

CLIMATE CHANGE AND THE CHANGING WATER BALANCE FOR CALIFORNIA'S NORTH FORK FEATHER RIVER

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ABSTRACT

Climate change has likely had a large role the changing water balance on northern California's North Fork Feather River (NFFR) in recent years. In addition to changes in both snowpack quantity and timing of the spring snowmelt, some of its subbasins are also revealing a declining trend in water year (October 1 through September 30) runoff, while others do not. Pacific Gas & Electric Company (PG&E) divides the NFFR into multiple subbasins and subbasin reaches for purposes of effectively forecasting runoff and scheduling reservoir releases for hydroelectric operations. In order to effectively manage the hydroelectric resources on this river, at the watershed level as a collective whole, it is important to recognize loss in both data stationarity and trends that change both historical runoff timing and quantity of runoff. NFFR's complex terrain geometry includes a combination of both windward facing slopes and rain-shadowed leeward slopes that result in a mix of climatic gradients. The combined effect of having relatively low elevation and topographic barriers in the form of mountain ridges provide opportunity for both orographic cooling to take place on the windward slopes and compressional warming to take place on the leeward slopes as the airflow of frontal systems pass through the NFFR Basin. On the leeward, rain-shadowed slopes, air descends and warms quickly through compressional heating. Precipitation amounts quickly diminish as the descending air warms and increases its capacity to hold moisture. Both the Lake Almanor and East Branch of the North Fork Feather (EBNFFR) subbasins are two rain-shadowed subbasins that exhibit a declining trend in water year runoff. Trend declines that approach 308 hm³ (250,000 AF)/year collectively from the two subbasins since the early 1960's were analyzed using a water balance approach to help understand the declining runoff trend in terms of changes taking place at the watershed level. Beginning in the 1970's, increased evapotranspiration is likely taking place in the mixed conifer forests due to rising air temperatures. Increased forest growth and warmer air temperatures are likely two of the contributing causes for the increased evapotranspiration that has taken place in recent years. The decrease in both the low elevation snowpack and the water year runoff has resulted in a decline in hydroelectric output and less outflow of the NFFR into Lake Oroville. (KEYWORDS: climate change, Feather River, orographic, water balance, rain shadow, northern California)

INTRODUCTION

California's Sierra Nevada Mountain Range ends the northern part of its approximately 644 km (400 mi) length in the Feather River Basin. Lake Almanor, a former meadow with several large springs, is located over the ending edge of the southern Cascades' porous volcanics, which in turn encounter the mostly impervious metamorphic rocks at the northern end of the Sierra. The northern Sierra and the Feather River Basin are relatively low elevation compared with the much higher southern Sierra that is often referred to as the 'High Sierra', which is often defined as starting its northern end in the headwaters above Yosemite Valley and extending southward along the Sierra crest. Uplift of the Sierra Nevada Mountains beginning in the early Pliocene Epoch approximately 5 million years ago has been most pronounced in the southern Sierra with lesser uplift and tilt taking place in the Yuba and Feather River Basins. Much of the ancestral Sierra rock remains exposed in the Feather, where the Western Metamorphic Belt widens in comparison with the central and southern Sierra. As a result of the lesser uplift, the Feather River cuts through the Sierra Crest. The west facing slopes are less sharply tilted into the Sacramento Valley, and as a result, much of the topographic complexity associated with the older Eocene-age drainage patterns remain. The Sierra south of the Feather River Basin is positioned such that winter storm fronts, which move eastward across the Central Valley encounter the relatively steep Sierra mostly at right angles to its west facing slopes causing orographic and adiabatic cooling through air mass expansion. As the air cools, it loses its capacity to hold moisture and the saturated air delivers precipitation, mostly in the form of snowfall to the higher slopes of the Sierra. The Feather River above Lake Oroville however has a somewhat complex topography characterized by a mixed arrangement of ridges and valleys, much more indicative of the older erosion surfaces,

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some which benefit immensely from orographic uplift and others that are sufficiently blocked by ridges to be considered as rain-shadowed subbasins. On the NFFR, air ascends upward and crosses the first westward facing ridges, losing much of its moisture, and quickly heats adiabatically as it compresses and descends into the various valleys such as at Lake Almanor (formally Big Meadows) and into the Indian and Genesee Valleys on the EBNFFR. As the flow of storm air crosses these valleys, the air mass warms sufficiently to hold much of its remaining moisture during its continued journey eastward. Consequently these valley areas, which are topographically blocked by ridges and various mountain peaks tend to be much warmer and drier than the Basin's other subbasin drainages. Snowpack accumulation for the west facing windward slopes and the canyon walls below Belden does not appear to have declined significantly (Freeman, 2010). The snow pack has shifted a portion of its melt regime from April into March, an effect of climate warming that seems to be increasingly becoming the norm for nearly all parts of the Sierra.

Both the 1,272 km² (491 mi²) Lake Almanor subbasin and the 2,655 km² (1,025 mi²) EBNFFR water year runoff started declining about 1960. Other subbasins such as Butt Valley, Bucks Creek, Grizzly, and the Feather River Canyon downstream of Canyon Dam and its confluence with the EBNFFR near Rich Bar are relatively high precipitation areas that have experienced relatively little change in both water year runoff and winter snowpack. These areas are characterized by windward facing slopes that cause the air to adiabatically rise, expand, and cool creating an increase in precipitation and snowfall due to loss in moisture holding capacity. While low elevation snowfall seems to be decreasing throughout northern California (Freeman, 2003, 2009), Freeman (2008, 2010) describes the Feather River as being relatively sensitive to the effects of climate change due to its relatively low elevation complex topography that includes some rain-shadowed subbasins. However, more recent study by Freeman, which is presented in this paper, indicates that rain-shadowed subbasins in northern CA are especially sensitive to climate change impacts characterized by changed hydrological pathways and water balances that include reduced aquifer outflow of springs, decreased runoff from snow melt, increased evapotranspiration, and for some topographically blocked subbasins, reduced water year runoff. With the conclusion that precipitation amounts have not significantly changed, and that a decline in aquifer outflow from springs has occurred, it seems likely that evapotranspiration has increased possibly as a result of both increased forest growth and increased fire suppression in recent years. Early 20th century pictures of the forest on the EBNFFR (Gruell, 2001) show a less dense forest than is currently observed. A less dense conifer distribution would have less evapotranspiration and

