

Figure 11 - Water Levels of Lake Mead: 1935 – Present  
(Hoerling & Eischeid, 2006)
Temperature Change

The global average surface temperature has increased over the 20th century by about 0.6°C (1.0°F), and is projected to rise by an additional 1.4 to 5.8°C (2.5 to 10.4°F) over the 21st century (Potential Effects of Climate Change on New Mexico, 2005). This can be seen below in Fig. 12. Eight of the ten warmest years since 1880 have occurred in the last decade, and the years of 2002, 2003 and 2004 were the second, third and fourth warmest years on record (Center, 2005).

![Global Average Surface Temperature](image)

The greatest human contribution to the greenhouse effect, which is resulting in an increase in the global mean surface temperature, has been by the burning of carbon based fuels such as coal, oil and natural gas. These changes in the global temperature are changing global and regional climates because heat in the atmosphere drives the climate
system. These changes are of extreme relevance to the Colorado River Basin hydrology because of the basins diversity of climate zones as well as its connection to the ESNO cycle. As temperatures are increasing the result is fluctuations in the ESNO cycle which in turn results in drastic changes in precipitation. These fluctuations come in the area of differing weather and precipitation patterns as well as changes in the annual stream flow (Potential Effects of Climate Change on New Mexico, 2005). The global temperature increase has affected the Colorado River Basin more so than any other area in the United States. The change in annual mean temperature for the Basin can be seen in Fig. 13.

![Figure 13 - Annual Mean Temperature for the Colorado River Basin from 1895 – 2000](image)

The red-line in Fig. 13 represents the annual values for temperature while the blue-line represents the 11-year running mean. It is important to note how much the temperature has increased during the recent drought as compared with the historical data. Both in terms of absolute degrees and in terms of annual standard deviation, the Colorado
River basin has warmed more than any region of the United States (Smerdon, 2007). This information is also depicted in Fig. 14 below.

![Figure 14 - 2000 to 2005 Temperature Departures from 1895 - 2000 Averages](http://www.colorado.edu/resources/Hoerling%20v2%20WWA%20Front%20Range%20Water.pdf)

When considering Fig. 14 it is important to note that the area of the Colorado Basin is the warmest area of the United States. Not only that, but the temperature in the region is increasing much faster than in any other area of the country. This is alarming because not only is the temperature in the arid desert climates increasing but also the temperature in the alpine regions is also increasing dramatically! These increases have affected the precipitation patterns in the Colorado River Basin that provide the water essential to the life of the Colorado River.

**Precipitation**

Precipitation in the Colorado River Basin arrives mainly from two sources. The first major source is the southward shift of the sub-polar storm track in winter to and below the U.S.-Canadian border. This shift produces the predominantly winter
precipitation of the region which falls in declining amounts from north to south. As it moves back across the international border it produces the predominantly dry summer season which is characterized by its lack of precipitation. The second major source of precipitation is the Southwestern American Monsoon which provides the southern part of the Colorado River Basin with small amounts of moisture during the summer months (Wagner & Baron, 1998). Fig. 15 shows the yearly average rainfall at Lees Ferry Arizona which is in the Colorado River Basin. These data show that precipitation levels at Lees Ferry have been extremely low since 2000 but are slowly increasing as the graph approaches the present date.

Figure 15 - Yearly Average Rainfall at Lees Ferry (Hoerling & Eischeid, 2006)

The Colorado River is primarily a snowmelt-driven system, with most precipitation in the basin falling as winter snowfall in higher elevations of Colorado, Utah, and Wyoming. This snowfall is the result of synoptic-scale storms that have the greatest precipitation in regions of upslope airflow (Lewis Jr, 2003). The snowfall that accumulates in regions of high elevation is referred to as “snowpack” and is the main

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source of water flow for the Colorado River during the months of May, June and July as the temperature in the region increases. This temperature increase results in great amounts of melt water that enter the soil, ultimately ending up in the Colorado River system. The amount of water contained in this snowpack is extremely large and plays an important role in generating runoff and stream flow (McCabe & Hay, 1995).

