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QuickBird Satellite Image of Macau

This 0.7-m resolution image was acquired by QuickBird satellite on October 27, 2006

The Earth From Afar: Image Review

Editor: Paul R. Baumann
Department of Geography
State University of New York at Oneonta
Milne Library 317
Oneonta, NY 13820
U.S.A.

Drought in the Colorado River Basin: Shrinkage of Lake Powell

Paul R. Baumann
Department of Geography
State University of New York
Oneonta, NY 13820
U.S.A.

Created in1963 with the completion of the Glen Canyon Dam, Lake Powell became the second largest reservoir in the United States following Lake Mead. Construction on Glen Canyon Dam was started in 1956 and completed seven years later in 1963, after which the water from the Colorado River proceeded to backup behind the dam to form the lake. In June 1980, after seventeen years, Lake Powell reached full pool size with a volume of 27 million acre-feet (MAF)* and a surface area of 266 square miles (689 sq. km.). At full size the reservoir is nearly 186 miles (299 km.) in length with a water depth of 560 feet (170.7 m) at the dam.

With Lake Powell being located in an arid and semiarid region its water level varies considerably and provides a good barometer of water conditions within the Colorado River's 246,000-square mile (637,137 sq. km.) basin. From 1995 through 1999 its water level was above average and as late as September 1999, the reservoir was still 95 percent full. However, precipitation levels in the upper Colorado River basin from October through December 1999 fell to 70 percent below average, signaling a low runoff for 2000 and the beginning of an extreme drought. This paper, with the use of remotely sensed imagery, examines the impact of this drought on Lake Powell.

Colorado River Compact

Lake Powell came into existence as part of a larger project to control flooding on the Colorado River and provide water and electrical power throughout the southwest United States. Between 1905 and 1907, several large floods on the Colorado River destroyed crops and fields in southern California, mainly in the Imperial Valley. Floodwaters from the river broke through the irrigation floodgates and flowed into the valley forming the Salton Sea, a 450 square mile (1165.5 sq. km.) lake. From these disasters the idea of building dams to control the river and use its water to meet the growing needs of the dry West was formed. By obtaining money from western land sales and irrigation water the Newlands Reclamation Act of 1902 provided the financial means to build these dams (Topping).

In 1922, the Colorado River Compact was established to control the river, and in the process, divided the river into the Lower Basin (Arizona, Nevada, and California) and the Upper Basin (Utah, Colorado, Wyoming, and New Mexico). See Figure 1. Shortly after the compact was formulized, dam construction in the Lower Basin started (Topping). Completed in 1936, Hoover Dam was built to regulate flooding and erosion and provide a dependable water supply and hydroelectric power. Downriver from Hoover Dam, the Davis, Parker, and Imperial dams were built to assist in controlling floods. As part of the compact agreement the Upper Basin had to provide the Lower Basin each year with 7.5 MAF of water. In addition, the 1944 Mexican Water Treaty required the United States to release to Mexico annually .73 MAF of Colorado River water, later increased to 1.5 MAF. This water also had to come from the Upper Basin.

Because moisture conditions within the Upper Basin varied greatly from one year to another, the Upper Basin states frequently found it difficult to supply the annual 9.0 MAF of water (Carothers and Brown). To alleviate this situation the

* "An acre-foot is roughly 326,000 gallons of water, enough to supply an average family of four for a year." (Lenart) An acre-foot is also equaled to 1,233,482 liters of water.

U.S. Congress passed in 1956 a bill to build several dams in the Upper Basin. The largest of these dams was the Glen Canyon Dam. Two more large dams, built farther upriver, were the Flaming Gorge Dam on the Green River and the Navajo Dam on the San Juan River. Both of these dams are in headwater sections of the Colorado River Basin.

Today, with a dam almost every hundred miles, the Colorado River is the most dammed river in the United States, which results in it no longer providing water to the Gulf of California. Except in very wet years, the river's delta is a desert, and what water does reach the area simply disappears into the ground in northern Mexico.

In addition to controlling the river the compact was also established to make sure that each state within the Colorado River Basin received a fair share of the river's water. In the early 1920s the states within the basin were concerned about California's growth, and thereby, its increasing consumption and appropriation of the water within the river. This concern was further exacerbated by the fact that California contributed little water to the river. This concern still exists as California continues to grow and take unused water from the river, beyond its allotment.