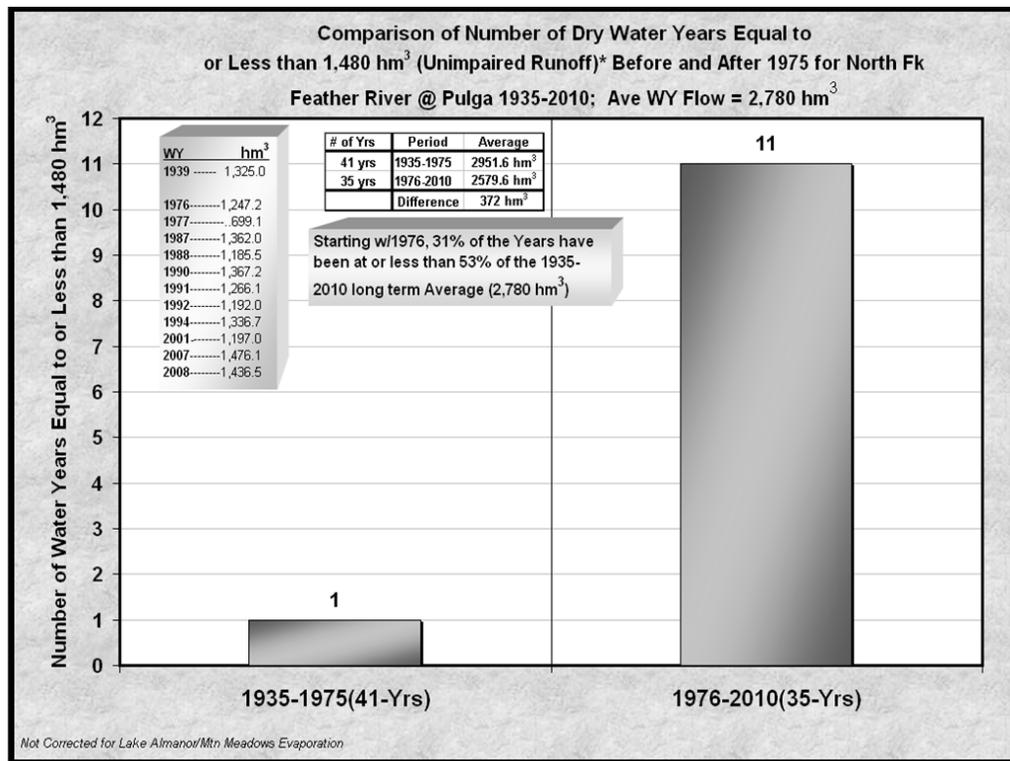


Figure 1. A comparison of the number of low flow water years for two different periods on the NFFR.

likely produce greater runoff compared with the current thicker conifer density. In recent years, runoff for a given amount of precipitation is most reduced in those years that are on the dry side. This observation appears to indicate that if soil moisture availability is limited, then runoff is further reduced as plant transpiration continues its demand on available soil moisture at and above the wilting point. Runoff is likely diminished in inverse proportion to increased evapotranspiration that is used in part to support leaf cooling and increased forest growth. Figure 1 illustrates that compared with prior years; starting in 1976 there is an increased frequency of low flow years for the NFFR @ Pulga. The NFFR @ Pulga collectively includes all upstream subbasins. In spite of the number of years for the more recent period being less following the 1935-1975 period, there are 11 times the number of years, which are less than 53% of the long term mean. This is consistent with the increased shift in the water balance from runoff to evapotranspiration. Groundwater for the Lake Almanor subbasin has continuously decreased in recent years. The springs for this subbasin consist primarily of relatively shallow porous volcanic basalts. Their depletion long term indicates susceptibility for drought imposed flow reduction. Prior to about 1970, aquifer outflow in the form of springs into and under the Lake accounted for more than 50% of the water year flow in average water years. Today that drought resistant reserve has become significantly reduced and accounts for less than 40% of the water year flow. Similar declines in outflow from springs have been found on the McKenzie River near Eugene, Oregon (Jefferson et al., 2008). Figures 2 and 3 illustrate the decline in aquifer outflow currently being observed for the Lake Almanor subbasin. An indexed approach, being used at PG&E, utilizes fall base flows to track and monitor aquifer outflow in a consistent manner. Once depleted to a low rate of outflow, it may take multiple years of wetness to restore the aquifers to their former storage levels. The springs under Lake Almanor are mostly the result of porous volcanic lava flows north and northeast of the Lake that encounter the harder, relatively impervious metasedimentary rocks of the Sierra block. The loss of low elevation snowfall may have also decreased the rate of aquifer recharge opportunity from snowmelt. The relatively slow release of water from the snowpack typically creates an ideal opportunity for groundwater recharge. During wetter than normal precipitation years when soil moisture recharge is not limited from precipitation or snowpack amount, recharge opportunity is maximized and can satisfy all evapotranspiration demands as well as provide a directly proportional increase of runoff from each centimeter of precipitation added. Contributing factors to increased forest growth likely include warmer temperatures, increases in carbon dioxide, and fire suppression in recent years. If vegetation is not moisture stressed, then the increase in carbon dioxide that accompanies climate change may possibly be accelerating forest growth, utilizing increased amounts of water, which in prior years was available for surface

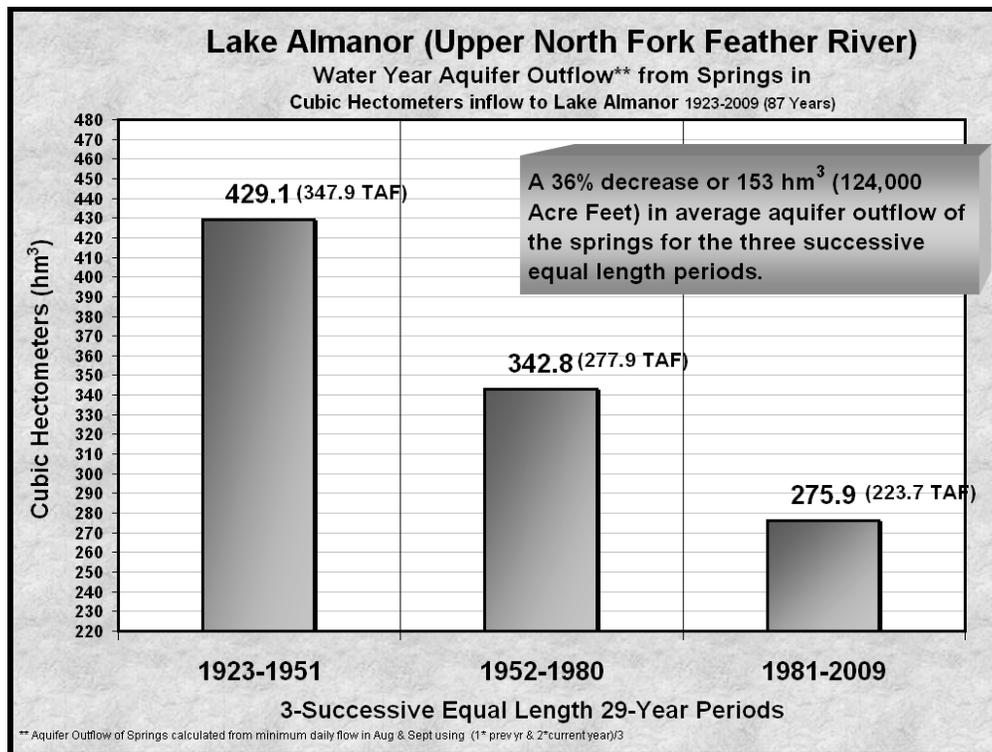


Figure 2. The long term decline in aquifer outflow of springs into Lake Almanor.