The effects of warming can be seen in terms of the change in precipitation in the region with particular interest to snowpack. As warming occurs rain would occur at higher elevations than usually seen in the mountain areas where snow would generally fall. The altitude of the snowline position will recede up the mountain leaving more vegetation exposed which will ultimately consume more water. This shift in precipitation based on the increase in temperature would have a few consequences. First, less snow will accumulate during winter months, which in turn, means that there will be less overall snowpack to contribute to the stream flow of the Colorado River. The timing of the spring snowmelt would also change, annually occurring earlier than historical data would predict which will lead to lower than average stream flows during the months of May, June and July. The effects of which are increased likelihood of drought during the summer months and potential flooding during the start of spring. Second, this change in temperature will lead to a shift in the peak seasonal runoff, which is driven by the snowmelt, to earlier in the year. (Smerdon, 2007) The shift in precipitation could also increase erosion rates which would result in more brackish water during times of low flow rate. (Wagner & Baron, 1998).

The summer precipitation is much different from winter precipitation. Summer precipitation is usually seen in the form of localized thunder storms and almost all the
summer precipitation is intercepted by vegetation or evaporates directly into the atmosphere. The rest of the precipitation infiltrates into the soil column and is either transpired by plants or just evaporates. The main source of summer moisture is the North American monsoon, which transports moisture into the region from sources in the subtropical Pacific and Gulf of Mexico. A relatively small percent of summer precipitation makes its way into aquifers and streams of the Colorado River and because of that summer precipitation has little effect on the overall flow of the river (Smerdon, 2007).

Increasing temperatures have lead to longer and hotter warm seasons. The result of this is longer periods of low flow and lower minimum flows in the late summer months. The longer and hotter warm season will also lead to shortages for water supply systems due to increased evaporation and larger reservoirs may suffer seasonal shortages from a reduction in average runoff. There will be less aquifer recharge and lower summer stream flows will strain aquatic communities. These lower stream flows will result in higher concentrations of downstream pollutants as well as more sediment in the water (Smerdon, 2007).

Another effect of warming conditions will be a reduction in the available water as a result of increased evapotranspiration during summer months. Evapotranspiration is defined as “the water lost to the atmosphere from the ground surface, evaporation from the capillary fringe of the groundwater table, and the transpiration of groundwater by plants whose roots tap the capillary fringe of the groundwater table” (USGS). The transpiration aspect of evapotranspiration is essentially evaporation of water from plant leaves. As temperature increases more water is lost from the soil and plant life through evapotranspiration. It will reach a point where
evapotranspiration will exceed the percolation of water into the soil. Once this occurs there will be significant strain on the underground aquifers that will no longer be replenished.

In the winter months from October to April temperatures are generally right at or below the freezing point. Potential evapotranspiration (PET) during this time is exceeded by precipitation which produces a surplus of water in the soil. During the summer months PET exceeds precipitation. During the winter months precipitation exceeds PET. The surplus of precipitation in excess of PET that occurs during the winter months is stored as snowpack (McCabe & Hay, 1995). As temperatures increase, the predicted result is a change in the PET which can be seen in Fig. 16 below. As we can see the most dramatic changes to the PET will occur in the Southwestern United States which contains the Colorado River. As more and more evapotranspiration occurs in the area the effects will be synergetic with snowfall accumulation and precipitation. Snowpack’s will be continually reduced resulting in lower summer time stream flows.
Overall, the effects of the changes in temperature and climate in the Colorado River Basin will be great. Municipalities will have a longer demand season for water and a shorter supply season from which to replenish their supplies. Dryer summers will lead to greater water demand coupled with lower water quality which is a huge issue for the Colorado River Basin Region. Warming and greater summer precipitation will affect erosion, flooring potential and reservoir capacity. A warmer atmosphere will increase the risk of flooding, the probability and frequency of wildfire, and will also result in more frequent storms. These floods and storms will have increased intensity. The most important aspect in figuring out how the Great Basin will respond to global warming will depend most importantly on how the ENSO patterns will be affected (Lewis Jr, 2003).
Freezing will occur at higher elevations and more precipitation in the region will fall as rain rather than snow. This will result in less snow accumulation and as the snowpack’s melt earlier they will result in an earlier peak flow for the Colorado River. This aspect alone will greatly affect the water rights of the area and the planning of water storage. There will be more runoff and flood peaks during the winter months and lower water availability during the late-summer months. The growing seasons will be longer which will also result in a decrease in available water in the region due to increased water demands by plants. The future picture for available water in the Colorado River Basin does not look good. In an area that already suffers from a lack of useable water, the effects of increasing temperature and changes in climate are only worsening the problem.

