# TRACKING THE IMPACT OF CLIMATE CHANGE ON CENTRAL AND NORTHERN CALIFORNIA'S SPRING SNOWMELT SUBBASIN RUNOFF

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## ABSTRACT

A simplified index system was set up at Pacific Gas & Electric Company (PG&E) to evaluate the current impact of climate change and produce a simplified trend forecast of spring snowmelt runoff for relatively small hydroelectric operational subbasins in central and northern California. Central and northern California mountain subbasins differ significantly in terms of topography, geology, soil porosity, aquifer storage, active energy land surfaces, runoff recovery efficiency, and a number of other parameters. The need for PG&E to classify and index these relatively small subbasin drainages in terms of runoff impact from climate change became apparent with the need to increase overall awareness of the relatively rapid change in water availability timing since about 1970 and to focus on identifying potential associated business risks. Spring runoff from snowmelt has historically been depended upon for filling the nearly one hundred seasonal reservoirs that PG&E manages. The timing of runoff is critical for both reservoir release and hydroelectric generation planning. While overall to date almost no impact on PG&E's hydroelectric generation has occurred for the system as a whole, it is important to be aware which subbasins are currently being impacted, how the change in runoff timing affects reservoir filling, and how the system's hydroelectric generation may be at risk for change. Within any given large watershed, there are considerable differences in the characteristics of contributing subbasin reaches, and those characteristics influence how the subbasin runoff will respond to climate change. Topographic barriers in the form of steep mountains exist at various mountain locations that increase precipitation through the adiabatic process that takes place with frontal advection and the orographic enhancement of precipitation and snowfall from the cooling process. Isohyetal maps can sometimes be utilized to identify these areas from averaged precipitation amounts that are often related to topography and elevation differences. During this review, it was found that orographically influenced subbasins were least impacted from the effects of climate change, while those areas that were either in a rain shadow or were behind topographic barriers revealed larger climate change impact in the form of reduced snowpack, spring runoff, and sometimes runoff for the water year.

## INTRODUCTION

Earlier studies by Freeman (2008, 2009) that focused on the Sierra Nevada and southern Cascades indicated that both the Feather and Yuba River Basins were currently showing some of the largest timing changes in runoff and loss of low elevation snowpack from climate change. This impact was in general attributed to the combined result of geology and the relatively low elevation of northern California watersheds. However early efforts by PG&E did not attempt to characterize climate change impact on runoff at the hydroelectric operational subbasin level of watershed detail. Hydroelectric scheduling at PG&E is a process in which the forecasted unimpaired sidewater runoff from contributing subbasin reaches that flow into forebay and afterbay pondages to and between the various diversion dams are forecasted as a probabilistic ensemble of unimpaired runoff, then optimally recompiled back into a hedged, optimal schedule of water releases from reservoirs that include unimpaired sidewater inflows. Hydroelectric scheduling optimization at PG&E utilizes a network type approach of arcs and nodes and is based upon the objective function of forecasted energy pricing (Jacobs et al., 1995). A stationarity type change to the historical runoff time series such as from the impact of a declining low elevation snowpack has potential to affect the forecast accuracy and increase the uncertainty for reservoir filling (Freeman, 2003a, Milly et al., 2008). Historically, many PG&E reservoirs were taken to their minimum operating level by December 31 each year, and often remained at that level through March. These same relatively small reservoirs then often spilled in May or June due to having insufficient storage capacity to effectively capture and utilize the snowmelt inflows. Shifting some of the water year (October 1 through September 30 period) runoff into January, February, and March reduces the likelihood of late spring spills from snowmelt. For some subbasins, a small increase in rainfall-produced runoff can have a positive economic value by providing an opportunity to generate power, while for other subbasins a negative impact occurs. Overall no significant negative generation value impact has been noticed or is anticipated for the next 10-15 years for PG&E's hydroelectric system. The level of runoff variance during that

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Paper presented Western Snow Conference 2010

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period is within the modeling and facility planning design that was based on California's normal envelope of both hydrometeorological variance and 'extremes'. Planning is now in place to identify and develop adaptative water management alternatives with the assumption that climate change impacts on snowpack and runoff timing will likely accelerate change in annual snowpack. Continued change in precipitation type from snowfall to rainfall is anticipated to begin having an effect on PG&E's overall hydroelectric energy production by about 2020-2025. This paper will primarily focus on identifying, tracking, and comparing changes in spring runoff at the subbasin level for the central and northern Sierra.

