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Citation Information

Pulwarty, Roger S., "Climate Variability and Western Water: What Can We Expect?" (2000). *Water and Growth in the West (Summer Conference, June 7-9)*.
<https://scholar.law.colorado.edu/water-and-growth-in-west/13>

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Roger S. Pulwarty, *Climate Variability and Western Water: What Can We Expect?*, in *WATER AND GROWTH IN THE WEST* (Natural Res. Law Ctr., Univ. of Colo. Sch. of Law 2000).

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Climate Variability and Western Water: What Can We Expect?

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Fresh water has been called a strategic resource that structures the West's natural and cultural landscapes and is a major determinant of sub-regional economies and demographic patterns. The West is characterized by variable climates, diverse topography and ecosystems. The past and present alterations of hydrology in the western U.S. reflect complex histories of human settlement, large-scale water diversions, the development and evolution of water policy and law and, expanding frameworks of water resources management. The nine western water regions identified by the USGS (excluding Alaska and Hawaii) account for 90% of the total (surface and ground) water withdrawn for irrigation and almost half of the total freshwater withdrawals in the U.S. About 47% of all dams and 55% of the total storage in the U.S. occur in the 17 western states (Frederick, 1990). Rapid, relatively recent, population increases, economic growth (including agriculture), the rise of urban centers over the last century (and more so recently) have resulted in intense pressures being placed on western lands, water and institutions. Recent emphases on water demand management, on meeting long-standing obligations, and on environmental concerns have also altered the traditional roles of federal, state and local agencies. In the midst of all of this, the complications of major changes in the spatial and temporal distribution of precipitation, soil moisture, runoff, frequency, duration and magnitudes of droughts and floods, have not, in many cases, been explicitly included in response planning.

Among the primary climate-related stresses in the West are modulations of wildfire occurrence and water supply variability in urban rural and wilderness areas. Precipitation in the Interior West is largely associated with atmospheric transport of moisture from the Pacific Ocean and the Gulf of California (NRC 1991a), with secondary contributions from the Gulf of Mexico, particularly in spring and summer. Through much of the region, there are two annual precipitation maxima: one in the cold season (winter to spring) associated with large-scale storms and orographic forcing, and the other in summer associated with the American southwest monsoon. The relative magnitudes and timing of the two maxima vary significantly through the region, and also display substantial year-to-year variations that are of critical importance to the hydrologic budgets throughout the region. Mechanisms that control the annual cycle and interannual variability in precipitation of the Interior West are only partially understood. There is, however, substantial evidence that the El Niño - Southern Oscillation (ENSO) phenomenon plays an important role in interannual variability of precipitation and climate in general in this region. Tree-ring records also indicate the occurrence of periods of intense, large-scale, and prolonged drought, such as occurred in the 1930s and 1950s, for much of the West over the last 1000 years. The worst of these having occurred in the 16th Century. In this presentation these and more recently identified phenomena will be discussed. In particular, the climatological conditions of Western Regions over the past two decades will be put in the context of climate throughout the 20th Century. The shifts in climate (for instance extended periods of wet conditions

followed by extended periods of dry conditions) will be put in the context of recent insights into the role of the Pacific Ocean on the short (daily to seasonal) and the long-term (decade to decade) climate of the Western U.S. It will be argued that these changes in climate "regimes" may have masked or modulated the efficacy of at least some of the natural resource management efforts during the post-World War II period, confounding possible lessons learned from these programs.

As is now well recognized, decadal-scale (greater than 10 years) climatic factors have influenced present water allocations in the Colorado Basin (Stockton and Jacoby, 1978, Howe and Murphy, 1980). Briefly, the period 1905-1930 was the wettest such period in 400 years of record, with 16 million acre feet (maf) reconstructed annual average flow at Lees Ferry. The Colorado River Compact (1922) among basin states used this average as the base minimum for fixed allocation between Upper and Lower Basins. Since the signing of the Compact the estimated annual virgin flow (1922-1997) has been 14.3 maf, with an historic low flow of 5.6 maf in 1934. During the 1930s streamflow averaged 10.2 maf. Under similar future conditions if the Upper Colorado River Basin states consume the 7.5 maf allocated to them by the Compact they would default on the legal obligation to the Lower Basin. Under the Compact these Lower Basin states have the first right to the allotment. The engineering solution was to construct a dam above Lees Ferry that could store water in wet years and release water in dry ones.

