SNOWMELT RUNOFF IN THE SIERRA NEVADA AND SOUTHERN CASCADES DURING CALIFORNIA'S FOURTH CONSECUTIVE YEAR OF DROUGHT

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ABSTRACT

For California statewide the 2015 water year, which followed three prior dry years, produced several new hydrometeorological records including but not limited to low runoff, dryness and warmer than normal minimum temperatures. The 2015 spring freshet from snowmelt reflected the general lack of snowpack, setting several new records for low spring flows leaving most of California reservoirs less than full. Headwaters which drained the Sierra's exposed granites suffered some of the lowest late summer and fall flows on record. Northern California's rivers such as the Pit, McCloud, Upper Sacramento, Klamath, and North Fork Feather River above Lake Almanor which have portions of their watersheds overlaying the High Cascades volcanic aquifer systems while at some of their lowest flow rates on record still managed to maintain higher flow rates than for the Sierra exposed granites. While water year precipitation was less than normal, the majority of precipitation occurred in December 2014 with storms delivering the majority of water year precipitation during a couple weeks mostly in the form of rainfall. A large number of the storms that entered California during the 2015 water year occurred as atmospheric rivers with rainfall occurring on the higher headwater areas of the Sierra. The relatively high elevation southern Sierra was much drier than northern California, so despite its higher elevation conducive to snowfall, precipitation was among the driest on record, leaving only a shallow snowpack on summits above 2,700-3,300 meters elevation. Precipitation and unimpaired flows for the past four years were analyzed and compared with prior drought periods to gather perspective as to the severity of the drought. Years such as the 2015 water year can provide foresight into what California's late summer and fall mountain flows may look like with continued warming temperatures. Several studies have indicated a significant reduction in snowpack for California's mountain areas by the end of the 21st century. (KEYWORDS: drought, climate change, snowpack, volcanic aquifer systems).

INTRODUCTION

In spite of a very wet December 2014, during the April 1, 2015 snow survey at the Phillips snow course on the headwaters of the American River, Governor Jerry Brown directed the first ever statewide mandatory water reductions for California including a mandatory 25 percent cut in urban water use. The governor's emergency order came after a year of requests for 20 percent voluntary conservation and a record-breaking warm and dry spell culminating in the worst April snowpack in recorded history, which failed to alarm many Californians enough to cut back on water (Weiser and Siders, 2015). The absence of a sizable snowpack in California, accompanied by a 16 year trend of both declining precipitation and volcanic aquifer outflows in northern California and some of the warmest temperatures on record (Freeman, 2014 and 2015) created concern that the State's current population would be challenged beyond that which was experienced in past droughts such as during the 1988-92, 1976-77, 1924-34 periods. Studies of paleoclimatology indicated that much of the twentieth century enjoyed an extended era of wetness not necessarily typical for the California. Ingram (2013) has shown evidence that extended periods of dryness or mega droughts are common for the southwest. This information along with increasing realization that continuing impacts from climate change is likely to increase the level of uncertainty regarding precipitation amounts increases planners' focus on drought preparedness. Since planning decisions for water releases typically begin in January for accommodating the spring freshet, reservoir management planning is difficult in low snow years (Freeman, 2015). During years such as 2015 which had a very shallow snowpack, reservoir planners do not have the certainty of a snowpack in place, but instead must rely on the uncertainties of remaining weather for filling and planning water releases. In 2015, there was increased incentive to store reservoir inflow; however, storing inflow can carry significant opportunity cost which is the cost of storing the water now for later use versus the risk of maintaining sufficient space to hold a large storm event. However, it turned out such that the late winter period and spring months remained drier than normal and for most locations spill from storm events became a nonissue for operators. The four years of drought added approximately 2 billion dollars in California's electricity costs (Pacific Institute, 2016). During a normal year, hydro can account for as much as 18 percent of the state's power supply.

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According the Oakland based Pacific Institute's report that percentage fell to 10.5 percent during the four years of drought, including a low of 7 percent in 2015. With the cutback in surface water deliveries to farmers and agriculture in California's Central Valley, wells were deepened and agriculture increasingly relied on groundwater pumping as an alternative to normally available surface water deliveries (Howard and Millsap, 2014). Excessive rates of groundwater pumping likewise created significant land subsidence issues in the San Joaquin Valley with some areas sinking nearly 5 centimeters per month (NASA-JPL, 2015).

PRECIPITATION

Precipitation for the 2015 water year was much below normal statewide. Figures 1 and 2 compare precipitation indices utilized by the California Department of Water Resources (DWR) for both the Northern 8-station and for the San Joaquin 5-station precipitation indices respectively. A large difference between the two charts occurs in December with the Northern index in Figure 1 showing 173% of average for the month, while