runoff. Today much of that water, which has in recent years become increasingly used to satisfy evapotranspiration is neither replenishing the aquifers nor running off as surface flow. The physiographic controls on how the Feather

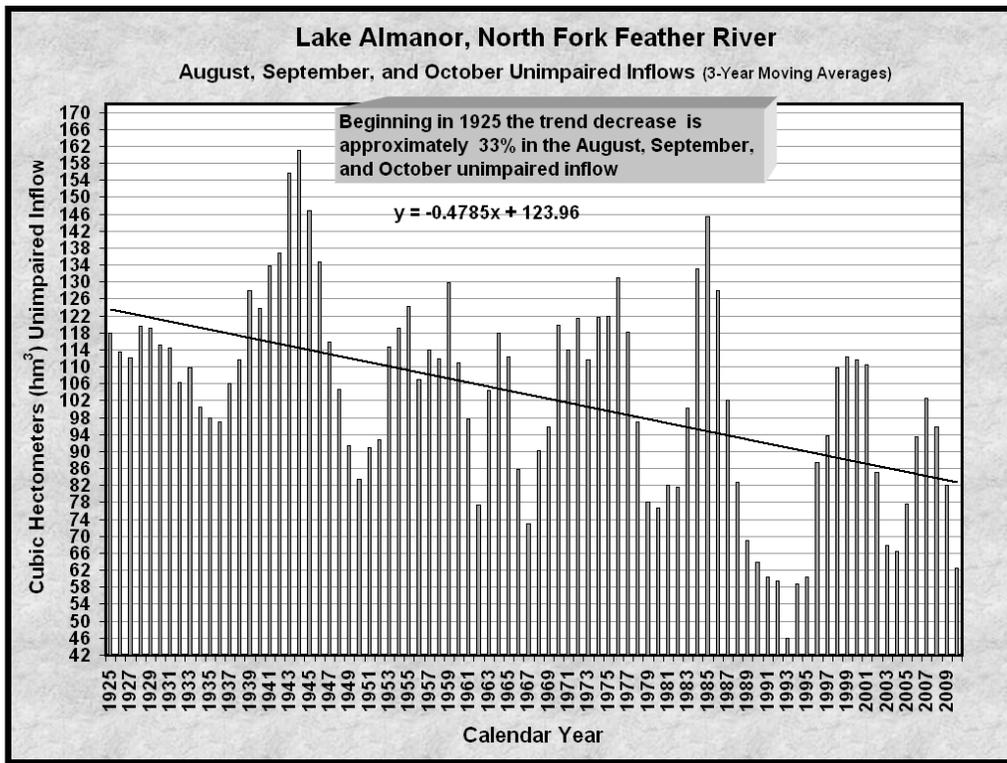


Figure 3. Summer and fall unimpaired inflows to Lake Almanor have declined approximately 33% (trended change) since 1925.

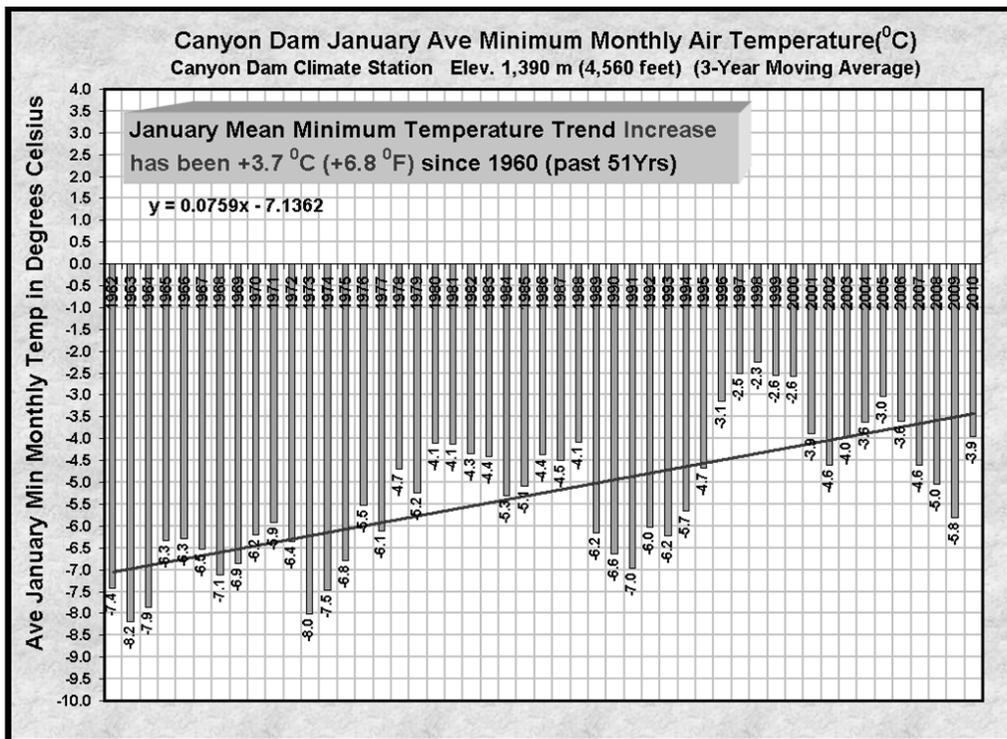


Figure 4. Increase in the mean minimum January temperature at Canyon Dam.

River’s vegetation including the forests respond to change in energy and water flux mostly in the form of increased warming and soil moisture stress are not well understood. At this time there is a scarcity of ground based instrumentation with sufficient good quality record to fully understand what is taking place.

