SNOWPACK TRENDS IN THE CENTRAL SIERRA NEVADA AFFECTING WATER SUPPLY FORECASTS IN THE EAST SLOPE SIERRA BASINS

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ABSTRACT: Water supply forecasts in the Western US have long been based on historical statistical relations between the predominantly winter precipitation and subsequent spring and summer streamflow. The snowpack in the mountainous West, and specifically in the central Sierra Nevada has been measured since the early 1900s. Currently the USDA Natural Resources Conservation Service and the California State Cooperative Snow Survey program measure snow in the Sierra Nevada and keep long term records of the snowpack. These historic data are a good indicator of seasonal precipitation in the building of the snowpack in the region. A statistical analysis of the snowpack record at Donner Summit compared to Tahoe City precipitation reveals a shift in the relation that occurred in the late 1970s. This change is significant at the .999 confidence level. Since the late 1970s, there has been a decrease in the amount of cumulative snowpack on April 1 in comparison to the seasonal accumulated precipitation from October 1 through March 31 between these two sites. This indicates that from 1980 to 2007 there has been more rain than snow compared to the previous 43 years. The change has been observed at other locations in the region.

Figure 1. Lake Tahoe and the Truckee River Basin on the California/Nevada border.
INTRODUCTION

The snowpack has been measured in the West since the early 1900s. At the time it was recognized that the building snowpack represented the majority of the water supply for the arid West. These snowpack measurements which began in the central Sierra Nevada have been the basis of water forecast modeling since that time. The central Sierra Nevada Mountains (figure 1), have a well defined seasonal precipitation pattern that falls primarily as snow. Snow was first measured to determine the amount of water held in reserve until snowmelt provided the water to the streamflow providing water for Reno NV, and surrounding agriculture. From these early times to the present day, the USDA Natural Resources Conservation Service and the California State Cooperative Snow Survey program measure snow in the Sierra Nevada and keep long-term records of the snowpack. These long-term records are a good indicator of seasonal precipitation resulting in the building and melting of the snowpack in the region.

The relation between snowpack and streamflow was determined early in the 1900s to be the best determination of the available water supply for the coming spring and summer, since it provided the majority of water needed by municipalities, agriculture and other water interests in the form of snowmelt runoff. Long term records of both parameters made the relation easy to determine using simple regression techniques. Currently, snowpack, precipitation, temperature, and streamflow all are used in the relation to create the most accurate statistical forecast model available for determining future water supplies. The assumption that is paramount is that the historic record is an accurate reflection of the stationarity and/or the steady state of the relation. In other words, the relation is static and will continue for the current and subsequent years. Unfortunately, with the changing climate, this assumption may not be reliable.

CLIMATE CONDITIONS

The climate is changing continuously, and it is an ongoing subject of many major research efforts by many entities in the US and around the world. One of the most often characterized affects will be the reduction of snowpack in the Western US and Canadian mountains by the middle of the 21st century (IPCC#2, p. 102). In the projections of the climate trends into the future, snowpack in the Western US is predicted to be reduced below historic records. Some of this change was thought to be related at the time to the pacific decadal oscillation (PDO), (Koczot and Dettinger, 2003). Several authors noted that the general climate in the Western US had shifted to a new paradigm in the late 1970’s (Pagano and Garen, 2005). Across the West in the late 1970’s, a severe drought occurred, and water supply conditions were severe for a few years. Snowpack measurements recorded at the time were at their lowest amounts of snow water equivalent (SWE) since measurements began in the early 1900s. This unprecedented dry period lead to speculation of the causes and predictability of these events and the climate index of a strong El Niño of that year came into the common public vocabulary.

Figure 2 from the IPCC indicates a rising trend from 1961 in global average sea level, surface temperature, and shows the pattern of annual snowpack changes that have changed in respect to a global perspective. Local changes can be different and more profound, and are affected by the influence of the changes in weather patterns.
STREAMFLOW FORECAST MODELING

Streamflow forecasting from snowpack SWE has occurred since the early 1900s. There is a strong correlation between snowpack and subsequent streamflow, especially in the Western US. The precipitation in the mountainous West falls primarily in the winter season and mainly as snow. The snowpack represents up to 80 percent of the entire year’s precipitation. Statistical models to predict streamflow were initially developed using simple correlations, while the current more sophisticated statistical models use multiple regression principal components techniques (Garen, 1993). Independent statistical model parameter selections are optimized by NRCS custom modeling software which also assists in other testing of the robustness of the models developed.

One of the primary water management forecasts for the Reno area is the predicted streamflow at the Truckee River at Farad, CA USGS streamgage. This forecast is vital to water management for downstream water allocations necessary to meet competing water needs for agriculture, endangered fish species, tribal and municipal needs. The record of the streamgage at the Truckee River at Farad (Figure 3), shows the historical annual variability in the long term record. The period of record trend shows very little change in volume. The figure displays a 5 year moving average, which best illustrates the changes in streamflow pattern over the record. In the pre-1980 period, there was not a well determined pattern of flows from year to year. Since that time there are more persistent high flow years following high flow years, and low flow years following other low flow years. This change in increase of magnitude of flows seems to be following about a 20 year pattern in the 5 year moving average. Also of note is an increase in persistence of this series of wet and dry years which are remarkably different than earlier years in the record. This increase in persistence and variability was also noted by Pagano and Garen.
(Pagano and Garen, 2005). They studied the increase in variability and persistence of extreme years and noted that it has been increasing.

Figure 3. The Truckee River at Farad, CA full natural flow water year period of record.