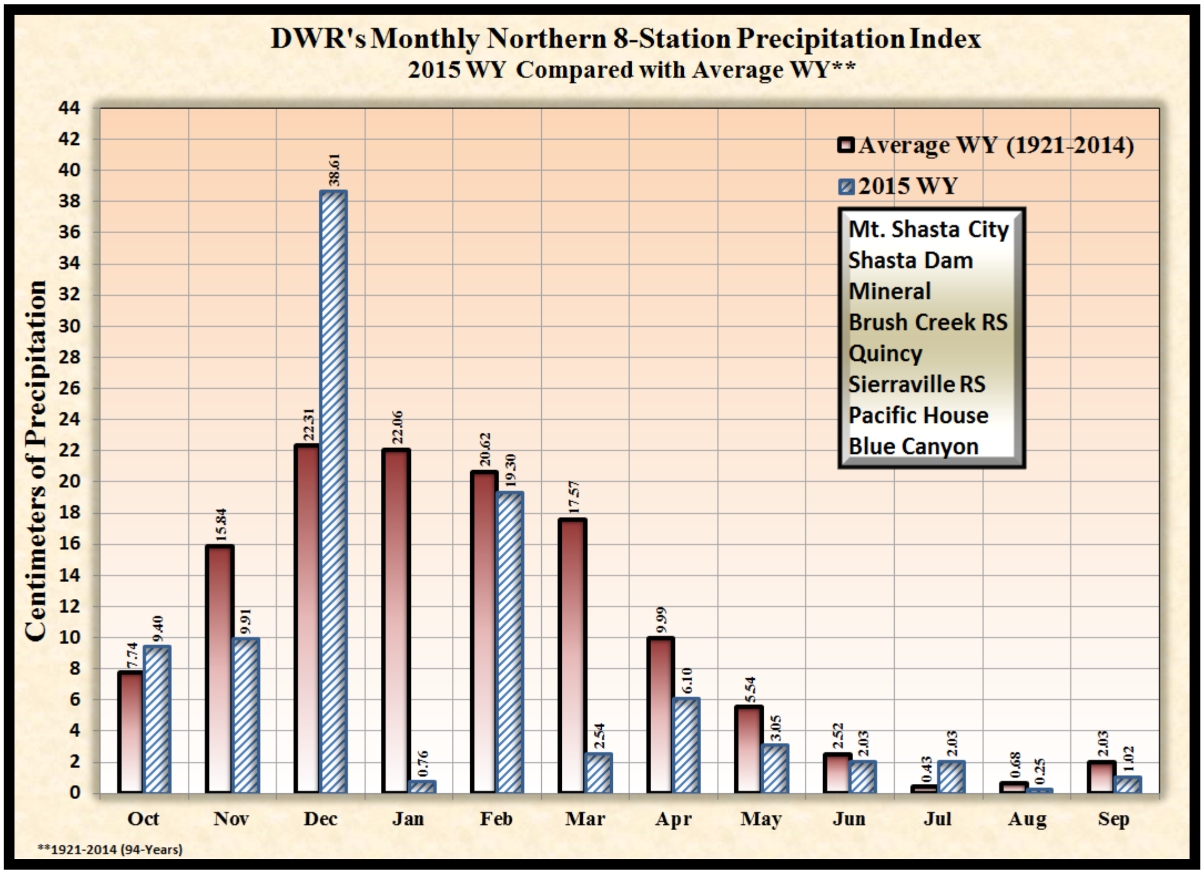

Figure 1. DWR's Monthly Northern 8-Station Precipitation Index. 2015 WY compared with historical average.

the San Joaquin Index shows only 92% of average. Water year percent of average for both indices was below average with the San Joaquin Index at 49% of average being less than the Northern 8-station index which was 75% of average. The 2015 San Joaquin water year index with 19.00 inches was the third lowest on record with only 1977 (15.37") and 1924 (14.63") having been lower for the 92-year period of record. For the San Joaquin Index, the 4-year 2012 through 2015 water year period was the driest 4-year period on record for records starting in 1913 (103 years). Likewise the 4-year 2012-2015 water year period was the lowest on record for DWR's northern 8-station precipitation index. The persistence of the high pressure ridge in the eastern Pacific may have been a factor (Henson, 2015). There were indications that climate change and consequent arctic amplification may slow and increase the waviness of the jet stream leading to an increase in the frequency and severity of persistent weather patterns in the Pacific (Francis, 2012 and 2015). The combination of record high temperatures and the record four consecutive years of dryness led to an increase in Pine Bark Beetle infestation, which in turn has killed over 12

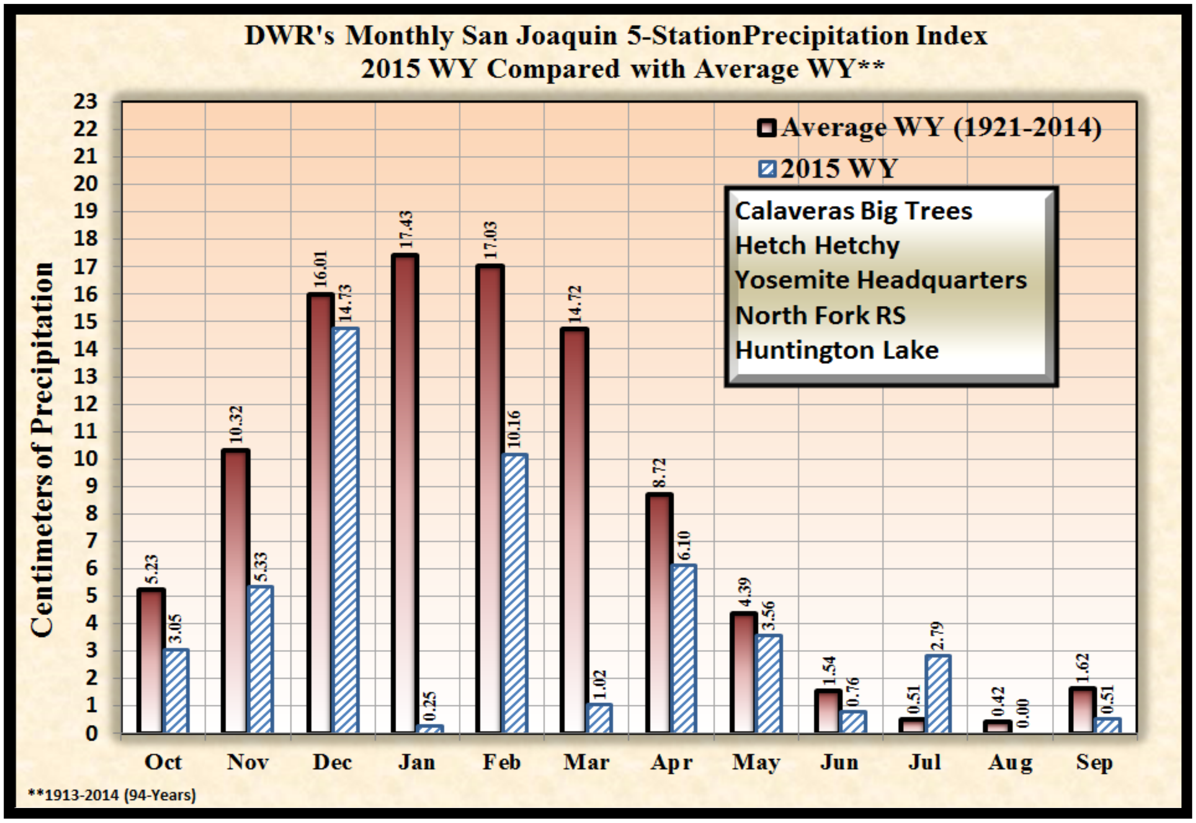

Figure 2. DWR's Monthly San Joaquin 5-Station Precipitation Index. 2015 WY compared with historical average.