Arizona was especially disturbed about California's growing water demands and did not ratify the compact until 1944, 22 years after it was initially negotiated. Arizona's ratification of the compact was linked to the development of the Central Arizona Project, a 336-mile long system of aqueducts designed to deliver 1.8 MAF of water per year to the state's southern growth area. However, before this project commenced, California and Arizona had to resolve their differences as to how much water each state would receive from the river. These differences resulted in an 11-year, complicated court case that eventually went to the U.S. Supreme Court. Finally, the case was resolved with California receiving 4.4 MAF, Arizona 2.8 MAF and Nevada .3 MAF. See Table 1. In addition, each state was allowed to use all the water in the tributaries located within the state's boundaries (Gelt). Relative to its population size, Arizona was the big winner in this case. In the early 1950s when the case was being litigated, Nevada did not visualize the recent rapid growth of Las Vegas and environs. Today, Nevada might argue for a larger allocation.

The Upper Basin states worked together in a more cooperative manner than the Lower Basin states and quickly formulated a contract that allotted 51.75% of the Upper Basin water to Colorado, 23% to Utah, 14% to Wyoming, and 11. 25% to New Mexico. Percentages were used rather than actual amounts since the states did not know how much water would be available to the Upper Basin each year due to the combination of precipitation variability and the requirement of providing 9.0 MAF to the Lower Basin and Mexico (Gelt).

Precipitation Patterns

The arid and semiarid American Southwest constantly faces precipitation variability. What moisture the region receives to feed the Colorado River and its major tributaries, the Green River and San Juan River, is the result of various climatic conditions. A change in any one of these conditions could bring on a flood or drought. The Upper Basin falls mainly on the Colorado Plateau, which experiences both a winter and summer precipitation regime. In the basin's higher elevations that form its headwaters precipitation falls rather evenly throughout the year, building large snowpacks during the cold months. Cold frontal systems developing over the North Pacific Ocean bring large amounts of precipitation during the winter and spring months. These systems acting like large rivers flowing eastward across western United States carry moisture at high levels in the atmosphere. As these atmospheric rivers encounter the high elevations of the Colorado Plateau, orographic conditions occur, resulting in increasing amounts of precipitation with the increase in elevation. In the San Juan, Uinta, and Wind River mountains these systems create large snowpacks that normally meltdown at a gradual rate during the late spring and early summer to provide water for the Colorado River throughout the summer and into the fall. If these winter frontal systems originate over warmer waters in the Pacific Ocean, precipitation in the form of rain might fall on the mountain snowpacks producing fast, high runoff and floods on the rivers.

During the summer regime rain over the Colorado River Basin comes from convectional systems. Low-level moisture arriving from the Gulf of Mexico, the Gulf of California, and the eastern Pacific Ocean generate thunderstorms in July and August. This atmospheric condition is referred to as the "North American monsoon," and normally generates 30 to 40 percent of the annual rainfall in the Lower Basin where the rainfall ranges between 3 and 10 inches (76.2 and 254 mm) per year. These storms generally produce high-intensity rainfall in the Lower Basin where high summer temperatures and low elevations exist. Lower-intensity rainfall occurs more in the cooler and higher Upper Basin. These thunderstorms tend to be local in geographic coverage. They can create flash flooding but contribute little to the large rivers within the basin.

The factors producing the drought conditions throughout major areas of western United States including the Colorado River Basin are not fully understood. The expansion of the warm El Nino ocean current within the equatorial portion of the Pacific Ocean has been associated with floods and droughts in western United States. Warm winter storms originating from warm ocean surfaces result in rapid meltdown of mountain snowpacks. Such meltdowns produce early above-average runoff followed by later below-average inflow into the basin. However, an El Nino event normally lasts 6 to 18 months, not long enough to create the current six-year drought. Another factor might be an ocean temperature pattern occurring in the North Pacific Ocean outside the equatorial region. Called the Pacific Decadal Oscillation (PDO) (Mantua and Hare) it varies between a warm and cold cycle over a 30 to 50 year period. The causes behind the variations in the PDO are not known but recent research points out an association between the PDO phases with the above- and below-average precipitation and