(McCabe & Hay, 1995)
Water Resources and Management  
Management of the Colorado River’s Resources

Geography of the River

The Colorado River falls over 12,000 feet as it travels from the Rocky Mountains, in Colorado and Wyoming, to its outlet in the Gulf of California. The river, with a drainage base that covers over 244,000 square miles, travels through Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming while traveling over 1,440 miles (Anderson, 2002). While the river may exceed 17.5 million acre-feet (MAF) of flow a year, the Colorado River ranks only sixth in the United States for annual flow (Anderson, 2002). Providing more than 60 MAF of capacity (1 acre foot is equivalent to roughly 326,000 gallons), the river provides water for more than 31 million people including major metropolitan areas such as Las Vegas, Los Angeles, San Diego, and Denver. The Colorado River Basin extends from the North in Wyoming down through Lee’s Ferry, the dividing point of the Upper and Lower Basins, Arizona and continues through the American southwest to California’s southern tip, and at one time emptied into the Gulf of California. The Upper and Lower Basins comprise over 246,000 square miles of land supplying over 4 million acres of irrigated land and servicing 31 million people with water. (Anderson, 2002)

Storage on the river is authorized by the Colorado River Storage Project which enables the development of water resources of the Upper Basin states to meet the entitlements of the Lower Basin. Six dams make up the CRSP storage units which include the Blue Mesa, Crystal, Morrow Point, Flaming Gorge, Navajo, and Glen Canyon
The full capacity of the dams exceeds 30.6 MAF which is accommodated near entirely by the Glen Canyon Dam and Lake Powell. At full capacity Lake Powell can hold 26.3 MAF. (Glen Canyon Dam Adaptive Management Program Home Page, 2008)

**History of the River: The Development of River Management**

Since the late 1800s the river has provided water to the California Imperial valley. Californian construction of an All-American Canal that would divert water to the Imperial Valley from the Colorado River was proposed in the early 1900s. This canal, which was proposed to develop hydroelectric power to the growing Los Angeles population, faced adversity upon proposal. By constructing the canal, California would require the government’s assistance which raised issues regarding the six other basin states and the control of water use from the river. The solution to this problem appeared as the Colorado River Compact of 1922, an agreement between state and federal negotiators that split the river system into an Upper Basin and Lower Basin and would partition the water rights between the basins. Lee’s Ferry was the decided measuring point where the Upper Basin and Lower Basin were divided. The basins were each proportioned 7.5 MAF of water annually from the river with an option for an additional MAF for the Lower Basin (Anderson, 2002). While the negotiators were able to appropriate water usage to the Upper and Lower Basins, they were unsuccessful in attempts to divide the water rights between individual states as originally intended. While an original agreement was met, it was not until the ratification of the Boulder Canyon Project Act of 1928 that the agreement was law after six states agreed to the terms and a further 16 years until Arizona, the final state, would ratify the agreement.
The Colorado River Compact was only the first step in a long history of negotiations that have served to create a “Law of the River”.

The Law of the River has been amended by numerous negotiations including the following:

- Boulder Canyon Project Act of 1928
- Mexican Treat of 1944
- Upper Colorado River Basin Compact of 1948
- Colorado River Storage Project Act of 1956
- 1963 U.S. Supreme Court decision, Arizona v. California
- Colorado River Basin Project Act of 1968
- 1970 Criteria for Coordinated Long-Range Operations of Colorado River Reservoirs
- Minute 242 of the 1973 International Boundary and Water Commission
- Colorado River Basin Salinity Control Act of 1974
- Grand Canyon Protection Act of 1992
- 2001 Colorado River Interim Surplus Guidelines.