Demographic, institutional, and climatic variations and changes can disrupt existing relationships and current wisdom about climate-society interactions. As shown by the Powell Consortium study, while the Lower Colorado River Basin is indeed drier than the Upper Basin, it is the Upper Basin that may be vulnerable to severe, long-term drought, because of Compact requirements.

There are other documented cases of climatic variations and responses in the West. For instance in the Columbia River there are at least four occasions on which climate variability resulted in major shifts in policy (see Callahan et al 1999):

1. The 1870's-1880s when severe winters devastated the cattle industry on the Columbia Plateau and induced a shift from grazing to agriculture
2. In the early 20 th Century, when declining precipitation brought with it the large-scale irrigation of the Columbia Plateau.
3. In 1948 when severe flooding resulted in the Columbia Basin Project and a proliferation of dams
4. In the 1970's when a series of droughts caused significant power shortages, further reinforcing the calls for increased reservoir capacity

Similarly the Great Basin has experienced prolonged periods of extreme drought in the 1920s and 1930s , in the late 1940s through the early 1960s and from the late 1980s through the early 1990s. Drought occurrences often extends over at least half of the land

area in the Great Basin. Other changes such as that resulting from the oceanic environment influences on Pacific Salmon productivity will be discussed further below.

Year to Year Variations in Western Climate

Much of the year to year variability of precipitation in the West is modulated by the occurrence of El Nino and La Nina events in the tropical Pacific. One of the most notable characteristics of precipitation variability in western North America is the contrasting variation (or seesaw) of precipitation between the northwest and the southwest. When one is dry the other is usually wet. Precipitation usually shifts southward when the tropics are in their El Nino phases and northward during La Nina. El Nino is an irregular, near-cyclical phenomenon in the tropics; the effects of which are felt around the world. In the Pacific Northwest El Nino (warmer than normal sea surface temperatures in the tropical Pacific) winters tend to be warmer and drier than normal. During La Ninas (colder than normal seas surface temperatures in the tropical eastern Pacific) the PNW winters tend to be cooler and wetter than normal.

Natural streamflow in the Columbia (derived from measured streamflow by accounting for diversions, storage in reservoirs, and increased evaporation) tends to be about 10-15% higher during the La Nina events, and correspondingly lower during the warm phase (El Nino). There are, however, several years that do not fit this pattern (such as 1982-83) with warm-phase years with above-average streamflow and cool-phase years with below-average streamflow. The correlation between Columbia River streamflow and the Southern Oscillation Index (SOI) is about 0.45-0.50.

The climate response in the PNW appears to depend on the strength of the ENSO event. Snowpack in the Columbia Basin similarly tends to be low during warm-phase years and high during cool-phase years. This difference does not emerge until midway through the winter accumulation period. It appears that the transition from snow accumulation to snowmelt may occur earlier during warm-phase years. Flooding has historically occurred mostly during the cool phase of ENSO i.e. La Nina, with the major exception being that the devastating 1948 Vanport flood occurred when ENSO was in its neutral phase. Droughts (notably that of 1972-1973) have usually occurred during the warm phase of ENSO.

In the Southwest El Nino conditions are associated with wetter Winters and Springs, and drier Summers in the year following an events. Conversely La Nina conditions are associated with drier Winters and Springs, and wetter Summers in the year following the event. The variability and extremes of precipitation and temperatures after the end of the normal accumulation season (April 1) may also dictate the sonowmelt rates and runoff characteristics (timing and shape) .

Decades-long Changes in the West: The impacts of the Pacific Decadal Oscillation

Recent research has led to a characterization of what is now referred to as the Pacific Decadal Oscillation . The Pacific Decadal Oscillation (hereafter PDO)is an alternating pattern of warm and cold sea surface temperatures in the North Pacific. The

PDO has positive and negative phases. In its positive phase there are colder than normal sea surface temperatures in a large area of the central northern Pacific and warmer than normal ocean temperatures along the eastern edges of the basin (i.e. the West Coast of temperate North America). It was its negative (or cold) phase from 1900-1925, positive from 1925-1945, negative from 1945-1977, and positive since 1977. Extremes in the PDO pattern are marked by widespread variations in Pacific Basin and North American climate. Basically, research has suggested that there is a fairly regular pattern of high and low pressure systems over the northern portions of the Pacific Ocean, off the coast of Alaska and Canada. The pattern correlates with relatively wetter or drier periods in the western portion of North America. Despite the strength and scope of changes initiated by the 1977 regime shift, 10-15 years had passed before the event was fully recognized.

