Climatic Fluctuations, Drought, and Flow in the Colorado River

Introduction

Climatic fluctuations have profound effects on water resources in the western United States (Fig. 1). In the arid and semiarid parts of the Southwest, climatic fluctuations affect many hydrologic characteristics of watersheds, including the quantity of base flow, the occurrence of large floods, and the timing of snowmelt runoff (Cayan and others, 1999; Stewart and others, 2004). Since the start of a persistent drought in about the year 2000, inflows to Lake Powell on the Colorado River have been below average, leading to drawdown of both Lakes Mead and Powell, the primary flow-regulation structures on the river (Fig. 2). The recent drought, referred to here as the early 21st century drought, has its origins in several global-scale atmospheric and oceanic processes that reduce delivery of atmospheric moisture to the Colorado River basin. The purpose of this Fact Sheet is to discuss the causes of drought in the Colorado River basin and the predictability of river flows using global climate indices.

Figure 1. Moisture sources to the Colorado River basin.

Sources of Moisture to the Colorado River Basin

Precipitation is biseasonal (winter and summer) in the Colorado River basin (Fig. 1) on the Colorado Plateau (Hereford and others, 2002). In the headwaters precipitation is evenly distributed across the four seasons, mostly accumulating in snowpacks. Moisture comes from several sources (Fig. 1). Frontal systems in winter and spring originate in the North Pacific Ocean and provide the largest and most important source of moisture. These systems tend to carry moisture at high levels in the atmosphere, and precipitation is orographic, meaning it increases with elevation in the mountainous West. Cold frontal systems produce substantial amounts of snow above about 5,000 feet and rainfall at lower elevations in the Rocky, Uinta, and Wind River Mountains, which are the headwaters of the Colorado River and its principal tributary, the Green River. These storms build snowpacks that melt in the late spring, providing runoff to the Colorado River. Warm winter storms, which originate in the tropical Pacific Ocean, may cause rainfall on snowpacks, resulting in high runoff and floods on major rivers. The frequency and moisture content of frontal systems are strongly affected by atmospheric circulation patterns (particularly their strength) and sea-surface temperature (SSTs) of the tropical and North Pacific Oceans.

Moisture delivered to the Colorado River basin during summer is typically a mixture of moist air from the Gulf of Mexico, the Gulf of California, and the eastern Pacific Ocean. Known as the “Arizona monsoon,” this moisture arrives in July and August at low levels in the atmosphere. The moist air rises rapidly over the desert landscape, spawning thunderstorms that deliver high-intensity rainfall to elevations less than 7,000 feet and lower-intensity rainfall at higher elevations. Thunderstorms tend to be of small spatial extent, and although they spawn severe flash flooding locally, few floods are generated on the larger rivers in the region.

Finally, tropical cyclones, which range from tropical depressions to hurricanes, form in the eastern North Pacific Ocean off the west coast of Mexico. These storms rarely make landfall on the continental United States, instead they dissipate over the ocean. The residual moisture from tropical cyclones, which can be considerable, is either carried inland in weak monsoonal flow during summer months or embedded within stronger cutoff low-pressure systems from the Pacific Ocean. The combination of tropical cyclones and cutoff lows creates conditions for generation of large floods in the southern half of the Colorado River basin.

Indices of Global Climate

Several indices of atmospheric and oceanic processes are used to explain climate variability in the United States. The best-known of these is the El Niño – Southern Oscillation (ENSO) phenomenon in the Pacific Ocean.

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Figure 2. Replicate photographs of Lake Powell at the confluence with the Dirty Devil River (entering from left). A. June 29, 2002. B. December 23, 2003. (Photographs by John C. Dohrenwend.)

The Southern Oscillation Index (SOI) is used to indicate the status of ENSO (Webb and Betancourt, 1992; Cayan and others, 1999). As its name implies, ENSO reflects an oscillation between two basic states of the ocean. The warm phase (negative SOI), called the El Niño, involves warming of the eastern tropical Pacific Ocean off the coast of Peru. The warm water spreads northward in the eastern North Pacific Ocean off the west coast of the United States. The cold phase (positive SOI), called La Niña, is the opposite, resulting in a cooling of the water off western North America. A neutral condition intervenes for several years between the two end states (Fig. 3A).

ENSO reflects interannual variation of climate and helps to explain the occurrence of floods (Webb and Betancourt, 1992) as well as droughts (Cayan and others, 1999). Warm-winter storms tend to be enhanced during El Niño, causing above-average runoff and floods, such as during 1982-1983. Although the incidence of dissipating tropical cyclones tends to be increased during El Niño conditions, the summer monsoon may be diminished in many years. Not all El Niño events lead to increased runoff; for example, runoff during the 2003 El Niño was below average in the Colorado River basin. La Niña conditions, which dominated the period of 1996 through 2002 (punctuated by the El Niño of 1998), caused below-average flow in the Colorado River.