In order to accelerate the planning process, a relatively simplified procedure was developed utilizing long period 30-year moving averages of spring snowmelt runoff starting in 1964. While PG&E's water management team may eventually apply the runoff simulations from downscaled global climate modeling (GCM) to its hydroelectric system network, that effort would likely not take place for a few years. As described in this paper, a relatively simple index approach can provide useful and meaningful information for immediate planning by simply utilizing already available hydrological data. That was the intent of this subbasin classification effort and the results to date have been consistent with expectations based on earlier studies at PG&E. With development of the current tracking procedure, additional efforts will likely focus on the time length for the moving average, understanding how the subbasin characteristics affect the change process, and adaptation of current water management practices to effectively deal with change for the most impacted subbasins. If the current procedure to track impact of climate change on the declining snowpack continues to prove successful; less emphasis, at least for the short term, will be placed on waiting for climate change modeling development by others outside of PG&E and the need to financially support large, complicated, downscaled GCM modeling efforts.

## PROCEDURE

Initial efforts to track climate change at PG&E focused on snowpack data, however with the large variance in snow course data due to exposure, aspect, slope, and other physiographic factors for snow courses at similar elevations in close proximity, it was decided that spring runoff from snowmelt would represent a more meaningful tracking parameter for the purposes of evaluating impact to hydroelectric operations. The April through June runoff was utilized for the Mokelumne River northward and April through July runoff was utilized for the Stanislaus River southward. Including July for the Stanislaus River and southern Sierra helps account for the later runoff typical of the higher elevation southern Sierra subbasins. While an attempt was made to evaluate runoff on the Pit and McCloud watersheds, results proved too noisy for revealing meaningful results. Spring runoff for the Pit and McCloud watersheds, an area characterized by porous volcanic lava flows, is mostly determined by current aquifer outflow rates of large springs, and is not necessarily indicative of low elevation snow loss. Earlier studies have indicated that the aquifers can experience multi-decadal-long droughts and periods of higher than normal hydrostatic pressure. The annual baseflow component for subbasins such as Fall River, which is tributary to the Pit River, makes up approximately 88% of the total water year flow. The focus for this study was primarily on the Mokelumne River north to the Feather River. The Feather River was anticipated from earlier studies to show the most significant impact from climate change (Freeman, 2008). In an effort to dampen the inter annual variance and to also dampen the oscillating effect of possible ENSO or other climate related harmonics that often reveal themselves as having a 14-15-year period (Freeman, 2001), the author finally chose a 30-year moving average as providing the needed stability for linear extension of trends. Figures 1 and 2 show the differences for the same subbasin first utilizing in Figure 1 an 8-year moving average without dampening the 14-15 year oscillation and then in Figure 2 the 30-year moving average that's more closely fitted to the wave length. Several subbasins lacked sufficient data for compiling unimpaired subbasin runoff starting in 1935. 1964 was chosen as the starting year for the 30-year moving average that used the years 1935-1964, however some of the early period unimpaired runoff data for subbasins was not included due to lack of usable data. Lower elevation subbasins often suffered from relatively large cumulative error uncertainty, reflecting the inadequacies of stand-alone stream gauging data collection techniques (Freeman, 1999, 2003b). Some subbasins were not included for the above reason that the data lacked meaningful hydrological continuity with upstream (or in some cases with downstream) reaches. Results in terms of runoff for nearby subbasins often differed significantly even on the same river. As will be discussed in the next section, there appear to be a whole array of factors that influence the impact of climate change on a subbasin's spring runoff. Charts for each of the subbasins were created and a linear trend line developed along with its associated equation. The equation allows linear extension for future prediction. While such an approach may be overly simplistic of what will happen, it provides a conservative and useful estimate for planning purposes. The current year was determined along with the linear estimate for the years 2025, 2050, 2075, and 2100.