The PDO has been described as a long-lived El Niño-like pattern of Pacific climate variability (Mantua et al 1997). However, typical PDO "events" have shown remarkably greater persistence than El Niño events. In this century, major PDO regimes have persisted for 20 to 30 years at a time. Second, the climatic "fingerprints" of the PDO are most visible in the North Pacific and North America, with secondary signatures in the tropics; the opposite is true with El Niño.

Naturalized Columbia River streamflow tends to be higher than normal in the negative phase of the PDO, and lower than normal in the positive phase. The magnitude of the difference is about the same as for ENSO. Snowpack was generally deeper in the years 1945-1975 than in the years 1925-1945 or 1975-1995. Interestingly the year with the greatest snowpack (1956) was followed by four years of below normal snowpack. There is usually a tendency for unusual warmth (air temperatures and sea surface temperatures) to coincide with unusually low precipitation, snowpack, and streamflow. Tree-ring studies show that the warm dry period of 1925-1945 was the warmest and driest in the Pacific Northwest during the last 250 years. Oceanic conditions associated with PDO have now been shown to have a significant effect on Pacific Salmon numbers in the Northwest.

In the Southwest twentieth century climatic trends stemming from the decade to decade climate behavior include wet winters in the early part of the century (1905-1930), a mid-century dry period (1942-1964) and the warm wet winters and erratic summers since 1976. Recent research has shown that the PDO phases can combine with El Niño/La Niña conditions in certain ways to affect precipitation in the West, particularly in winter. The positive phase of the PDO tends to enhance El Niño conditions and weaken the effects of La Ninas, while the PDO negative phase can enhance the effects of La Ninas and weaken the effects of El Ninos. The suggestion for the Southwest is that, when the PDO is in its positive phase, as it has been since 1977, the Southwest tends to experience wetter El Niño winters, but relatively normal La Niña winters. This combination of climatic conditions tends to improve water supply and land surface moisture.

There is increasing evidence that the PDO may have shifted its signs or phase (since 1995). The winter of 1996-97 in the PNW, with its very high runoff bear strong resemblance to that of the 1950s. In the past such strong flows have been associated

almost exclusively with the negative has of the PDO. In addition there has been a decline in the Bristol Bay salmon catch and the resurgence of Sacramento River Chinook runs. In the past a negative PDO has favored California, Oregon and Washington salmon runs.

If this change has indeed occurred, the Southwest can expect drier La Nina winters, and have El Nino winters that more closely reflect the long-term average precipitation. An extended period of, on average, drier than usual winters would likely produce a decrease in renewable water supplies and thus, the onset of a negative PDO phase could cause the Southwest to experience persistently drier conditions over the next several decades. As yet there are no reliable forecasts for the possible magnitude and duration of such changes. Most of the region experienced a prolonged and severe drought during the 1950s, in the midst of the last PDO negative phase. If a drought of similar magnitude and duration occurred today, the consequences could be anticipated to be at least severe. Even moderately drier than normal conditions could have serious effects in some sectors. For instance, forest fire management is another area crucially influenced by such climatic conditions and trends. University of Arizona researchers have documented that ranching operations in the Southwest are highly sensitive to climatic conditions and have already been affected by dry conditions of the past couple of winters. In addition as was shown during the 1987-1992 drought in California environmental stresses in wilderness and protected areas are usually impacted even when the economic impacts are mitigated.

Decreases in winter precipitation associated with negative PDO conditions and intensified La Nina conditions could, for example, put stress on the urban water systems of the Southwest. The UA's Climate Assessment Project for the Southwest (CLIMAS), operating under funding provided by the National Oceanic and Atmospheric Administration (NOAA), conducted an analysis of the effects of prolonged drought on the urban water supplies in the Phoenix and Tucson Active Management Areas (AMAs). The research team assumed a ten-year drought of the magnitude of the one that occurred in the 1950s and demand levels projected by the Arizona Department of Water Resources for 2025. Even assuming full availability of Central Arizona Project (CAP) water, the Phoenix AMA could well exceed its renewable water supply by 39 percent. This constitutes a 15 percent increase over the 24 percent overdraft the AMA has already projected for 2025 in its recently completed Third Management Plan. Likewise, even under normal climate conditions, the Tucson AMA expects to see a 15 percent groundwater overdraft in the year 2025. A ten-year drought comparable to that experienced in the 1950s could increase the overdraft by another 10 percent.