million trees in across California (Sabalow, 2015). For DWR's San Joaquin Valley precipitation index, the 17-year period which began in 1999 and lasted through 2015 was 19% drier compared with the previous 17-year period. Statewide, the impact of the very dry 2015 water year likely seemed greater than otherwise as temperatures were warmer than those of past droughts and water resources were lacking from the three previous dry years. Starting with 1999, with the exception of a couple wet years, there was a 16 year period characterized by most years having below average precipitation. In spite of a 5 year-drought which occurred during the 1988-1992 period, overall the 1982-1998 period was unusually wet, even if much of the precipitation came as floods. For the Lake Spaulding precipitation station along Highway 80, January 2015 had only one day with precipitation leaving it with the fewest wet days in the month of January for the past 67 years (1949-2015). The trend during that period has been a slight increased number of dry days in January (Figure 3).

SNOWPACK

In addition to 2015 having the lowest statewide snowpack on record dating back to 1955 (Figure 4), both the Sacramento and San Joaquin snowpacks had the lowest 4-year moving average (30% and 33% respectively) on record, with 1990 being the next lowest at 47.5% of average for both areas. DWR's Northern 8-station precipitation index for the period November 1 through March 31 was compared with the overall percent of average snowpack for the Sacramento Valley on April 1.The ratio of snowpack to precipitation for 2015 was at 7% the lowest on record. The next lowest ratio was 1988 (32%) followed by 1997(37%). 2015's unusually warm temperatures clearly created an unusual snow situation, one not historically typical for the Sierra and southern Cascades. Multiyear lack of snowpack can result in higher than normal water temperatures for the large rim reservoirs such as Lake Shasta and Oroville. Also summer replenishment of soil moisture during the active growing season for watershed vegetation can lead to stress and lack of healthy sap flow. This became increasingly evident during the 2015 water year when late summer and fall soil moisture was inadequate to support healthy forest growth. Also the lack of a reflective snowpack led to increased soil surface heating further drying forest soils. Figure 5 which plots the 2015 snowpack

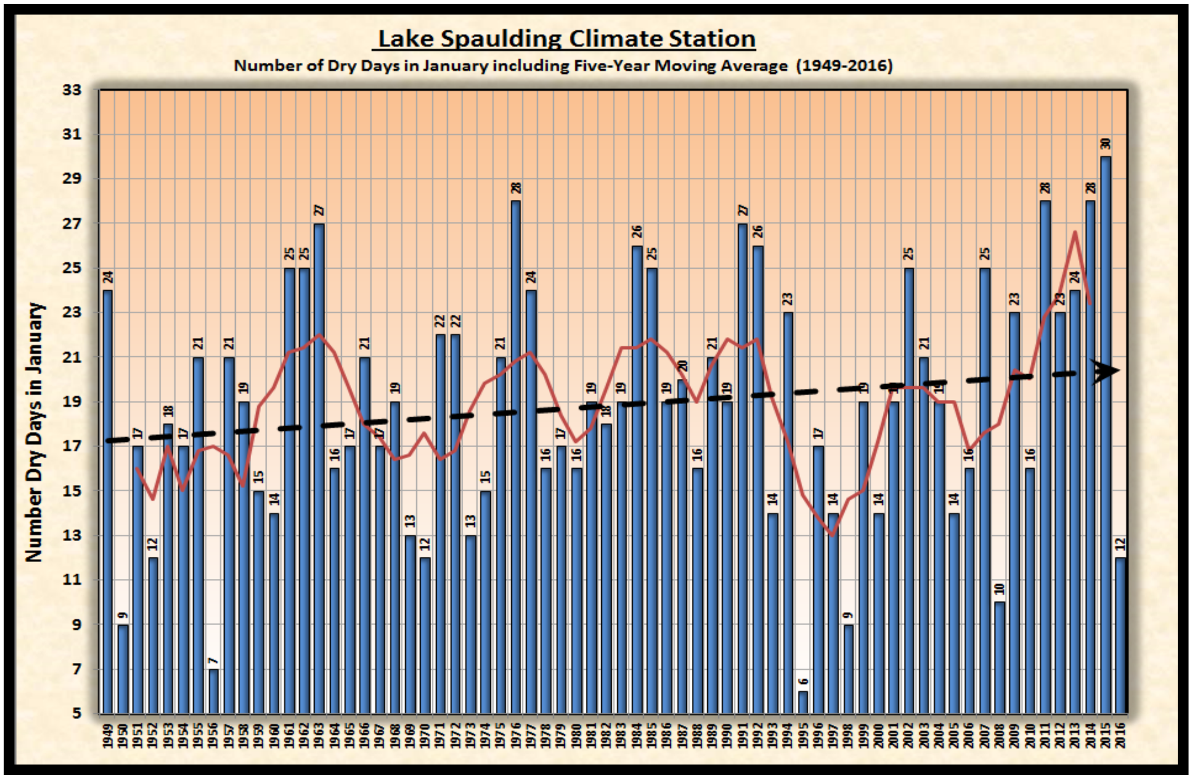

Figure 3. Number of Dry Days in January for the 1949-2016 period.