Minimum January temperatures were analyzed at existing climate stations on the Feather River. Minimum January trended temperatures were an average of 5.1⁰C (9.2⁰F) degrees warmer at Quincy on the EBNFFR, 3.8⁰C (6.8⁰F) degrees warmer for Canyon Dam, and 2.8⁰C (5.0⁰F) degrees warmer at Chester since the early 1960’s. This is 2-4 times the increase observed for most mountain locations elsewhere in the Sierra to the south. Figure 4 is an example of data charted for the Canyon Dam climate station. The minimum temperature at the nearby Prattville climate station showed a similar increase. While there is only a limited number of climate stations in the area, the much warmer winter temperatures, loss of snowpack, and decrease in annual runoff appear supportive that the hydrology is changing for at least the two of the subbasins, EBNFFR and Lake Almanor on the upper NFFR.

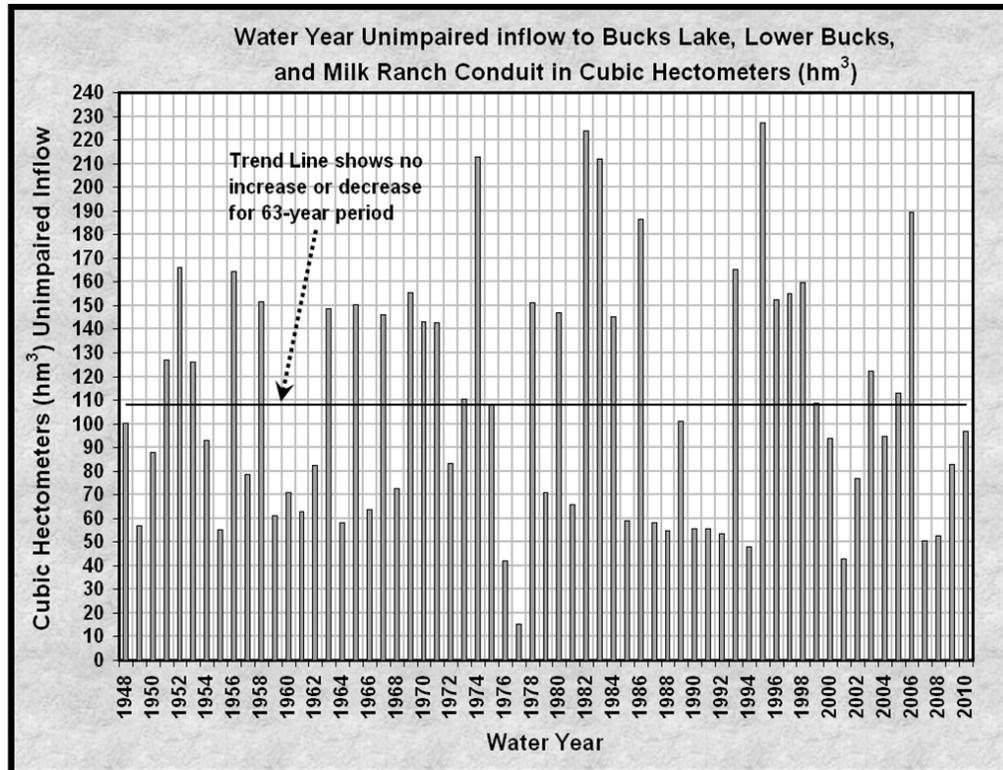


Figure 5. The Bucks Lake Subbasin is characterized by strong orographic cooling.

The Bucks Lake and Lower Bucks Diversion subbasin exhibits strong orographically caused precipitation increases during storm systems. The water year runoff shown in Figure 5 reveals very little change for water year runoff quantity from the warming climate. The Bucks Lake low elevation snowpack has mostly remained unchanged historically, but with warmer air having the capacity to hold more water, annual precipitation amount in the future could potentially increase for these types of windward facing subbasins that are orographically cooled (Freeman, 2010). The warming climate’s impact on areas with very strong orographic cooling has the overall potential to increase precipitation and snowfall for isolated peaks such as at Mt. Shasta and Mt. Lassen (Freeman, 2010; Howat, et al., 2007) and also for the higher elevations in the southern Sierra (Howat and Tulaczyk, 2005).

WARMER STORMS IN RECENT YEARS

A comparison of average daily minimum storm temperatures from the Canyon Dam climate station as shown in Figure 6 for days with precipitation for two successive 34-year periods shows an average 1.4 ⁰C (2.5⁰F) increase for the more recent January through March period. This increase supports the decrease in low elevation snowpack being observed for snow courses on the Feather River such as for the Mt. Stover snow course at the 1,646 m

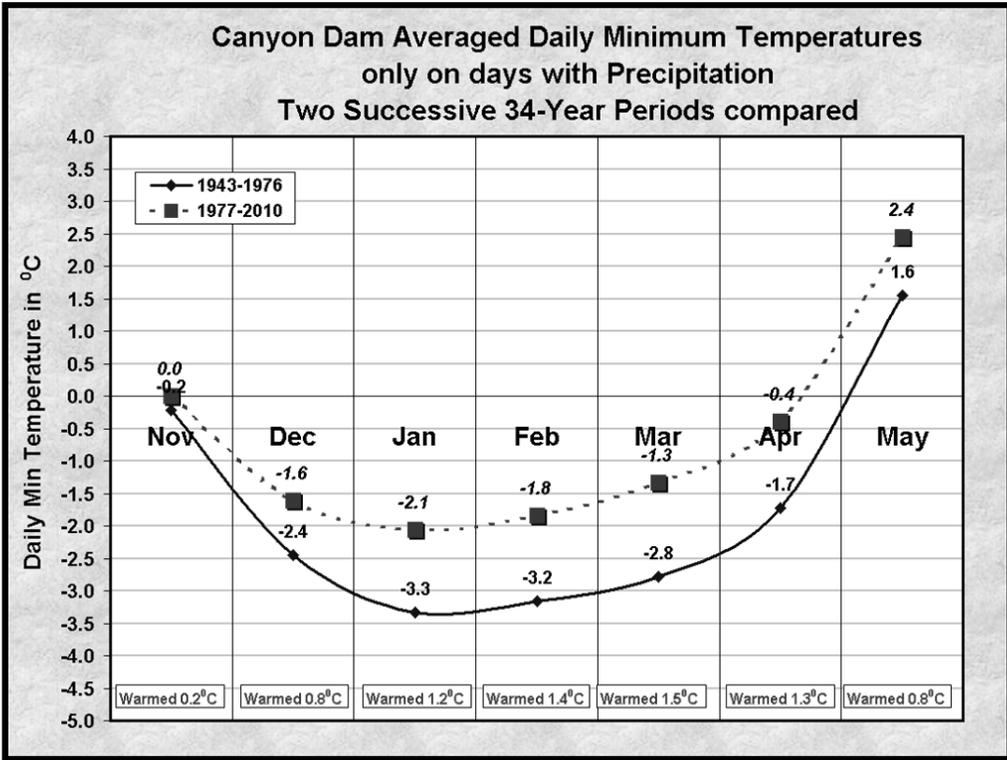


Figure 6. Canyon Dam averaged daily minimum temperatures only on days with precipitation for two successive 34-year periods.