The variations and changes described above can mask both positive and negative land and water management program, confounding the lessons that may be learned from various approaches. For instance it has been argued that because of the lack of incorporation of decadal scale climate variation, fisheries managers in the Northwest have misinterpreted three major situations (see Anderson, 1999) (1) managers have overestimated the significance of harvest on the catch decline after 1920 by not accounting for climatic influences that lowered ocean survival, (2) managers have underestimated the detrimental effect of the hydrosystem by not accounting for good ocean survival conditions during the years of hydrosystem development, and (3) it has

become difficult to consolidate the successes of stock rebuilding measures in the last two decades because of concomitant poor oceanic conditions

The Southwestern region has experienced considerable growth and change in the past two decades, a time when conditions have been relatively wet. Great improvements in range conditions since the major deterioration in the 1950s, in the Southwest, may have been heavily influenced by the recovery of favorable precipitation conditions in the last two decades.

Conclusions

Most Western basins exhibit the characteristics of "closing water systems", where, the development of mechanisms to get resource users to acknowledge interdependence and to engage in negotiations and binding agreements becomes necessary (Peabody, et al, 1981). The result so far has been a somewhat constrained regional capacity to implement plans relating to the impacts of environmental variability and change. Even in the water-rich Pacific Northwest region, trade-offs, (for example between hydropower and salmon migration requirements) have appeared to bring allocation systems to their limits, threatening the very sense of community and reducing the likelihood of water transfers to drier regions.

From the brief overview above we can conclude the following:

Precipitation variability in much of the western US is characterized by regional north-south contrasts that appear at many timescales

There is ample evidence for climate behavior of wet and dry periods on "decadal scales (15-30 year periods) in both the instrumental and tree-ring records

The Southwest has been experiencing wetter conditions that is normal since 1976 (and vice versa for the Pacific Northwest)

There is some evidence indicating a shift in this regime to conditions similar to the pre-1976 (post 1945) situation

The Western U.S. offers and has offered unique opportunities for identifying lessons for strategic learning about the management of cross-scale issues including climatic risks (see Table 1)

There needs to be greater focus on the cumulative effects of high probability low impact events as well as low probability, high impacts events. This includes explicit examination as to why some expected outcomes are not occurring in spite of "best available knowledge" (e.g. Pacific Northwest wild salmon recovery programs).

Water resource systems are in a state of constant adaptation to past events. While there is now needed focus on trends in event occurrence and decadal-scale variations, there is still limited knowledge of how the evolution of responses during and between

events informs preparedness to abrupt, prolonged changes or surprises (such as the 1977 regime shift)

One problem is that both researchers and resource managers have difficulties anticipating how complex systems will respond to environmental stresses. While water banking and inter-basin transfers have been used to mitigate the effects of short-term drought, the maintenance of supply during periods of severe long-term droughts of 10 years to 100 years (the timescales of project implementation and ecosystem management efforts), known to have occurred in the West over the past 100-1000 years, is as yet untested. The spatial extent and persistence of drought may produce shortages not only in the locale considered but also in neighboring regions that otherwise are supposed to make surplus water available for inter-basin transfers. On the other hand the transformation of the Red River in North Dakota in the spring of 1997 and on the Colorado in 1983 remind of what can happen when too much water arrives in too short a time. Increases in flood and drought variability would require a re-examination of emergency design assumptions, operating rules, system optimization, and contingency measures for existing and planned water management systems (see Stakhiv, 1993). Engaging the many dimensions of multiple-stress problems, accumulating over the decadal-scale, requires more than ever, the need to understand the interactions of social, cultural, climatic, economic, hydrological and ecological histories and networks, that help to shape shared community interests and values.

Table 1. Examples of cross-scale issues in river management on the Colorado River (Ingram et al 1990, Pulwarty and Melis, 2000)

Temporal scales

Indeterminate: Flows necessary to protect endangered species

Long-term: Inter-basin allocations and those allocations among basin states

Decade: Upper Basin delivery obligations, life-cycle of humpback chub (*Gila cypha*)

Year: Lake Powell fill obligations to achieve equalization with Lake Mead storage

Seasonal: peak heating and cooling months

Daily-monthly: Flood control operations, Kanab ambersnail impacts

Hourly: Western Area Power Administration's power generation decisions

Spatial scales

Global- Climate influences, Grand Canyon National Park World Heritage Site

National-Western water development: irrigation, Grand Canyon Protection Act (1992)

Regional-Prior appropriation, Upper Colorado River Commission, Upper and Lower Basin Agreements, energy grid

State-Different agreements on water marketing within and out-of-state, Water Districts

Municipal--community-household