An elaborate index called the Pacific Decadal Oscillation (PDO; Fig. 3B) reflects decadal SST variability and sea-level pressure of the North Pacific Ocean north of 20°N (Mantua and Hare, 2002), and is related to indices of ENSO. The PDO reflects decadal-scale variability and is used to explain long-term periods of above- or below-average precipitation in the region. Shifts in the PDO occurred in about 1944, 1964, and 1977 (McCabe and others, 2004). The recent shift in the PDO in about 1996 is thought to herald a change from wet to dry conditions in the Southwest.

The recently developed index of the Atlantic Multidecadal Oscillation (AMO; Enfield and others, 2001) reflects conditions in the Atlantic Ocean that may affect climate in North America (Fig. 3C). Although the Atlantic Ocean is downstream from the moisture-delivery sources to the Southwest, warm conditions indicated by positive AMO are indicative of drought, for example the Dust Bowl of the early 1930s (Schubert and others, 2004) and at other times during the last century (McCabe and others, 2004). During positive AMO conditions, atmospheric flow is shifted to deliver less moisture to the continental United States. Fluctuations in the AMO, combined with the PDO, may help to explain some of the long-term fluctuations in runoff in the Colorado River basin, while the SOI may explain variation within the shorter-term climatic state.

Drought and Indices of Global Climate

Drought is caused by persistent deficits in precipitation over a region. As such, the severity of droughts is a function of spatial extent, duration, and the magnitude of the precipitation deficit. This combination of variables makes drought prediction an extremely difficult proposition. The record of 20th century drought usually is depicted using the Palmer Drought Severity Index (PDSI), which takes into account both precipitation and potential evapotranspiration. Using a state-wide PDSI index (Fig. 3D; National Oceanic and Atmospheric Administration, 2004), the most severe droughts in Utah occurred between about 1896 and 1904, during the early 1940s, between 1948 and 1963 (the mid-century drought), between 1972 and 1976, from 1985 through 1991, and after 1996.

Researchers use a combination of the SOI, PDO, and AMO indices to explain the occurrence and spatial extent of droughts (McCabe and others, 2004). Persistent positive SOI conditions (La Niña) are indicative that a drought of at least short-term duration is going to occur in the Southwest. In contrast, persistent negative SOI conditions, which indicate the occurrence of El Niño, indicate a potential range from drought to extremely wet conditions. However, neither La Niña nor El Niño conditions persist for more than 2-4 years before switching states. Long-term droughts, such as the mid-century event, are associated with persistent negative PDO and positive AMO indices.

Flow in the Colorado River

Flow in the Colorado River has varied significantly during the 20th century. Lee's Ferry (Fig. 1), is the separation point of flow between the upper-basin states of Wyoming, Colorado, Utah, and

New Mexico and the lower-basin states of Nevada, Arizona, and California as determined in the Colorado River Compact of 1922. Calendar-year flow volumes presented in Figure 3E were combined from three data sets that were measured or estimated using different techniques. The primary data for the Colorado River at Lee's Ferry were collected from the start of streamflow gaging in 1923 through 1962, one year before flow regulation began at Glen Canyon Dam. From 1895 through 1922, we use annual flow volumes at Lee's Ferry that were estimated by LaRue (1925, p. 108).

From 1963 through 2003, we assume that flow at Lee's Ferry can be approximated as the sum of flow volumes of the principal rivers flowing into Lake Powell. From 1950 through 1962, comparison of these inflows with measured flow at Lee's Ferry indicated that the inflow was on average 290,000 acre-feet per year less than the measured flow (about 2% of annual flow volume). Although this is well within measurement error of gaging stations, we used the simple linear regression,

$$Q_{LF} = 1.044 \cdot Q_{in} - 0.1688, (R^2 = 0.999)$$

where Q_{LF} = annual flow volume at Lee's Ferry and Q_{in} = annual inflows to Lake Powell, to increase the inflows to Lake Powell for the period of 1963 through 2003. We also estimated annual volumes for the peak runoff season of April through July (Fig. 3F) for 1923 through 2003 (LaRue (1925) did not estimate monthly volumes).

The time series of flow volumes (Fig. 3E-F) shows that the average annual volume is 12.4 MAF from 1895 through 2003. This volume is less than the more-commonly quoted annual volume of 15.1 MAF because our analyses do not include water that is consumptively used in the upper basin states. This usage is partially reflected by regression of annual and seasonal (April through July) flows, which indicate that flow volumes in the Colorado River at Lee's Ferry have decreased by about 0.5 MAF/decade from 1895 through 2003 (Figs. 3E, 3F).