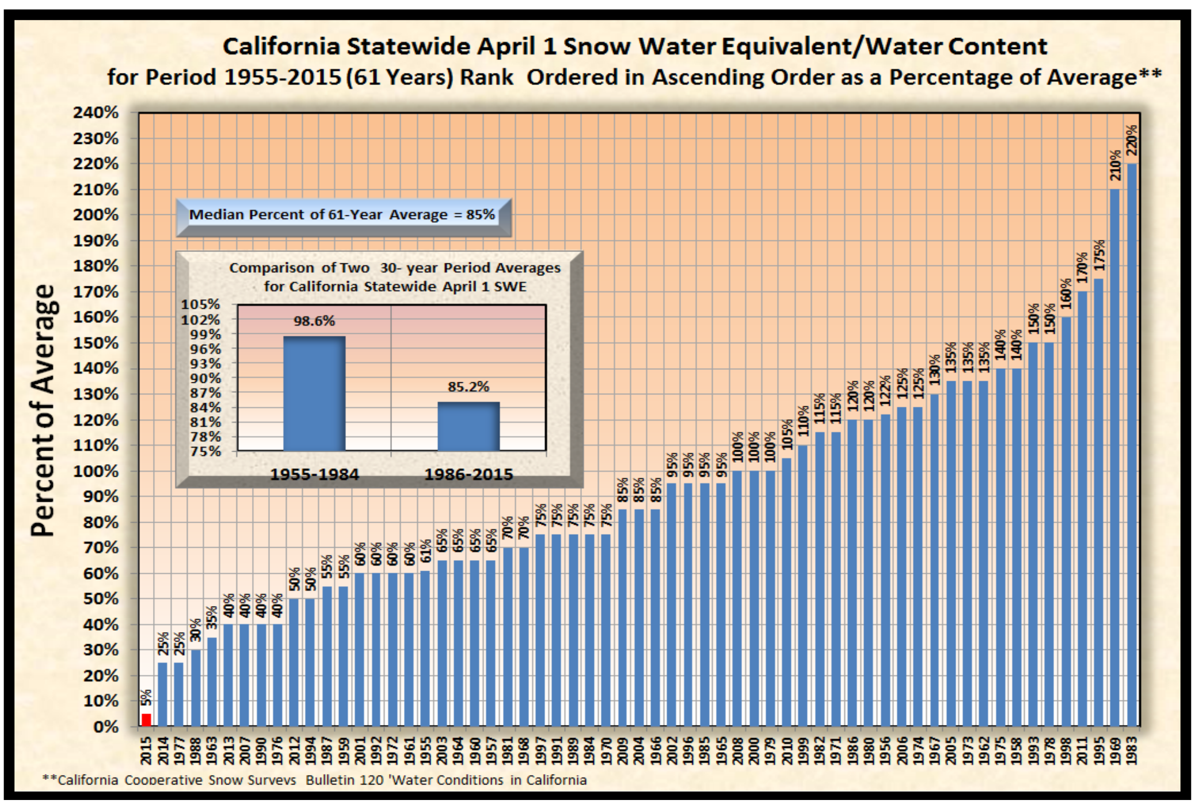

Figure 4. Statewide April 1 SWE as a percent of average for period 1955-2015 (61 years) sorted in ascending order.

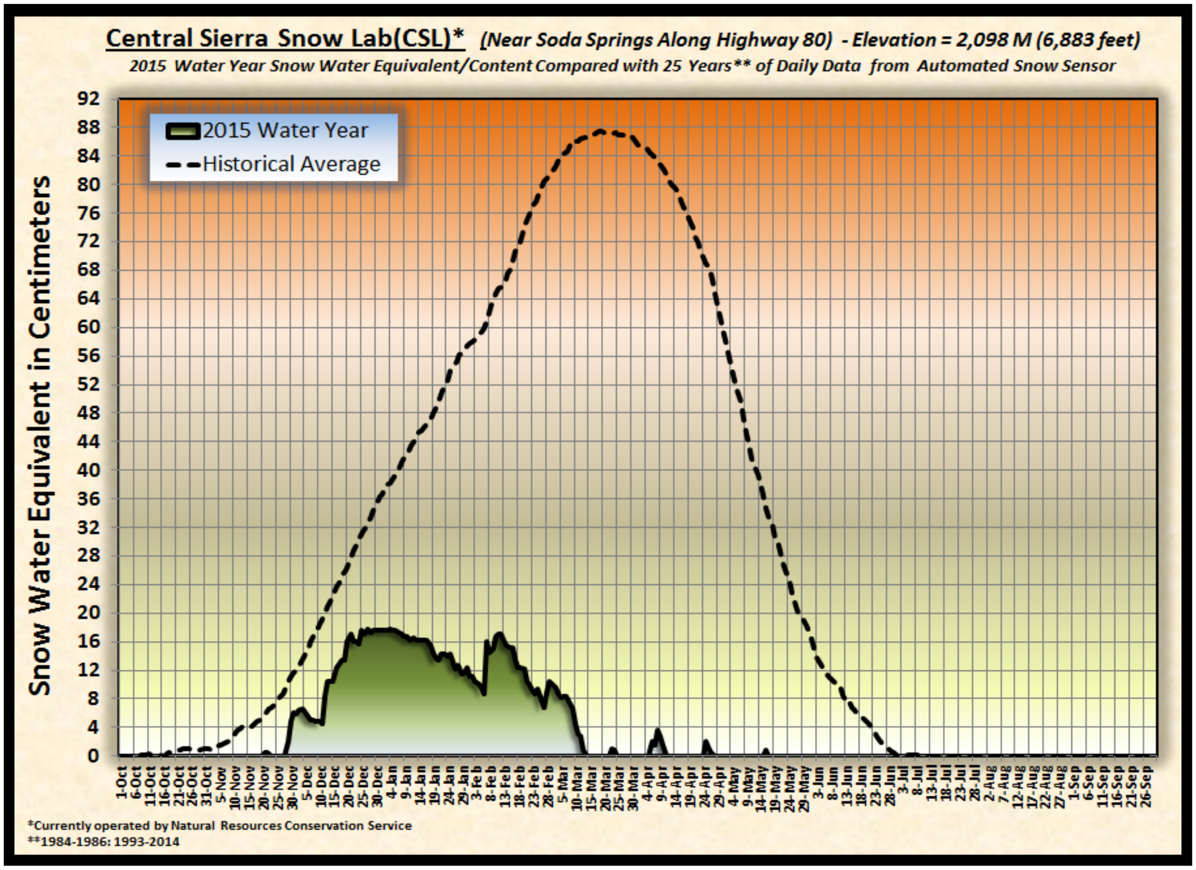

Figure 5. 2015 Water year record compared with historical daily average for the automated snow sensor at the Central Sierra Snow Lab near Soda Springs in the Central Sierra.