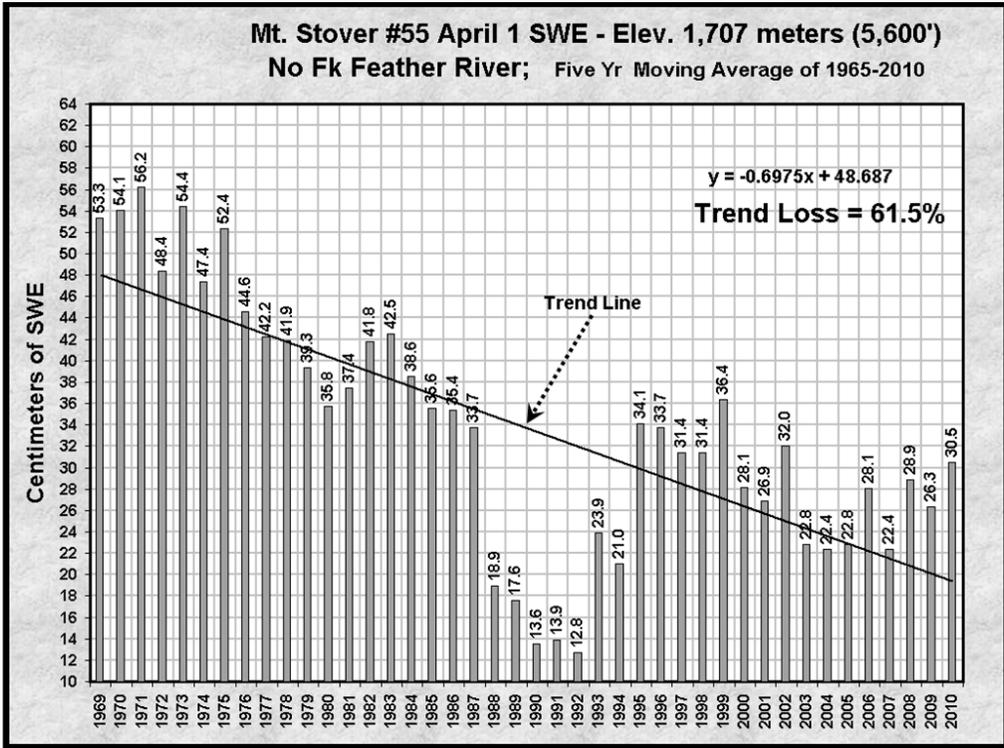


Figure 7. A 5-year moving average for the April 1 snow water equivalent at the Mt. Stover snow course on the Lake Almanor subbasin. The trend loss is almost 63%.

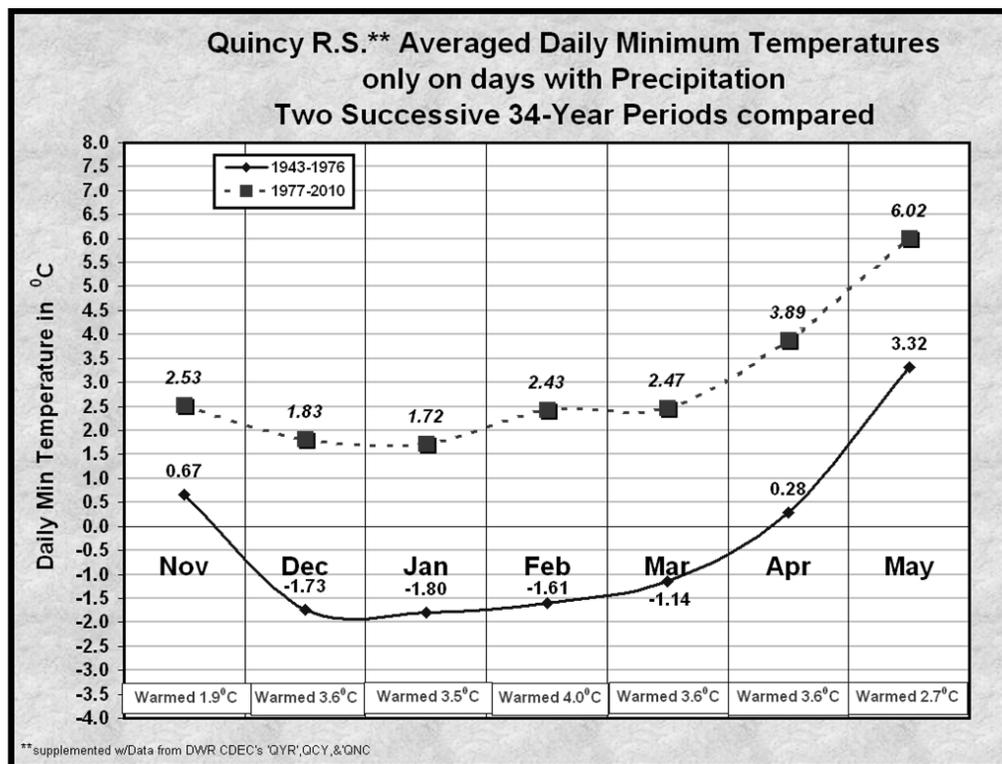


Figure 8. Quincy Ranger Station's averaged daily minimum temperatures only on days with precipitation for two successive 34-year periods.

(5,600 ft) elevation (Figure 7). The reduced April 1 snow water equivalent appears consistent with both less snowfall in recent years and an earlier snowmelt with increased runoff that now occurs in the month of March. Because such a large portion of the Lake Almanor subbasin is below the 1,646 m (5,600 ft) elevation, a large proportion of the watershed's snowpack no longer exists in most years. The loss of mountain snowpack observed for the NFFR is consistent with findings by others (Stewart, 2009, Pierce, et al., 2008). The loss of the low elevation snowpack may likely be limiting groundwater recharge. However, reduced aquifer outflow also seems to have partly been the result of increased evapotranspiration taking place on the subbasin. Regardless of the long term trend, it should be kept in mind that even with a strong trend, individual year variation can result in an occasional year having a large April 1 snowpack such as occurred in 2010 when the April 1 SWE at Mt. Stover was 49.0 cm (19.3 in) and 131% of the 1951-2000 50-yr average of 37.3 cm (14.7 in). Trends and moving averages are simply the smoothed over statistic of the individual years with their included variance. Figure 8 shows a similar, but more significant increase in minimum temperature accompanying storms in the more recent 34-year period at the Quincy R.S. climate station, which was used to represent the rain-shadowed EBNFFR. The implications of warmer winter minimum temperatures accompanied by increasing snow loss from the low elevation snow zone could result in earlier drying of soils. Rainfall typically diminishes after April. This and the loss of the low elevation snowpack that typically provides spring and early summer soil moisture recharge from snowmelt may lead to earlier soil moisture loss. Warmer temperatures in recent years would support increased forest growth and the depletion of remaining soil moisture. The increased soil moisture demand on soils may explain some of the loss of aquifer outflow from the springs. The early spring loss of the thinning snowpack is also likely to lead to increased surface heating from loss of albedo. This has potential to cause increased soil warming and evapotranspiration.