The period 1905 to 1922, which was used to estimate water production allocated under the Colorado River Compact, had the highest long-term annual flow volume in the 20th century, averaging 16.1 million acre feet (MAF) at Lee's Ferry. The highest annual flow volume occurred in 1984 (22.2 MAF), and the highest three-year average is 20.3 MAF for 1983-1985. The lowest annual flow volume is 3.8 MAF in 2002, followed by 3.9 MAF in 1934 and 4.8 MAF in 1977. The early 21st century drought is the most severe in terms of flow deficit in more than a century. The current drought also has produced the lowest flow period in the record, with an average of only 5.4 MAF for 2001-2003. In contrast, the drought of the Dust Bowl years between 1930 and 1937 produced an average of 10.2 MAF. The predicted inflow into Lake Powell for 2004 is 49% of the long-term average (5.6 MAF), which indicates that the early 21st century drought is on-going (McCabe and others, 2004).

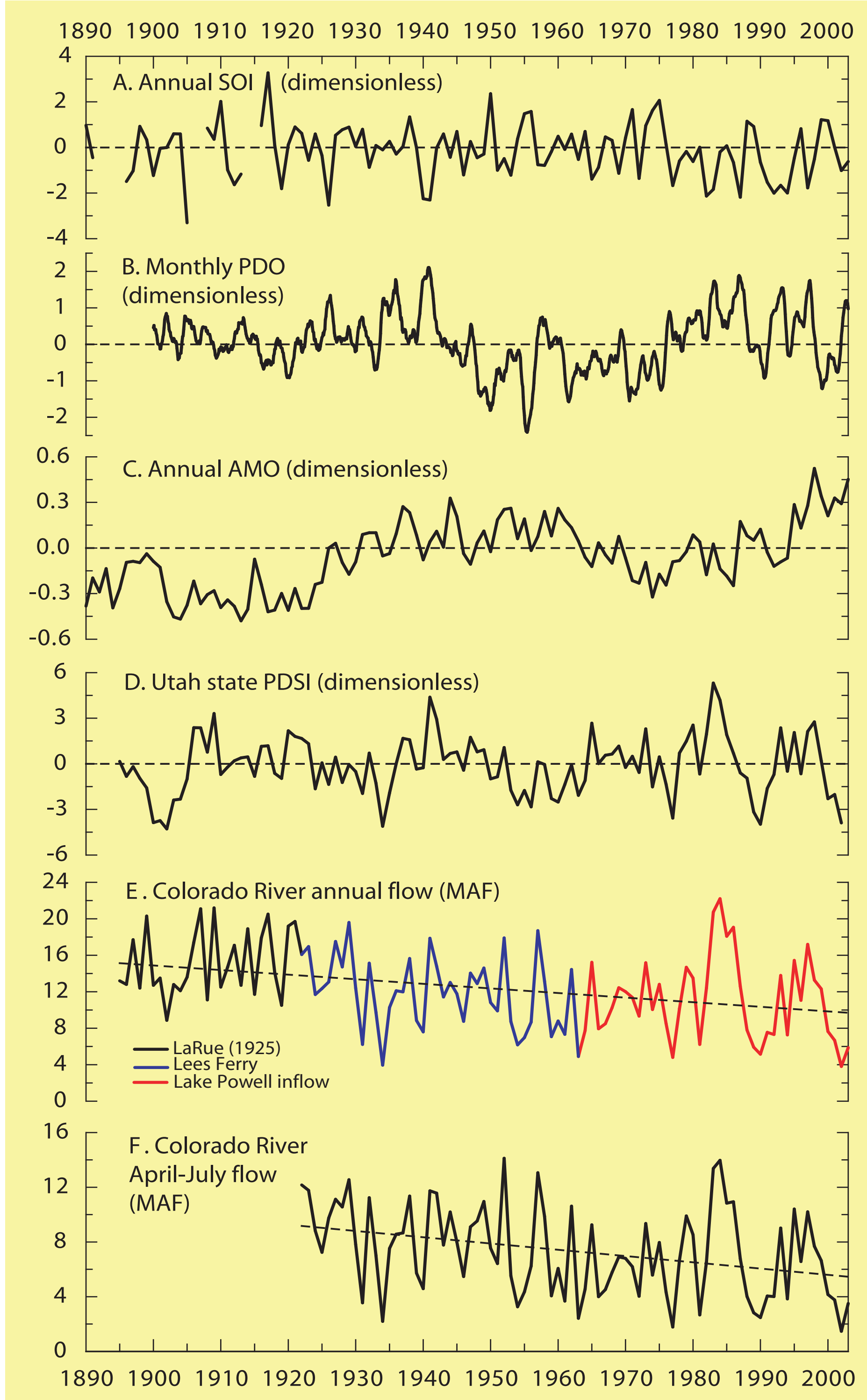

Figure 3. Graphs showing indices of global climate and annual flow volumes of the Colorado River from 1895 through 2003. A. Southern Oscillation Index (SOI). B. Pacific Decadal Oscillation (PDO). C. Atlantic Multdecadal Oscillation (AMO). D. Palmer Drought Severity Index (PDSI) for Utah. E. Annual flow volume. F. April-July flow volume. (A-D are dimensionless; E and F are in millions of acre-feet).