SWE at the Central Sierra Snow Lab near Soda Springs in central California against the historical average seasonal curve shows that by mid-March the snowpack had melted out, then recurred briefly a few more times, each time quickly melting out. For California with its Mediterranean climate, the lack of a snowpack for storing winter precipitation results in low stream flows for about half the year. Fortunately for the dry northern California water situation, the mountain reservoirs were at relatively low water levels prior to the December storms and were able to store nearly all of the rainfall generated inflow. In the absence of a snowpack for storing water, the ‘almost empty reservoirs’ could accommodate that which in most years would have occurred as snowpack. As temperatures continue to trend upward in California’s Sierra Nevada and southern Cascades mountain ranges from the effects of continued climate warming, the increased likelihood for less snowfall and an earlier snowmelt may be inevitable. It’s likely that feedback similar to arctic amplification, which are associated with the increasing loss of snowpack, will increasingly reduce albedo and increase the rate of warming accelerating the rate of snowmelt. In the absence of a snowpack, a darker surface is also likely to evaporate more water in the liquid phase through evapotranspiration than conversion of snowpack with its associated high latent heat needed for converting the snowpack to the vapor phase. Northern California’s relatively low elevation watersheds on the Upper North Fork Feather river have shown indications of an increased evapotranspiration rate evidenced by less runoff to the river and available for groundwater recharge. While Statewide on April 1, 2015 the snowpack was 5 percent of average, except for the highest elevation snow courses, most courses were already at zero snow water equivalent. Both the lack of precipitation and some of the warmest temperatures on record had melted most of California’s snowpack. Runoff recovery from snowmelt was below average as a large portion of the available melt simply resupplied dry soils. The lack of snow cover at most locations occurring by late March likely allowed soils to warm quicker than is typical, which would facilitate an earlier than normal growing period for forest vegetation. As soils quickly lost their available soil moisture, forest vegetation became increasingly vulnerable to disease, fires, and other risk related mortality (Guarin and Taylor, 2005). Springs and groundwater recharge areas that would have normally been charged during normal snowmelt type years were left without sufficient water to carry their normal late summer flows to the rivers.

TEMPERATURES

Record temperatures occurred in the 2015 water year. Conditions in the eastern Pacific were such that a large 'blob' of unusually warm water was located in the eastern Pacific Ocean. In addition to blocking storms that would otherwise advance into California, this ridge allowed much warmer air to continuously accompany storms coming across the Pacific. Minimum temperatures seemed most impacted and were much higher than normal. In addition to the extreme dryness, unusually warm temperatures created a highly unusual situation which both melted any existing snowpack and stressed forest vegetation which needs an ample supply of moisture during the growing season for evaporative cooling of leaves and healthy sap movement to prevent invasive borers. Accompanying the loss of snowpack, mountain streams and reservoirs experienced warmer than normal water temperatures, which likewise stressed the aquatic fauna and flora. It seems ironic that during times when runoff is at its lowest point, evapotranspiration is taking an increasing share. Figure 6 which plots data from the California Climate Tracker shows a trending increase in minimum temperatures in recent years with the 2015 water year breaking all records for the 120 years of record (California Climate Tracker. 2015). While average and maximum temperatures also broke records, minimum temperature can provide helpful insight into the impacts of climate change as they can indicate an increase of heat trapping greenhouse gases leading less effective nighttime cooling (Freeman, 2011 and 2012). Storms with higher snowlines in 2015 increasingly limited options for cloud seeding in the Sierra. Cloud seeding operations such as those operated by Pacific Gas and Electric Company generally set freezing level criteria as a trigger for conducting seeding operations. For the northern Sierra such as those that take place on the upper North Fork Feather River, seeding criteria were seldom met in 2015, and when triggered, the seeding period was limited more than was typical for winter storms.

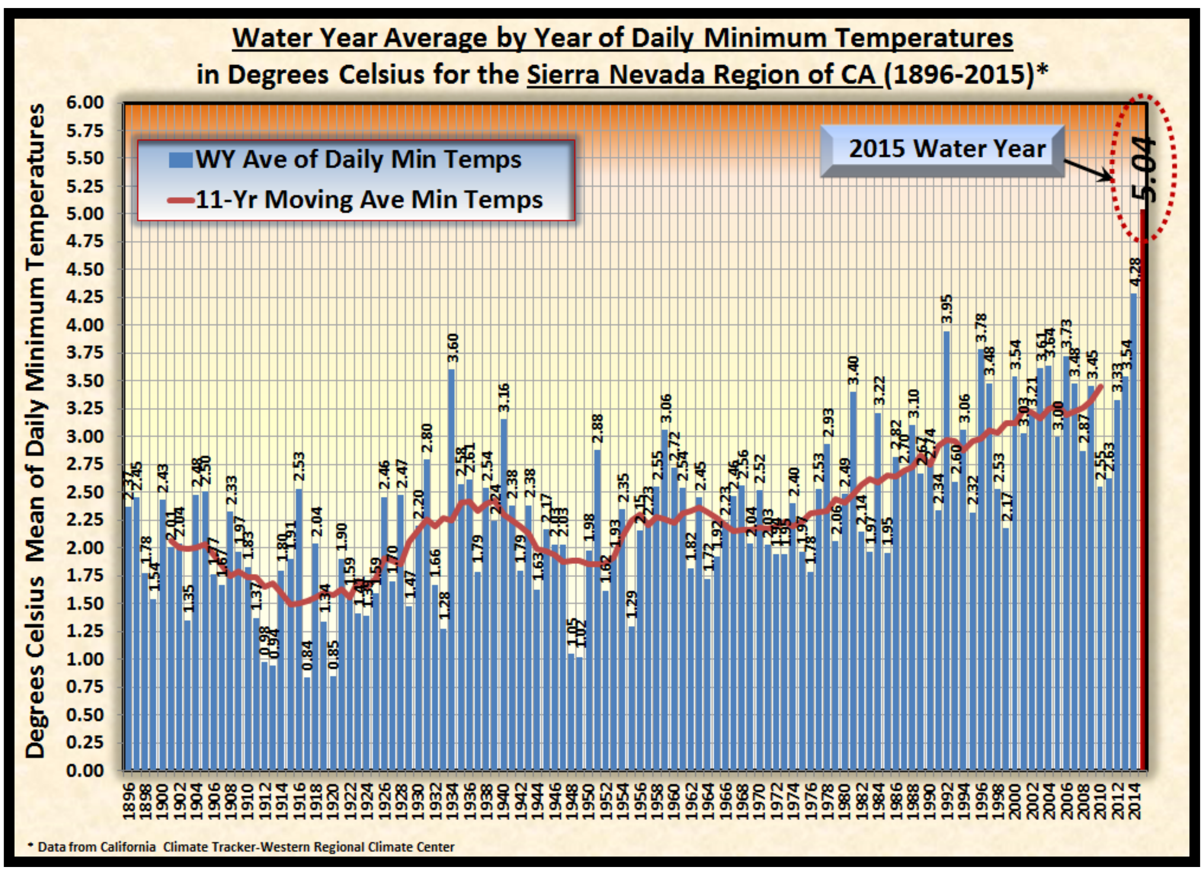

Figure 6. Water Year means of daily minimum temperatures for the Sierra Region of California. Data compiled from California Climate Tracker, Western Regional Climate Center.