THE IMPORTANCE OF OROGRAPHIC COOLING WITH A WARMING CLIMATE

For most of the Sierra Nevada Mountains, the west side slope is conducive to orographic cooling almost up to the summit. The Feather River in the northern end of the Sierra, however, has not been tilted or pushed upward from Basin and Range crustal extension nearly as much compared with the southern Sierra, such as west of the Owens Valley, which has been lifted more than 2,438 m (8,000 ft) in elevation. Much of the original ancestral

Sierra's metamorphic complexity remains as it did during the mid-Tertiary period. During winter storm fronts, if incoming air is not sufficiently cooled, the snowline rises. If air temperatures during storms continue to rise, there may eventually be a point in time where less water year precipitation occurs for the rain-shadowed subbasins on the Feather Basin. A minor loss appears to have already occurred in the Quincy area, but the data quality is insufficient to scientifically support making that conclusion. The water year runoff averages for those subbasins on the NFFR Basin which are strongly orographic influenced during storm fronts have remained essentially unchanged since the mid-1960's.

THE CHANGING WATER BALANCE

In terms of a mass balance, water year surface runoff equals water remaining from precipitation after evapotranspiration and infiltration is augmented by water flowing from soils and aquifers all for the same 12 month period. The water balance is reviewed in this section for both the rain-shadowed EBNFFR and for Lake Almanor. The Lake Almanor subbasin has considerable aquifer outflow from precipitation of past years that occurs from springs even during very dry years. In addition to the decrease in April through June runoff, the water year runoff for both subbasins has also declined since about the mid 1970's. Figure 9 illustrates this decline in water year runoff for the EBNFFR along with an estimate of increased evapotranspiration based on using the 1950-1970 20-year period as the zero base period. Assuming that the ground water storage has declined, the reduction in aquifer

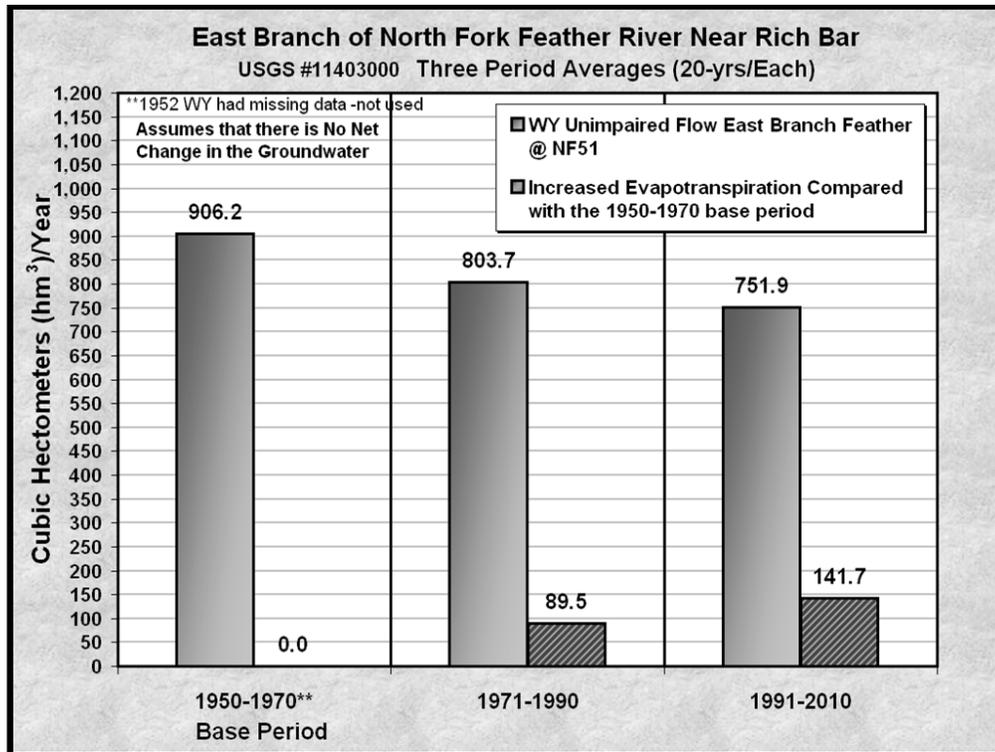


Figure 9. Three successive 20-year periods showing surface runoff decline for the EBNFFR near Rich Bar.

outflow may in part be due to lack of groundwater recharge opportunity. Snowmelt in the spring tends to occur at a sufficiently slow rate to provide maximum opportunity for infiltration and groundwater recharge. Since aquifer outflow has declined on the Lake Almanor subbasin, one needs to investigate the precipitation for the same period to verify that seasonal precipitation has not also declined. If the seasonal precipitation trend is stationary and the aquifer storage is declining as is indicated from aquifer outflow rates, then the evapotranspiration rate is likely increasing in direct proportion to the loss in runoff. The Quincy climate station has considerable missing precipitation record and for purpose of this analysis was considered poor quality. However, the Caribou Power House climate station, which is also partially rain-shadowed had reasonably good quality precipitation record and was utilized to compute the relative recovery factor decline for the three 20-year periods. This would also provide an indication of the period evapotranspiration increase for the two more recent periods. Figure 10 illustrates the

three-period decline in runoff recovery factors that have taken place with the evapotranspiration increases in recent years. The Caribou PH climate station shows only a slight decrease in the successive period precipitation amounts