This extensive list contains numerous revisions to state allocations of water rights as well as negotiations with Mexican and Native American representative to resolve disputed issues. Of note is the Upper Colorado River Basin Compact of 1948 which apportioned the water rights between the states as follows: Colorado – 51.75%, New Mexico – 11.25%, Utah – 23.00%, Wyoming – 14%, Arizona – 50,000 acre-feet (Anderson, 2002).
Management of the River

The Colorado River System is the principal water resource for the American Southwest. Traveling over 1,440 miles and encompassing over 244,000 square miles, the river travels through seven states (Anderson, 2002). Throughout the century long regulation of the river, conflict between opposing interest groups has slowed the process of regulating and managing the river. While at times, it was unnecessary for exacting laws to be in place, recent times have brought upon record consumption of water and a devastating drought that is predicted to last over a decade. The historic current drought has strained reservoir elevations during the past eight years, and brought about the first modern long-term drought of the Colorado River. Information regarding droughts in the past one hundred years have been investigated, concluding that major adjustments to the two largest trends in the west, urban population growth and climate warming, need to be implemented. Water gauging stations have long been used to understand the Colorado River’s flow and variability, however, data for this only began to be collected in the 1890s (Dettinger, 2005). Further data can be obtained using proxy data, that is, through such measuring methods as tree-ring data, which can be used to interpret available moisture by relating the thickness of annual rings to assumed conditions. Historically, the allocation and development of water has rested with the authority of the states, subject to federal discretion. While private use is held under the riparian idea that each landowner is entitled to “reasonable use” of the river’s “natural flow”, the states are responsible for the acquisition of water rights with a system of laws developed by the Supreme Court and the federal government mandating the use in any state-federal conflicts.
Definitions for the normal, surplus, and shortage conditions for the amount of mainstream water (greater than, less than or, equal to) 7.5 MAF, of annual consumption for the Lower Division states were decided. Alternatives were crafted in the case of extended droughts that would allow comparison to normal conditions and the need for action. Guidelines for implementation for Lake Powell and Lake Mead were drawn to determine quantitatively when and how water would be released during years of high water elevation and low water elevation (Kempthorne, 2007). California has long been using over its 4.4 MAF allotment of water and must curtail its consumption as other states grow in size and need (Muys, 2003).

The mean value of flow determined in the Colorado River Basin Compact assumed a flow of 15 MAF per year, a value that has become a supposed mean value for the river over long periods of time. Increased climate warming is having a greater effect on the water management of the river as higher temperatures are causing less precipitation to be stored as snow, increased evaporation during the warm season, and shifting snowmelts to earlier in the year. Population data have seen Arizona’s population increase by 40 percent, while Colorado’s population has boomed by 30 percent (Smerdon, 2007). These population booms are driving increased water demands even with reduced per capita use. Nevada, as well, has doubled its population in the past fifteen years, contributing to the increased water demands and inevitable increased costs. While increased urban consumption has been stymied by agricultural water agreements the amount of water available for municipal, industrial, and agricultural water demands is finite. Several methods to conserve water have been developed including desalination, water reuse, conservation, and storage. While technological developments may assist in coping with water shortfalls, the demand continues to rise and a better solution to water
demands must be developed. Enhanced interstate cooperation and collaboration for drought preparedness is necessary if the increasingly large states are to manage the finite amount of water each year (Smerdon, 2007).