Colorado River Flow and Multidecadal Climate Variability

Colorado River flow is related to

the indices of multidecadal climate variability, although in a complex way. From an interannual perspective, large floods and high runoff volumes typically occur during strong El Niño conditions, whereas La Niña conditions typically cause low-flow conditions (Webb and Betancourt, 1992). Hereford and others (2002) showed that precipitation on the Colorado Plateau is related to both the SOI and PDO indices. Other statistical analyses show that flows in the river only can be partially explained by the PDO (Hidalgo and Dracup, 2004). Our ability to predict water resources in the Colorado River basin remains poor.

As shown in Figure 4, variability in flow of the Colorado River is a complex response to both the AMO and PDO. Above-average flows reliably occur when the AMO index is negative and the PDO index is between –0.5 and +0.5. Below-average flows generally occur when the AMO is positive (Fig. 4). The deepest droughts appear strongly related to a range in AMO index from –1.0 to +1.0 (mostly from 0 to +1.0) and a PDO index of approximately –0.5. Figure 4 underscores the concept that drought results from a complex set of climatological factors that are not easily predicted or explained.

The watershed of the Colorado River spans a large latitudinal range, and precipitation patterns over that gradient do not respond in concert to regional and (or) multidecadal climatic fluctuations. Above-average runoff in part of the watershed (*e.g.*, the northern half) may overcome low runoff in other parts (*e.g.*, the southern half) during some droughts. For example, the mid-century drought, which was severe on the Colorado Plateau, caused only slightly below-average runoff in the entire basin; the average runoff volume during this period was 11.1 MAF. Similarly, the early 20th century drought (Fig. 3D) had an average runoff volume of 13.6 MAF. As a result, much of the variability in the annual flow record (Fig. 3E-F) is not easily explained by the PDO and AMO indices despite some compelling graphical relations (Fig. 4).

Dendrochronology and Colorado River Flows

Tree-ring reconstructions of Colorado River flows provide a longer-term flow record that can be used to assess drought frequency. One of the most important conclusions from dendrochronology is that the period from 1906 through 1930, which was partially used to determine flow allocations under the Colorado River Compact, was likely the highest period of runoff in 450 years (Stockton and Jacoby, 1976). This suggests that the most unusual aspect of Colorado River runoff during the 20th century is the high runoff volume in certain periods (1906-1920, 1983-1985), not the drought periods. The decade with the lowest annual flow volume (averaging about 9.71 MAF) reconstructed using dendrochronology occurred from A.D. 1584-1593 (Meko and others, 1995). For comparison, the 10-year period of 1995 through 2004 (2004 is a predicted volume) produces an average annual flow volume of 9.9 MAF (not corrected for upstream diversions or use). Similarly, the lowest 5-year average using tree rings is 8.84 MAF (A.D. 1590-1594), compared with 7.11 MAF from 1999 through 2003. These comparisons suggest that the current drought may be comparable to or more severe than the largest-known drought in 500 years.

The wide range of predictions of the persistence of the current drought reflect the poor explanation of past Colorado River flows using climatic indices. If the primary control on drought in the Colorado River basin is the AMO, then drought conditions might continue for several decades owing to the persistence of SST warming in the Atlantic Ocean (McCabe and others, 2004). Similar arguments are based on persistence of the PDO, although this index is currently positive (Fig. 3B), which suggests that a return to normal or above-average conditions may be imminent. As indicated by the tree-ring reconstructions, droughts seldom persist for longer than a decade, and if that remains the case, the current drought is only half over.

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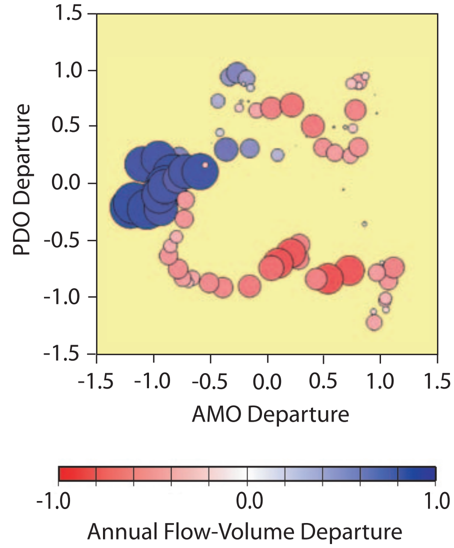

Figure 4. Graph showing above and below average Colorado River flows compared with the Atlantic Decadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO). Flow magnitudes are indicated by circle color and diameter.

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