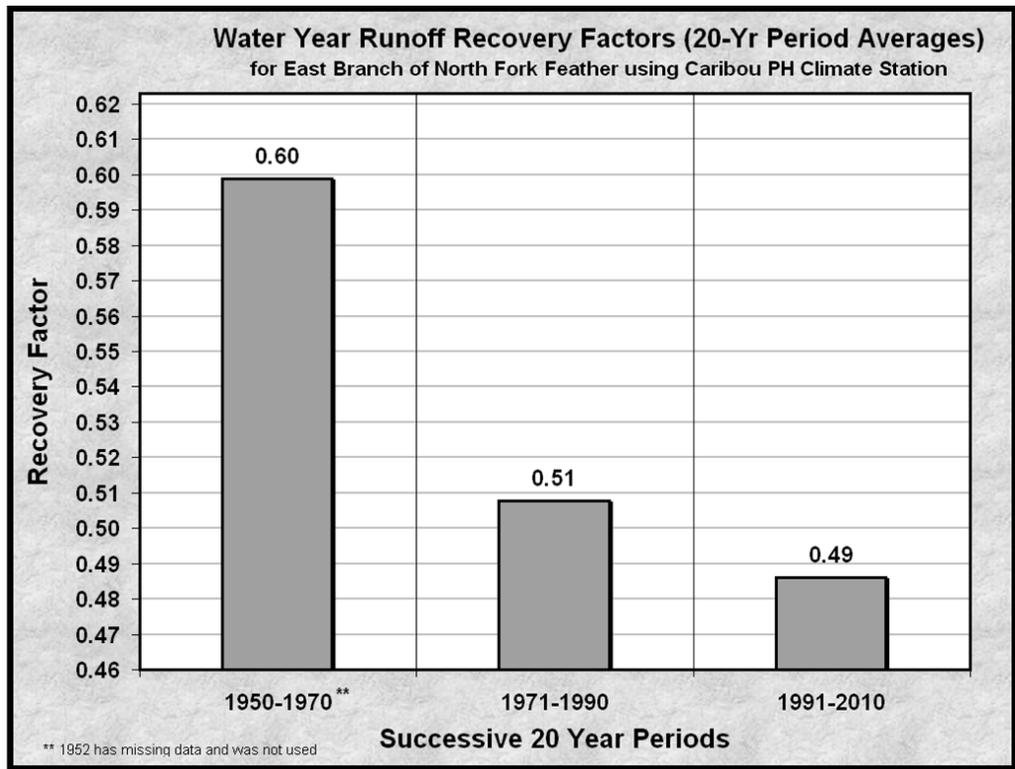


Figure 10. Runoff Recovery factors for the EBNFFR

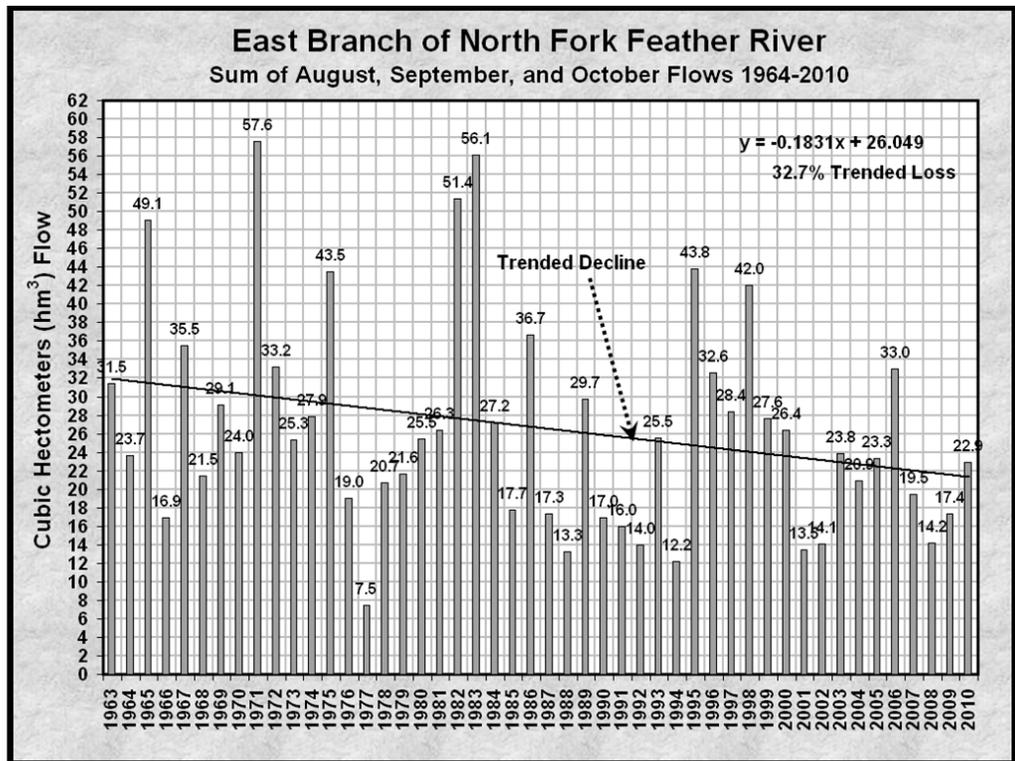


Figure 11. Decline in late summer and fall flows for the EBNFFR

Table 1. Recovery Factors for those water years on the EBNFFR that are 75% and 90% of normal (Caribou PH Climate Station).

Percent of 1950-2010 precipitation 61-Yr Average		90%	75%
Recovery Factor	1951-1980	0.40	0.35
Recovery Factor	1981-2010	0.33	0.30

during the three periods. Its decrease is essentially removed from the analysis by utilizing a single equation for computing the 3-period runoff recovery factor. Table 1 illustrates both a decrease in surface runoff recovery that takes place in the more recent period and also the decrease that occurs as precipitation decreases from 90% and less to 75% and less than normal. All of the recovery factors for below normal precipitation years are less than those for the most recent period of Figure 10. The general decrease in surface runoff recovery from water year precipitation likely results from the vegetation’s moisture needs to support both its growth and increased need for evaporative cooling. Along with the reduced infiltration of water from the decline in low elevation snowmelt, the need for