Up to seventy-five percent of water supplied in the western United States is derived from snowmelt (Dettinger, 2005). This places a large amount of responsibility of water management on the knowledge of snowmelt runoff into reservoirs and lowlands during the beginning of the warm season. During the winter season the need for water is much lower and the probability of flooding is a greater threat than water resource management, however, during the warm season the water demands for irrigation and municipal use are greatest. Diminished snowpack and earlier snowmelt is now occurring in the western states and is resulting in altered precipitation and stream flow timing. Water-resource and flood-management systems in western states are based upon a set timetable of consumption and production and the current changes are causing a shift which disrupts the assumed timetable. Stream flow timing is of great concern due to the fraction of total flow that occurs by a “spring-pulse date” where a rapid transition occurs from low-flow winter conditions to high-flow warm season conditions. Several decades of increasingly earlier stream flow has created a cause for concern as the water flow from April-July is becoming increasingly reduced, creating less available water resources for the most demanding months. Although it is not a part of the Colorado Basin, comparing the average daily discharge in the Clark Fork Yellowstone River during the 1950s with the 1990s, of note is how the average flows are similar, however the 1990s average center-of-volume date occurred four days prior to the 1950s peak (Fig. 17). This result is mild compared to reports in numerous western streams where center-of-volume runoff is occurring one to three weeks prior to mid 20th century dates as seen in Fig. 18 (Dettinger,
These early runoff dates can be seen in the Sierra Nevada of California, the Rocky Mountains, and parts of southern Alaska. These effects are most attributed to winter and spring warming trends and effects of greenhouse gases on the climate of the southwest. If the trends can be properly attributed to man-made causes then mountainous regions will face increasingly drought-like characteristics and water-resource management and flood risk will change in unpredictable ways.

The availability of water resources in the western United States are governed highly by the climatic fluctuations over time. The hydrologic characteristics of watersheds, the quantity of available water, timing of snowmelt runoff, and flow are all related to the climatic fluctuations of the region. Currently, a drought that began around the year 2000 has caused below-average flows to Lake Powell and lead Mead, primary storage units on the Colorado River. Moisture over the Colorado River Basin comes from numerous sources with snowpack and North Pacific fronts in the winter providing the most important sources of moisture. Snowpack created from cold frontal systems produce large amounts of snow at elevations greater than 5,000 feet allowing for large runoffs created from the melting in the spring. During the summer months, moist air from the Gulf of Mexico, Gulf of California, and Pacific Ocean combine to create high elevation storms that, although small in extent, cause flash flooding locally, but have little
effects on larger river systems. Large scale ocean systems such as the El Niño-Southern Oscillation and the Pacific Decadal Oscillation have been described as having decadal scale fluctuations of warm and cold periods of sea-surface temperature. These decade long cycles are believed to be associated with various droughts in history as shown in Fig. 19. Water flow recorded in compliance with the Colorado River Compact has created a flow volume log of the past one hundred years. Regression analysis has shown an average annual volume of 12.4 MAF from 1895 through 2003, well below the estimated 15.0 MAF quoted in the river compact (USGS, Changes in Streamflow Timing in the Western United States in Recent Decades, 2005). This decrease however, is due to increased upstream usage of water. Tree-ring analyses date back almost one thousand years and have shown decade long drought periods implying that the current drought may persist for several more years or perhaps upwards of a decade (USGS, Climatic Fluctuations, Drought, and Flow in the Colorado River Basin, 2004). The increased knowledge of wet and dry cycles will require further management of water resources in order for the burgeoning population of the American southwest to provide for itself.

Figure 19 - Climatic Fluctuations, Drought, and Flow: Colorado River Basin (USGS, Climatic Fluctuations, Drought, and Flow in the Colorado River Basin, 2004)
http://pubs.usgs.gov/fs/2004/3062/
Increased human activity has assisted in the passing of over 9 million tons of salt every year past Lee’s Ferry. Of this salt, 47% occurs naturally and the other 53% is the result of human activity. Salinity levels, while at levels as low as 300mg/l in the Colorado and Green Rivers, become increasingly greater as more salt enters the river downstream reaching values as high as 900 mg/l in the southern reaches of New Mexico (Jacobson, 2007). The causes of this salinity include major factors such as runoff from irrigation, erosion of badlands and springs, and minor contributions from the mining industry and from reservoir contributions. An example of a natural salt-loading cause is that of La Verkin Springs, while the increased salt at Crystal Geyser near Green River, Utah is the result of human contributions. The runoff from main canals, laterals, irrigated crops, and open drains all permeate the soil into the ground water increasing the concentration of salt as the ground water travels and feeds into the Colorado River. The damages caused by increased salinity measure in the hundreds of millions of dollars. Household and crop damages are estimated to exceed $250 million combined with over $100 million in damages in the commercial, utility, industrial, and management sectors (Jacobson, 2007). The agricultural damages manifest themselves as lower yields and a large limitation on the type of crop that can be grown. In addition to the limitations and lower yields, increased water use and operating and maintenance costs arise, incurring large damages to the agricultural industry. Increased salt causes large municipal damages by accelerating appliance and pipe deterioration and limiting the treatment and reuse of such devices. The industrial sector faces the same limitations of the municipal sector having to replace deteriorated pipes and face increased maintenance costs. The effects of increased salinity and population growth can be seen in the resultant effects of the metropolitan areas of Las Vegas and Nevada with salinity levels in excess of 700 mg/l.
south of the Hoover Dam. The effects of other metropolitan areas such as the southern California and central Arizona can be seen in increased salinity levels exceeding 700 mg/l below Parker Dam and the damages caused by the agricultural industry in California and Arizona have caused a salinity level in excess of 850 mg/l at the Imperial Dam (Jacobson, 2007).