**SNOWPACK AND PRECIPITATION CHANGES**

Historical traces of precipitation and snowpack show changes similar to the streamflow observations in the Truckee River. An example of the long term snowpack measurements is the Donner Summit Snow Course (Figure 4). This manual snow course has been measured monthly from February through May since 1910 and is one of the oldest snow courses in the West. This long term record can be used to determine possible trends in the snowpack. Of most interest is the snowpack during the spring months, and the comparison between the March 1 to the April 1 SWE measurements which have long been considered the peak snowpack in this area. In Figure 4, it can be seen that the April 1 measurements are most typically larger than the March 1 snowpack for most of the record, until the mid 1980s. The early 1980s trend was dominated by the large record setting snowpack in 1983. At the current time, the March and April measurements are very similar as evident of the very closely running 5 year moving averages of the 2 records. In addition, the amount of precipitation and snowpack was markedly more variable during the later period, with dry years becoming drier than most previous years, and wet years becoming markedly wetter.
Figure 4. Donner Summit Snow Course March 1 and April 1 period of record SWE measurements and trends.

The nearby precipitation at the National Weather Service (NWS) Coop station Tahoe City California on the northern side of Lake Tahoe is shown in figure 5 represents the transition zone of snow and rain that can occur at these lower elevations near Lake Tahoe. The October through March winter precipitation long
term record shows a trend in increasing annual persistence and variability, especially in the 5 year moving average trend line, mirroring the trend seen in the Truckee River streamflow record. A comparison of the winter precipitation to the snowpack on April 1 is shown in figure 6. The 5 year moving average lines converge after the late 1970s, and continue much closer together at the present time. Figure 7 compares the seasonal precipitation as a percent of the April 1 snowpack.

Figure 6. Lake Tahoe at Tahoe City NWS Coop Station October 1 through March 31 total Precipitation and April 1 snowpack SWE at Donner Summit Snow Course.

Figure 7. Seasonal precipitation as a percent of the snowpack at Donner Summit on April 1.
With a few exceptions, since the late 1970’s, the precipitation has been close to or exceeded average many more times than in previous years. Figure 7 shows a trend of increasing precipitation to SWE on April 1, which suggests that less of the seasonal precipitation is being stored as snow. The relation from 1980 to present is different in comparison to the previous data record of 1900-1979. Research has documented this climate shift that occurred in the late 1970s in the West (Pagano and Garen, 2005). The more recent snowpack measurements show a change in the overall amount and persistence and variability, with multiple years of dry and wet conditions falling together. This change coupled with the change in the relation of winter precipitation in relation to snowpack suggests that there are also changes in snowmelt and runoff timing. The analysis reveals that since 1980, there has been a decrease in the amount of the April 1 cumulative snowpack when compared to the seasonal precipitation (October through March) between these two sites. This indicates that for the period 1980 to 2007 there has either been more rain than snow compared to the previous 43 years, and/or the snow is melting earlier, so less is on the ground on April 1.

**Statistical Significance**

There is a statistically significant change in the precipitation to snowpack ratio from the pre and post 1980 date. The change in the ratio between the April 1 snowpack at Donner Summit and October – March precipitation at Tahoe City before 1980 and after 1980 is statistically significant at the .99 level ($t = 3.0$). The change in the precipitation and snowpack at this time was significantly different, and suggests that there is less snowpack now than in the previous time period. Though this change is easily displayed as a trend, the true long term change is most likely not as simple as a trend line.

Historically, many statistical water supply forecast model calibrations which use 30 years or up to the period of record precipitation, snow, and streamflow assume a stable, long-term relation between these climate elements to continue. However, there is evidence that water supply statistical forecast modeling will now need to focus on the period of 1980 to present to best account for the current climatic regime.

**WATER SUPPLY FORECASTING EFFECTS**

The trend in the snowpack and precipitation in the Tahoe – Truckee basin suggest that the relation of the water stored as snow on April 1 is less in the spring in comparison to the cumulative winter precipitation from the October through March time period. This change will affect the long term statistical relation between the parameters. Forecast statistical models at the Truckee River at Farad are fairly accurate on April 1 (figure 8). As with most statistical models the model tends to underforecast high years and over forecast in low years, as the regression equation is a straight line relation, while the natural relation in extreme years is not linear.
Looking at the overall errors displayed in figure 9, it can be seen that there were some years where forecast errors were large. The early record shows primarily a positive overall bias, while the recent record shows a slight negative bias after 1989. This bias is especially evident looking at the 5 year running average of the errors. The bias can be attributed to changing statistical methods, data used, unstable relation between parameters, as well as a changing climate. While
in reality, the bias may be a combination of many variables that go into forecasting, additional research may determine that the bias is a result of only a few causes. A reduced snowpack with no overall change in average precipitation would intuitively have an effect on forecasting as there is less water available stored as snow for late spring and summer runoff. This bias in the errors will determine needed updates and changes to the forecasts in the basin. Other parameters may need to be tested, as well as changes to the timing that affect the target forecast period.

CONCLUSION AND DATA TRENDS

There are evident changes in variability, persistence and in the migration of the peak snowpack to earlier in the season within the Truckee River system. Precipitation trends show increased magnitude and persistence in winter period that may continue. The snowpack may continue to decrease in water content on the April 1 snowpack measurements at low and mid elevations. The current relation between the decreasing April 1 snowpack to a more static October – March precipitation may continue into the future. If trends persist, the peak snowpack may be measured closer to March 1 than April 1. There is no overall trend in the annual water runoff volume, though the timing is changing. This will require the water supply forecast models to change to take advantage of the current snowpack and winter precipitation and their relation to streamflow. Difficulties and challenges will continue and possibly increase in forecasting water supplies and managing water in a changing climate and runoff regime.

REFERENCES