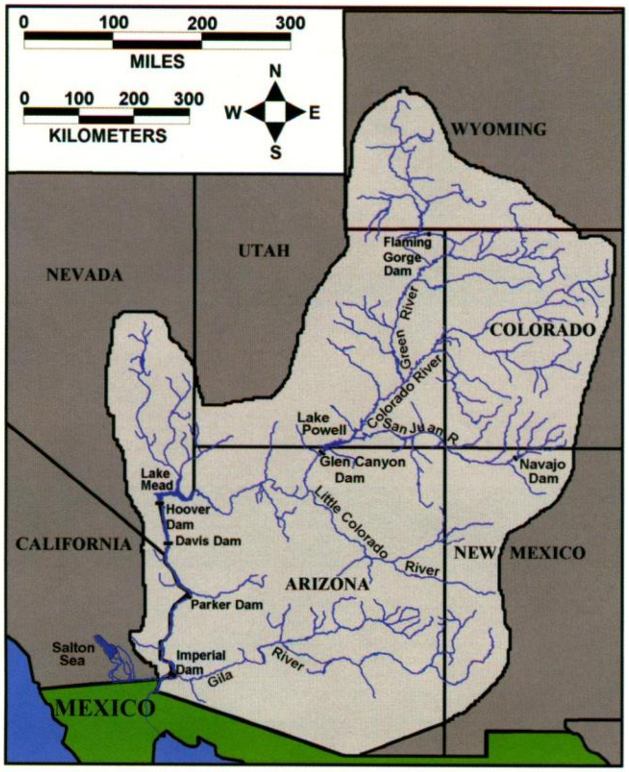

Figure 1 Colorado River Basin

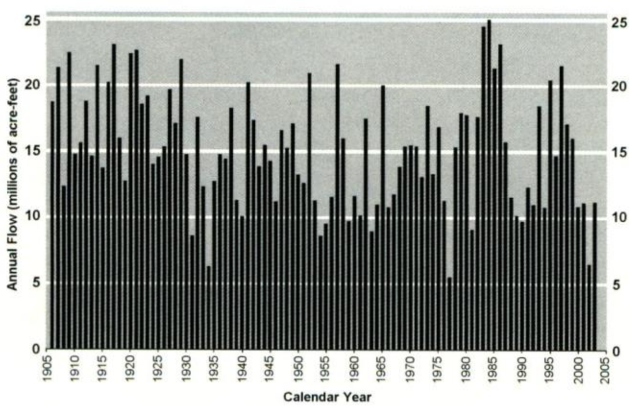

Figure 2 Estimates of Colorado River flow from 1906-2003. Source: U. S. Bureau of Reclamation.

streamflow in the Colorado River Basin (Hidalgo and Dracup).

Annual Water Flow

Based on the 1922 Colorado River Compact, Lee's Ferry, which is located just below the Glen Canyon Dam, separates the Upper Basin from the Lower Basin. Water flow data are collected at this point to measure the amount of water moving from the Upper Basin to the Lower Basin. Flow data has been measured or estimated at this point since 1885 but different measurement techniques have been employed over this long time period. From 1885 to 1922, estimated annual flow

Table 1 Colorado River Allocations

Political Entity	Annual allocation (in acre-feet)
Upper Basin States	7,500,000*
Colorado	3,900,000*
New Mexico	800,000*
Utah	1,700,000*
Wyoming	1,000,000*
Lower Basin States	7,500,000
California	4,400,000
Arizona	2,800,000
Nevada	300,000
Mexico	1,500,000
Total	16,500,000

Source: U.S. Bureau of Reclamation.
*Upper Basin states' allocations based on using percentage values with 7.5 million acre-feet.

amounts were determined for Lee's Ferry by E.C. LaRue, a U.S. Geological Survey engineer assigned to the Division of Water Utilization in the Southwest. From 1923 through 1962 stream gauges were used to determine the volume. In 1963 Glen Canyon Dam was completed; thus, from 1963 to the present the measurements at Lee's Ferry are assumed to approximate the total flow volume into Lake Powell.

Figure 2 illustrates this data set from 1906 to 2003. Measurements from 1905 to 1922 were used to ascertain the 15.0 MAF of water per year for the Colorado River Compact. The actual annual average during this period was 16.1 MAF, which was the highest long-term annual flow volume in the 20th century. During this period less annual variation in flow was recorded than for the period after 1922. The average annual flow during the seventeen-year period from 1986 to 2003 was 12.4 MAF, only 77 percent of the 16.1 MAF level from the seventeen-year period of 1905 to 1922.

Since Lake Powell reached full capacity in 1980 the highest annual volume flow occurred in 1984 with 25 MAF and the lowest in 2002 with 6.8 MAF. Flow in the basin varies significantly from one year to another based mainly on precipitation amounts and a growing upstream water use. Within this variation certain drought periods can be identified. Table 2 shows the drought periods over the most recent 70-year time span. The 2000-2004 (now extending to 2006) drought has the lowest average annual flow. The 9.9 MAF figure is an estimated average. Between 2001 and 2003 the flow reached a low of 5.4 MAF (U.S. Geological Survey). The duration of these droughts has been between 4 and 6 years, which might indicate an ending to the present drought. However, due to the low 2006 February precipitation levels within the basin, the U.S. National Weather Service predicts the April through July inflow to be 7.2 MAF, well below the average 9.9 MAF level for the drought. This low inflow is occurring at the time of the year when the greatest snowpack meltdown is taking place. Thus, the present drought does not