In order to offset the increased salinity levels caused by human activities it is necessary to implement both Federal and State programs to assist in the reduction of salinity. Several federal programs that exist include the Bureau of Reclamation, the U.S.D.A. Natural Resources Conservation Society, the Bureau of Land Management – Public Lands and the Fish and Wildlife Environmental Protection Agency and U.S. Geologic Service. The USDA has implemented several programs including Environmental Quality Incentive programs, technical assistance to improve irrigation efficiency, financial assistance to improve irrigation practice and agricultural producer cost-share improvements. The BLM has proposed well plugging, rangeland management, unified watershed characterization and resource management plans as methods to decrease salinity levels. The plans to improve reclamation include a request for proposal plan whereupon plans are proposed to the Bureau of Reclamation, salinity information is gathered from existing sources, bidding on installation costs occurs, and then the projects are ranked on cost effectiveness and risk factors. Currently over 1 million tons of salt are being controlled with USBR projects account for over 590,000 tons and USDA projects account for over 460,000 tons of salt each year. Program targets aim for 1,890,000 tons per year by 2020, an additional 800,000 tons over what is currently being controlled. Funding for Basinwide and the Natural Resources Conservation Service exceed ten and twenty-five million dollars respectively each year. (Jacobson, 2007)
Hydrological records including tree ring analysis have shown that perfect drought conditions are a natural cycle in the flow of the Sacramento and Colorado rivers. Future water planning must account for increasing population as well as the decreased availability for water as California draws greater amounts. The possibility of a prolonged perfect drought (several decades) without proper mitigation strategy may impact storage capacity and demands. (MacDonald, Rian, & Hidalgo, 2005)

The apportionment provisions of the River Compact states the percentage of the 7.5 MAF per year as an ideal annual flow as well as a “likely” scenario of 6 MAF a year. In both scenarios the percentages of apportioned water are as follows: Colorado – 51.75%, New Mexico – 11.25%, Utah -23%, Wyoming 14%. The Lower Basin Apportionment divides all water in the mainstream below Lee Ferry. Divided between the states are as follows: California – 4.4 MAF, Arizona – 2.8 MAF, Nevada - .3 MAF. Surplus is to be divided 50% to California, 46% to Arizona and 4% to Nevada (Eklund, 2007).

The Colorado River Compact was negotiated after several years of high flow on the River and as such it overestimated long-term annual flow. Average flow past Lee Ferry is approximately 14.8 MAF as of 2005. Total use by the Upper Basin has topped out around 4.2 MAF while the Lower Basin has consistently used 10-11 MAF (Eklund, 2007).