SNOWMELT RUNOFF

Consistent with a long term trending shift in seasonal runoff from the spring and early summer period into the winter period (Figure 7), the snowpack for the 2015 water year dramatically exhibited a rainfall- dominated type of

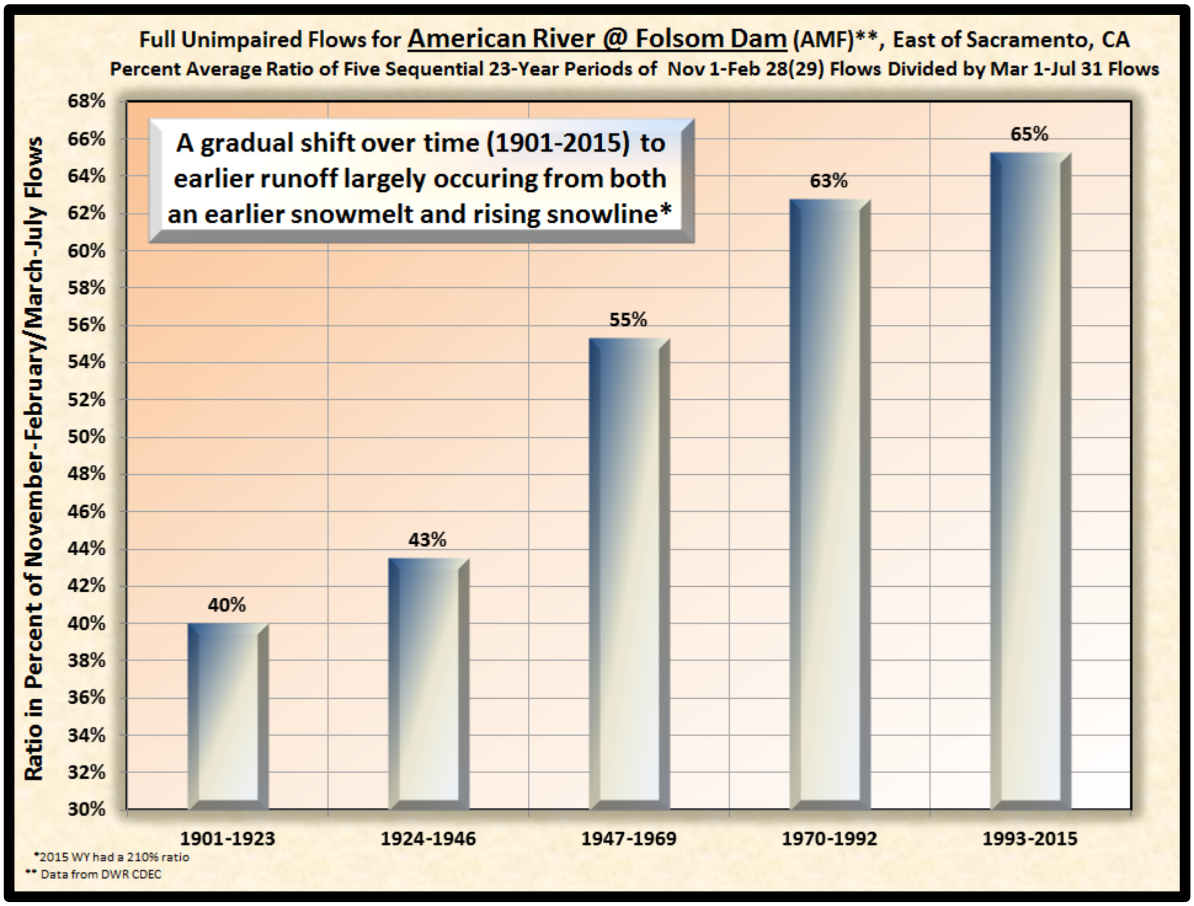

Figure 7. Shift in runoff timing for the American River from spring and summer into the winter period during the past 115 years.

climate with the spring freshet greatly diminished from a snowpack being only about 5 percent of the long term historical average (Figure 4). The lack of a significant spring freshet reflected a record low snowpack. During the 2015 water year atmospheric rivers were common and rainfall occurred at higher than normal elevations throughout the Sierra Nevada and southern Cascades. As expected the December 2014 storms were produced primarily from atmospheric rivers accompanied by high snowlines, which resulted in relatively intense rainfall. For areas burned the in prior years and the previous summer, an increase in precipitation occurring as rainfall posed significant erosion risk. Most of December's above average precipitation occurred north of Highway 80, on relatively deep metamorphic type soils, While significant runoff did occur in December the soils which were very dry from the three prior dry years were able to accommodate and hold much of the rainfall. A very dry January and continued warm temperatures quickly melted much of the snowpack which had accumulated in December. The April through July runoff for the Sierra was the lowest on record. Considering the general absence of snowpack along with unusually warm temperatures, evapotranspiration and soil moisture recharge likely took a larger than normal amount of the available water which would otherwise have produced runoff. The lack of sufficient water to maintain healthy trees was evident in an unusually high mortality rate especially for the southern Sierra where Pine Bark Beetle infestation resulted in mortality for many of the forests' stressed trees. Despite the northern 8-station precipitation index being 75 percent of average for the water year, the lack of a developing snowpack in the northern Sierra may be a good indicator of what conditions will be like with continued climate warming (Freeman, 2008 and