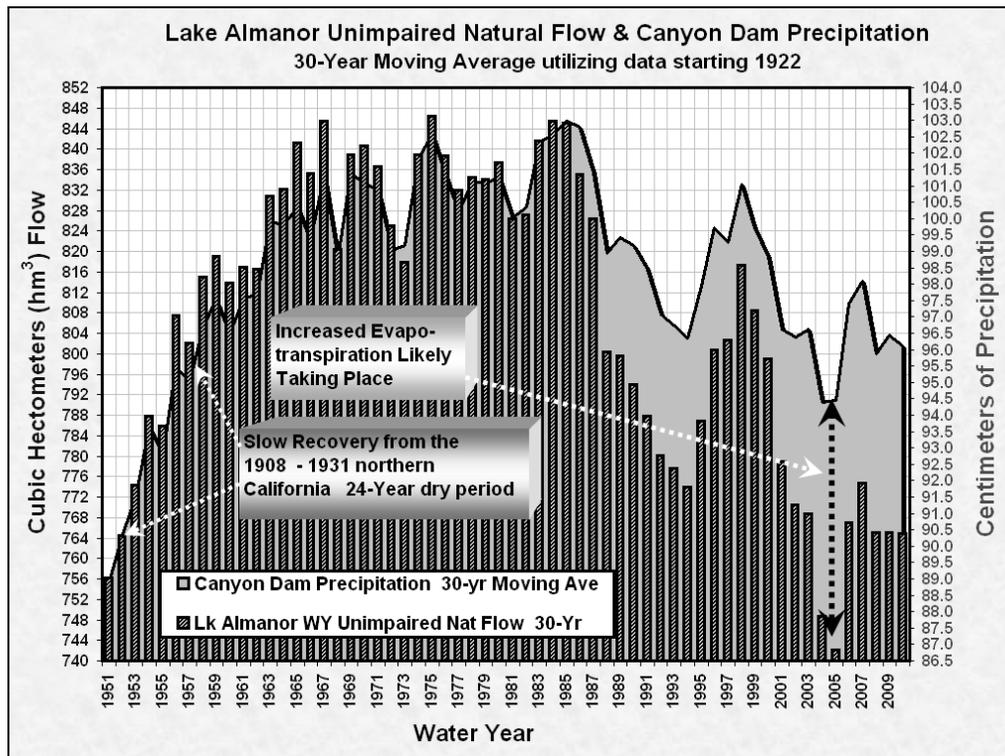


Figure 12. The Lake Almanor 30-year moving average of water year runoff plotted against the Canyon Dam 30-year moving average of water year precipitation.

vegetation to maintain a suitable Bowen Ratio by increased evapotranspiration also likely adds to the early summer soil moisture deficit and other losses that are taking place on the basin. While not volcanic like the headwaters above Lake Almanor, the soil moisture and ground water losses on the EBNFFR over the period of years since about the mid-1960’s, can be seen in Figure 11. The decrease in the August through October late summer and fall flows is consistent with an overall decline in soil moisture and groundwater decline in the years since the mid-1960’s. Utilizing long 30-year moving averages, Figure 12 utilizes data alignment through vertical axis scaling for the earlier years to illustrate this loss of surface runoff for equivalent quantities of precipitation that occurred in recent years. The long term averages utilized for Lake Almanor in Figure 12 also reveal the long term recovery that took place on northern California watersheds following the 1908 through 1931 ‘dry period’ (Freeman, 2001).

USE OF TRENDED HISTORICAL DATA TO DETECT AND QUANTIFY CLIMATE CHANGE IMPACT AT THE SUBBASIN LEVEL

The decline in water year runoff, observed temperature increase, and significant low elevation snowpack decline in the observed data on rain-shadowed subbasins in northern California since the mid-1970's may not be consistent with the regional temperature increases that are currently being predicted by many of the most commonly used Global Climate Models (GCMs) and their associated scenarios. Actual data from the rain-shadowed subbasins on the NFFR and elsewhere in northern California indicate three and four times the warming that has occurred elsewhere in the Sierra on the larger regional basis. Utilizing the results of regional GCM models that may have not been corrected for topographic complexity and associated problems with high resolution spatial scaling may add large uncertainty, and may not be in alignment with the actual data currently being observed for these subbasins. Similar concerns with defining the effects of a warming climate on mountains with complex topography and its effect on orographic cooling and snowfall have been investigated in the Cascade Mountains near Mt. Rainier (Minder, 2010). The orographically influenced subbasins in the Feather River Canyon downstream of Belden and in the Bucks-Grizzly subbasin have a hydrological response to winter storms, which is more typical of much of the west facing tilted Sierra block to the south. They are characterized by strong orographic cooling during most winter storms, which appears to greatly moderate the effects of climate warming. Knowing that regardless of the hydrological modeling approach utilized to study and predict climate change, whether it be the lumped or the distributed hydrological response unit approach, if the temperature change assumptions are not sufficiently sensitive to relatively small topographic features that determine orographic cooling and compressional heating at the subbasin level of detail, then the hydrological extension and future assumptions may not be relevant. The Water Management Team at PG&E has sufficiently detailed unimpaired flows at the operational subbasin level of detail throughout the Sierra and southern Cascades to compare and identify trends now taking place at the relatively small subbasin level of detail. At PG&E isohyetal maps are utilized as an initial tool for quickly locating rain-shadowed subbasins that may have potential to be negatively impacted by water year flow decline from climate change. Analysis of monthly and seasonal historical data then follows to evaluate the extent of subbasin impact (Freeman, 2010). If the GCM modeling technology along with downscaling methodology eventually proves relevant, aligned with, and reflective of actual historical data for these rain-shadowed subbasins, then use of GCM output for predicting hydrological water balance changes at the subbasin level would have increased value for operational hydroelectric planning. At this time, utilizing simple extension of the observed data trends such as are being made for rain-shadowed subbasins on the NFFR may be the simplest and most meaningful approach to identifying short term future impacts of warming.

SUMMARY AND CONCLUSIONS

Two rain-shadowed subbasins on the NFFR, Lake Almanor and EBNFFR, were found to not only have less April through June Runoff in recent years, but they are also losing water year runoff as well. Minimum average temperatures have increased for both of these subbasins and the minimum temperatures for days with precipitation have also increased. Increased air temperatures accompanied by a significant decline in low elevation snowpack have likely led to less available soil moisture for surface runoff. Forest vegetation appears to be doing well and appears to have increased in biomass since the mid-1970's. Increased evapotranspiration appears to be the most likely reason for the decline in water year runoff. The Lake Almanor subbasin has also lost aquifer outflow as evidenced in a decline of late summer and fall base flows. The opportunity for soil moisture recharge appears to have declined with the loss of low elevation snowpack. As summer soil moisture has become increasingly limited since the mid-1970's, forest vegetation appears to be satisfying its soil moisture needs to meet potential evapotranspiration at the expense of declining streamflow. Warmer air temperatures during the active growing season have likely resulted in increased evapotranspiration needed to meet leaf cooling and maintain growth. Both the EBNFFR and the Lake Almanor subbasin have shown significant late summer and fall runoff declines since the mid 1970's. Recovery factors of water year runoff from precipitation have declined the most during years with below average precipitation. These are years when actual evapotranspiration may be less than potential evapotranspiration. Subbasins such as the combined Bucks Lake and Grizzly drainage area as well as the Feather River Canyon Area below the confluence of the EBNFFR with the NFFR near Belden Powerhouse are strongly orographic with frontal systems typically being cooled and receiving normal snowfall. These areas do not seem to show any decline in water year runoff, however the March runoff has increased since the mid-1970's, indicating the same earlier snowmelt as is observed for most mountain locations in the Sierra. For the NFFR as a whole, there is

11 times the number of water years with runoff below 1,480 hm³ (1,200 TAF)/water year since the mid 1970's compared with the preceding period of equal length.

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