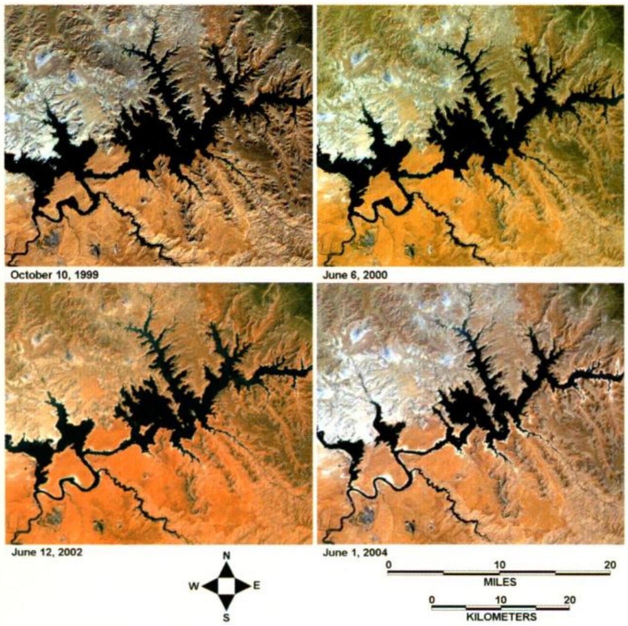

Figure 3 Landsat 7 images of Lake Powell at various times throughout the drought.

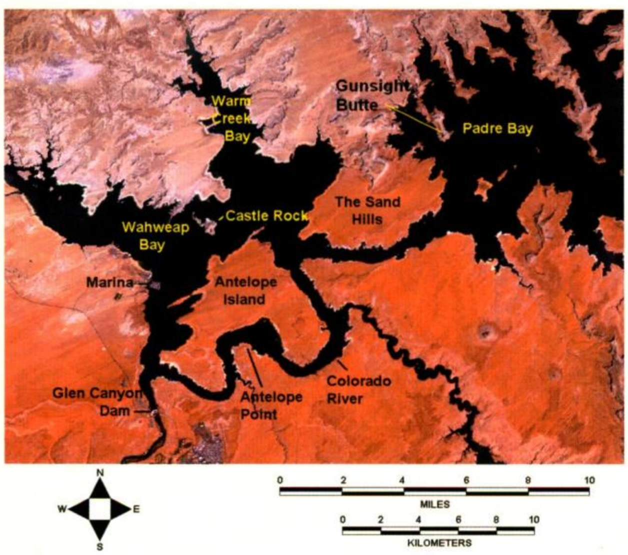

Figure 4 Selected geographic locations in the lower portion of Lake Powell.

appear to be ending. Also, between 1886 and 1904, an eighteen-year drought occurred, and tree-ring records over several centuries have revealed severe droughts lasting for decades (Lenart).

Lake Powell's Shrinkage

Figure 3 provides four Landsat 7 true color composite images of the lower portion of Lake Powell. The first image (top, left) was taken on October 10, 1999 when the reservoir contained 22,876,730 acre-feet of water.** The current drought basically started at the time when this image was recorded. The other three images were taken near the beginning of June in the years 2000, 2002, and 2004. By June much of the spring runoff from the snowpacks in the surrounding mountains has made it to the lower portion of Lake Powell. After June the summer and fall inflow to the reservoir generally decreases. The summer monsoons are sporadic in their location across the basin and might provide some summer flashflood conditions but do not contribute significantly to the reservoir.

The four images illustrate the shrinking size of the reservoir between 1999 and 2004. In 1999, Wahweap Bay was at its full extent and Castle Rock Island occupied the center of the bay. Figure 4 shows the location of these geographic places. Not much change occurred in the bay between 1999 and 2000. On June 6, 2000 Lake Powell's water level had dropped

Table 2 Average Flows During Recent Droughts

Time Frame	Duration	Average Annual Flow (in acre-feet)
2000-2004	5 years	9,900,000*
1953-1956	4 years	10,200,000
1988-1992	5 years	10,900,000
1959-1964	6 years	11,400,000
1931-1935	5 years	11,400,000

Source: U.S. Bureau of Reclamation.
*Preliminary estimate.