2010). The northern Sierra and southern Cascades are characterized by much lower elevation watersheds than occur for the southern Sierra. Fortunately for the Pit, McCloud and north Fork Feather Rivers, precipitation that occurs in the form of rainfall can be stored within their watershed's porous volcanic aquifer systems with almost equal infiltration as would occur from snowpack. With the exception of very intense rainfall, most precipitation that falls upon the porous volcanic aquifer recharge areas infiltrates into the aquifer systems later emerging from large springs that supply the tributaries to the Pit and McCloud Rivers. For the steeper granite headwater areas on the Yuba River southward, most rainfall quickly drains into the tributaries that supply runoff to the main stem rivers. Both the

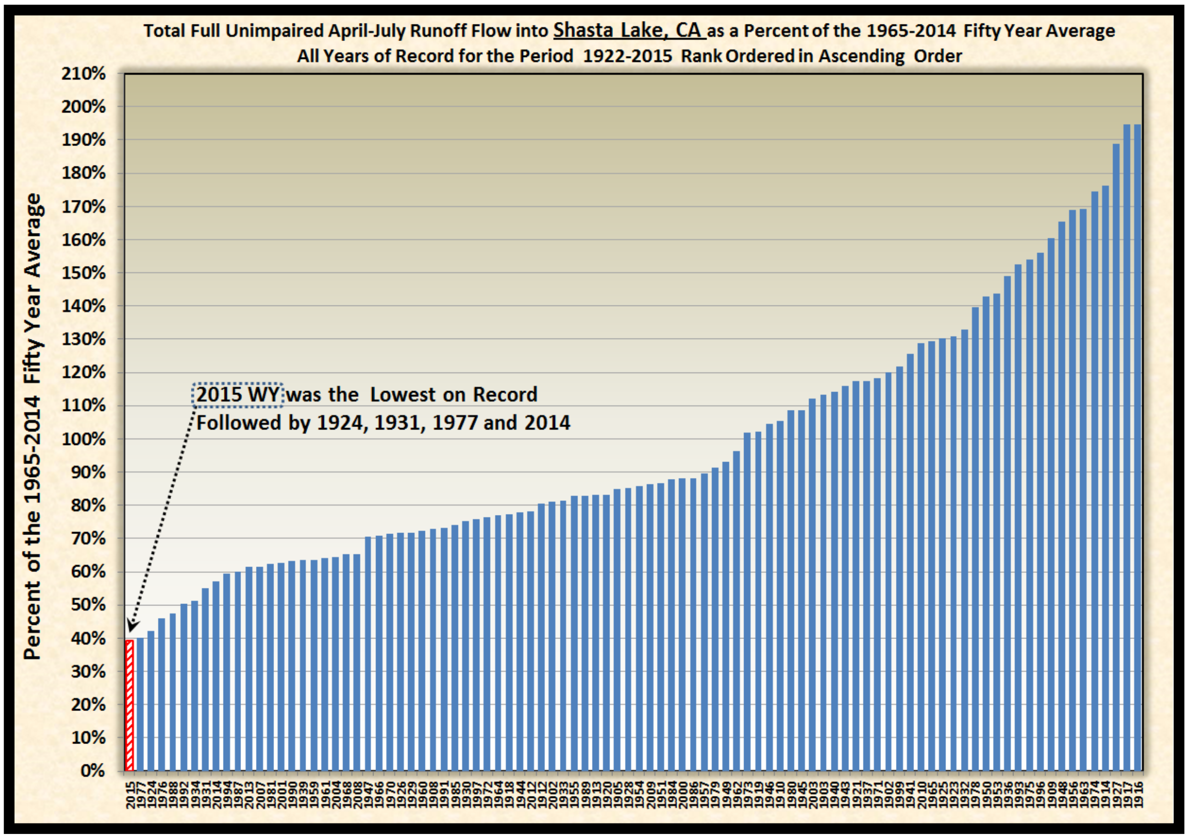

Figure 8. April through July runoff for the total full unimpaired flow into Lake Shasta, for the period 1965-2015. All values shown as a percent of the 1965-2014 fifty year average. Flows ranked in ascending order form lowest to highest.

Sacramento Valley and San Joaquin Indices had the lowest April through July runoff on record, however the average year snowmelt runoff for the Sacramento Valley Index represents only 35% of the water year sum, while for the San Joaquin Index, the average April through July runoff comprises 64% of the historical long term average water year flow. Not having the benefit of the large northern aquifer storage systems with their spring and summer drought resistant groundwater contribution leaves the San Joaquin Valley runoff much more vulnerable to years with little snowpack compared with the Sacramento Valley Index. Along with a reduced rate of snowmelt flow, the daily diurnal fluctuation is likewise reduced, such that the river's change of stage during a 24-hour period is likewise much reduced. Amphibians and other water related fauna are likely to be impacted if parts of their breeding cycle depend on typical daily water elevation falling and rising in harmony with the daily snowmelt cycle (Yarnell, 2012). While the April through July snowmelt runoff into northern California's reservoirs such as Lake Shasta was at an all-time low as shown in Figure 8, its four-month April through July flow quantity was higher than for reservoirs to the south. Its runoff was mostly composed of aquifer outflow of upstream volcanic contribution from groundwater storage of past years. When the aquifer outflow portion is separated from snowmelt and the current season April through July precipitation utilizing methodology developed for hydroelectric planning (Freeman, 2015), the non-groundwater portion accounted for approximately 22 percent of the total four month April-July flow. Over 550 TAF of the April through July runoff into Lake Shasta was from precipitation stored underground from prior years. While a large portion of that flow was from snowmelt, only about 22 percent was from the current year's contribution of snowpack and precipitation. The remainder was from groundwater recharge of prior years. California watersheds south of the Feather River do not have this capability to buffer droughts during low snowmelt years, so for example compared with 39 percent for the April through July runoff for unimpaired inflow to Lake Shasta, the Stanislaus at