Introduced in 1974, the Colorado River Basin Salinity Control Program authorizes agencies to cost-share with state and local organizations for construction projects to control salinity by decreasing the amount of salt entering the river. Control projects have been implemented in Utah, Colorado, Wyoming, New Mexico, and Nevada.
In charge of developing an Annual Operating Plan for Lower Basin reservoirs, the Secretary of the Interior must take into account available water supply, operational costs and limitations of the law. Through the careful consideration of these factors, the Secretary determines the amount of water available for the upcoming year and this will govern the water use of the Lower Basin. (Anderson, 2002)

The conflict between urban, agricultural, and environmental water interests is crippling the negotiations between parties to agree upon adequate policies to protect the renewability of the basin’s resources. Water management has typically made projections based on variables such as population, per-capita, water demand, agricultural production, and economic productivity. Legal entitlements to the river’s water currently exceed the river’s average annual flow, causing problems for long-term planned use. Although the river is over-apportioned, average annual consumption, as of 1996, is approximately 14.4 MAF. This problem is currently circumvented due to the fact that the Upper Basin uses less than half of its entitled water and this is seen as an available source for the Lower Basin. The problem of consumption, however, must be faced as the Lower Colorado River Sub-region is expected to grow by nearly 100% from 1990-2020. Consumption exceeded the allocated 7.5 MAF during three years over a period from 1988-1995 and the average consumption was approximately 7.3 MAF (The sustainable use of water in the lower Colorado River Basin, 2008).

It is necessary for the Secretary of the Interior and the seven states to formulate a plan of preparation and preparedness to combat these inevitable upcoming problems. By formulating a plan of action, they guarantee the necessary preparations should another drought of equal magnitude strike the area in the future with the increased complexities and problems of climate change and population.
Conclusion

The population of the southwestern United States has been growing at an alarming rate since the earlier 1900s. Over 1 million people moved within the borders of San Bernardino County, Riverside County, San Diego County, Orange County, and Los Angeles County in the 1980s alone. The population increase can be attested to the migration of textile jobs in the northern states out of the country and the new appearance of tech jobs in the southwest. The exponential population growth’s effect on the depreciating resources of water in the area is coupled with the abnormally high per capita daily water consumption in the area. The per capita water use in Utah decreased to from 1970 to 1990 to still be an astonishing two times the amount of water used on average across the United States. To add to the strain on the water supply in the southwestern United States, the Colorado Basin is currently experiencing a drought.

The Colorado River Basin encompasses climate zones ranging from alpine to arid desert. This region also experiences dramatic climate variability due to the El Nino Southern Oscillation (ENSO), which is a cyclic weather pattern produced by the interaction of the hot air in the Pacific Ocean with the costal trade winds. This pattern is then paired with the diversity of the landscape and the complex relationship between the different climate zones which produces great climatic variability. Recently, the Southwestern United States has been experiencing a temperature increase that is higher than anywhere else in the United States. This climatic change is leading to water-management issues for an area of the country where water is already scarce. Among these changes is the increase in evapotranspiration due to hotter temperatures. Less snow is accumulating in the snowpack during the winter months based on milder weather which
also leads to an earlier melting of the snowpack in the spring. This occurrence changes the timing of the peak flow of the Colorado River which supplies useable water to the entire area. Due to that, problems with water supply in the late summer months are a frequent occurrence. All of these factors are alarming when considering the drought that has been ongoing in the region for over 5 years.

The increased demand and responsibility for water rights and management has put a strain on the bureaus and organizations that must annually allocate water resources. Future use, highly dependent on the increasing population and temperature, must be decided between the seven states dependent on the Colorado River and the 15 MAF of water that pass down it. Many factors will affect how these groups allocate the water, including the increased demand by the agricultural sector in southern California, the increased use of water in the Upper Basin for major cities, and Arizona’s yet unused allocation of water. These factors, tempered by the current extreme drought and future predictions of harsh climate conditions, will find the allocation of water rights between the states and federal governments a continuing process. Ever increasing amounts of capital are being spent to reduce salinity levels and store water earlier in the year as factors such as earlier center-of-volume dates affected by snowmelt occur, higher agricultural runoff increases salinity, and increased population growth draws upon the limited water resources. The future of the American Southwest may be decided by how early and effective organizations and bureaus are in acknowledging the problems at hand and implementing change to accommodate the inevitably increased draw on water resources. With proper planning and commitment, the potential dangers of these various factors can be mitigated and the American Southwest will continue to grow.
Bibliography