Table 3 Colorado River Basin Depletion Projections (Unit: 1,000 acre-feet/year)

	1990	2000	2010	2020
Upper Basin				
Colorado	2,296	2,445	2,565	2,636
New Mexico	503	535	641	743
Utah857	951	1,030	1,073	
Wyoming	495	505	530	539
*Totals*4,151	4,436	4,766	4,991	
Lower Basin				
Nevada	214	258	304	341
Arizona	1,351	2,019	2,373	2,537
California	5,162	4,916	4,823	4,622
Totals	6,727	7,193	7,500	7,500

Source: Quality of Water, Colorado River Basin Progress Report, Number 18, January 1997. U.S. Department of the Interior Report.

** This figure represents the recorded amounts for the entire reservoir on the indicated dates.

only to 21,385,072 acre-feet, approximately 1.5 MAF below the October 10, 1999 level. By June 12, 2002 the drought had lowered the reservoir to 16,427,414 acre-feet and Castle Rock Island was no longer an island. A land bridge appeared linking the island to the lake edge. Also in 2002, only a narrow inlet connected the upper and lower portions of Wahwaep Bay. By June 1, 2004, the reservoir was at 10,575, 179 acre-feet, a 46.2 percent drop from the October 10, 1999 level. A wide land bridge closed the inlet and the two portions of the bay were now separated. Boats maintained in a marina located in the lower section of the bay now must enter the main channel of the Colorado River to reach the upper half of the bay. Antelope Island has merged with the mainland. Warm Creek Bay, just off of Wahweap Bay, shrank considerably within the four-year period.

In 1999 some small islands are located in Padre Bay, which is situated just upriver from Wahweap Bay. By June 2000, only nine months after the October 1999 image, these islands are noticeably larger in area. In the 2002 image some of these islands have coalesced and new islands have appeared as the reservoir's water level continues to drop. By 2004, a large land bridge extends from Gunsight Butte to these islands, making for a continuous land body. By 2002 and especially by 2004, a white line outlines much of the edge of the reservoir. This line identifies exposed land that only a few years before was under water. A rather large section of this newly exposed land appears on the Colorado River directly across from Antelope Point. The water level had to drop 30 feet (9.1 m) to show this area.

The last time that Lake Powell's water level was at this level occurred in May 1969 when the reservoir was still filling after the construction of Glen Canyon Dam in 1963. Seventeen years of normal inflow were required for the reservoir to reach its storage capacity. For the reservoir to return to this level again, eleven years of normal inflow would be needed. This time span does not take into consideration bringing Lake Mead back up to its capacity, which is presently at 54 percent, and the continuing growth and development within the basin. Some speculation exists that both Lake Mead and Lake Powell will never refill to their capacity levels. (Lenart)

In addition to not being able to provide freshwater to farms and cities, Lake Powell might have to stop production of hydroelectricity. Glen Canyon Power, which operates the dam's power facilities, has indicated that if the present drought continues, it will not be able to generate electricity by 2007. At full capacity, Lake Powell produces enough electricity to power 1.5 million homes, mainly in Arizona and New Mexico.

The Lower Basin states and Mexico continue to receive their combined 9.0 MAF of water per year. The Upper Basin states are now challenging the requirement of providing 7.5 MAF to the Lower Basin states each year, pointing out that according to the compact they must deliver 75 MAF every decade and they have provided in some decades surplus amounts of water. They also argue that the Lower Basin tributaries should be used to provide some of the water for Mexico. The Upper Basin possesses some leverage in trying to make adjustments in the compact. If Lake Powell cannot produce electricity, it is mainly the Lower Basin that will suffer.

Summary

Table 3 shows the actual water used in 1990 and 2000 by each state within the basin and the projected usages for 2010 and 2020. The Lower Basin has almost reached its full water allocation of 7.5 MAF per year. California is gradually lowering it usage but even by 2020 it still exceeds its allocation. Nevada will start exceeding its allocation by 2010. Only Arizona remains below its allocation but its usage is increasing. Agriculture consumes about 80 percent of the state's allocation. California and Nevada are presently using Arizona's surplus water. The question has been raised, "Why should the Upper Basin, more specifically Lake Powell, release water that allows California and Nevada to exceed their allocations?" The Upper Basin states remain well below their allocations but their water needs are gradually increasing. In 2000 the basin states used 11.6 MAF of water; this number increases to 12.2 MAF by 2010. Although these amounts are still below 15 MAF of water established by the compact for the basin states, they are very close to the average annual inflow of 12.4 MAF recorded between 1986 and 2003, a time period that appears to more accurately reflect Lake Powell's normal operational water level. Maybe with the severity of this drought and the dangerously low water level in Lake Powell, the time is appropriate for reconsidering the 15 MAF inflow figure.

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