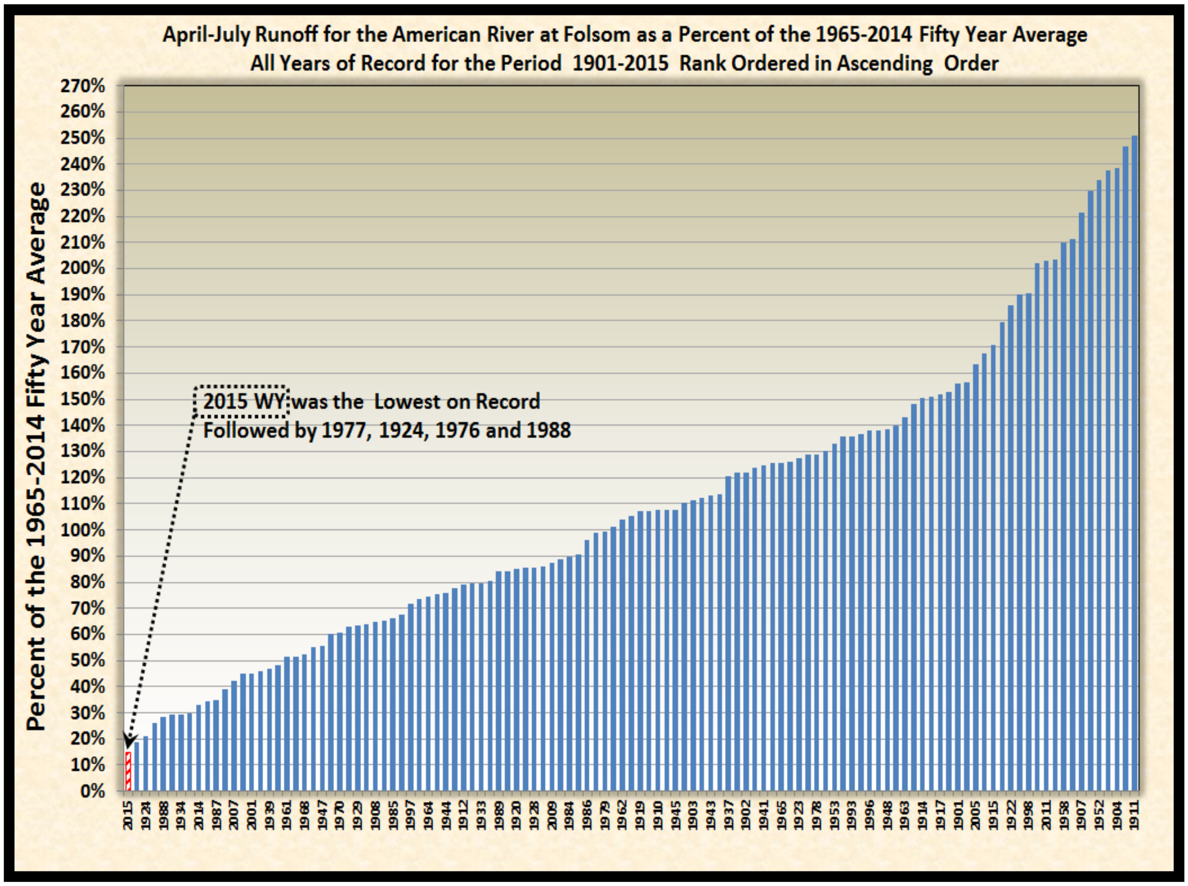

Figure 9. April through July runoff for the American River at Folsom, CA. for the period 1901-2015 – shown as a percent of the 1965-2014 fifty year average. Ranked in ascending order form lowest to highest flows.

Melones April through July unimpaired snowmelt flow had April through July snowmelt flows averaging only 19 percent of its 1965-2014 fifty-year average. The upper headwater portions of the American River lay upon mostly exposed granites with some older, relatively low permeability volcanics mixed in. Aquifer outflow contribution from the American River headwaters area is almost nonexistent, and as such there is no volcanic aquifer contribution such as occurs for Lake Shasta. During unusually low snow years, the lack of volcanic aquifer storage leaves watersheds south of the Feather River highly vulnerable to years with low snowpack. Figure 9 shows the April through July runoff for the American River at Lake Folsom. For those watersheds with headwaters on the exposed granites, other than the surface reservoirs, there is little other stored water available for the long dry Mediterranean summer period.

SUMMARY AND CONCLUSIONS

Several records for low snowpack, snowmelt runoff and warm temperatures were set during the 2015 water year. The 2015 water year was the fourth consecutive year of drought and in terms of cumulative impact to reservoir storage, groundwater levels, and temperatures, and mandated water rationing was the most severe in terms of overall hydrological impact. December 2014 was unusually wet for the American River watershed and those rivers north of the American River, however a significant snowpack failed to develop and that which did develop melted relatively quickly. Unusually warm winter and spring temperatures limited most storms to producing snowfall at the higher mountain elevations and that snowpack which did form quickly melted. By April 1 only slightly greater than 5% of average snowpack remained on the northern watersheds. While aquifer outflow of the volcanic aquifer systems was the lowest on record, it still provided a large portion of the late summer and fall flows available for inflow to Lake Shasta and Oroville. Water year runoff for the southern Sierra, while at about 14% of average was much less than that for the Sacramento Index which reached 40% of normal. In terms of its response to California's lowest snowpack on record, water management planners moved toward making major changes in how water is managed in California. In September 2014, California enacted landmark legislation known as the Sustainable Groundwater Management Act (SGMA). This legislation provides a framework for sustainable management of groundwater supplies by local authorities, with a limited role for state intervention as may be necessary to protect the resource (Association of California Water Agencies, 2014). During prolonged droughts California increasingly depends upon its groundwater storage for its water supply. With the expected continuing decline in snowpack due to climate change, the groundwater aquifers become an increasingly important part of California's long range sustainable water supply. As the annual snowmelt freshet continues its trending decline and earlier arrival, its storage benefits are diminished by an increased need to release sufficient water from the large multipurpose reservoirs to maintain flood control. For example in February 2016 with strong El Nino conditions still present in the eastern Pacific and following a wet January in which runoff occurred from relatively warm storms crossing the central Sierra, operators at Folsom Dam started releasing water to assure that sufficient flood storage capacity could be maintained. This followed several months in 2015 of much below average reservoir levels in Folsom Reservoir. In many ways, the 2015 water year and the 3-dry years preceding its record breaking drought, provided a preview of what California can expect from continued climate change.

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