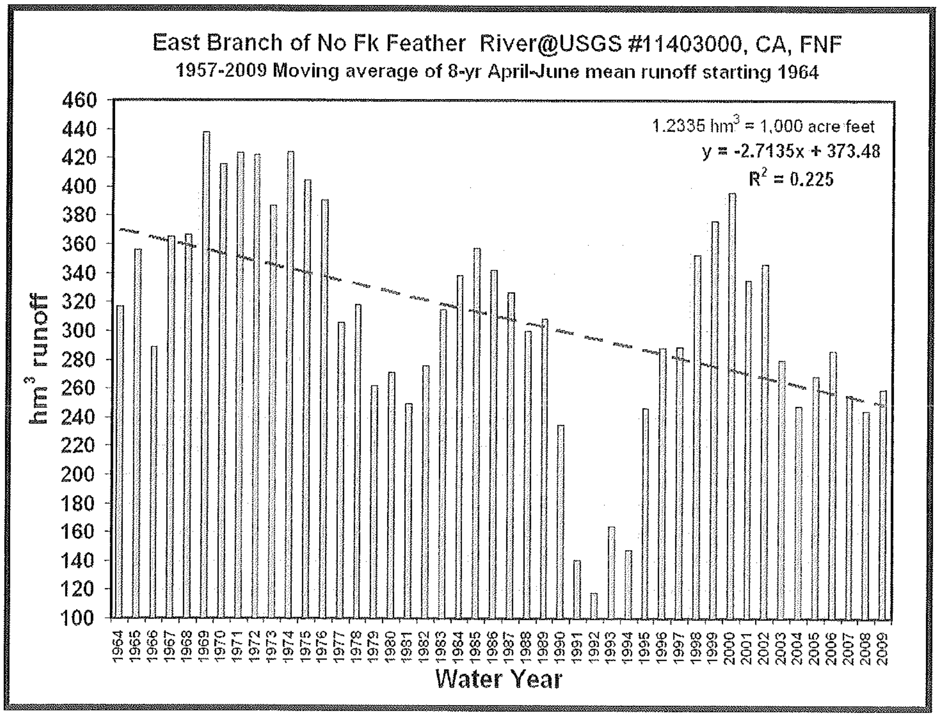


Figure 1. East Branch of the North Fork Feather River with an 8-year moving average without correcting for the 14-15 year harmonic (approximate peaks in 1972, 1986, and 2000).

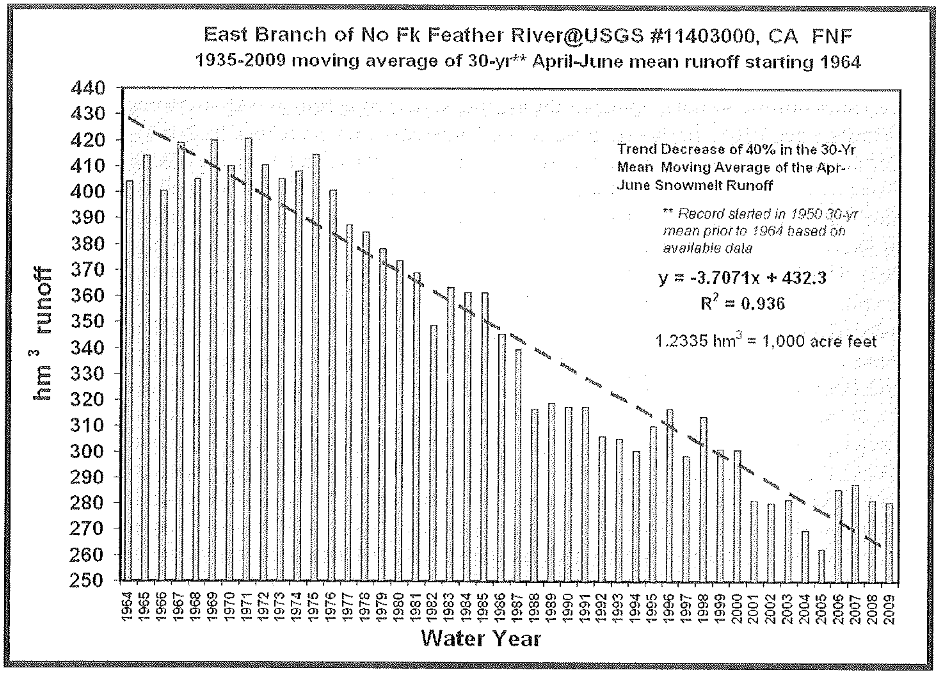


Figure 2. East Branch of the North Fork Feather River utilizing a 30-yr moving average that greatly dampens out the 14-15 year harmonic oscillation.

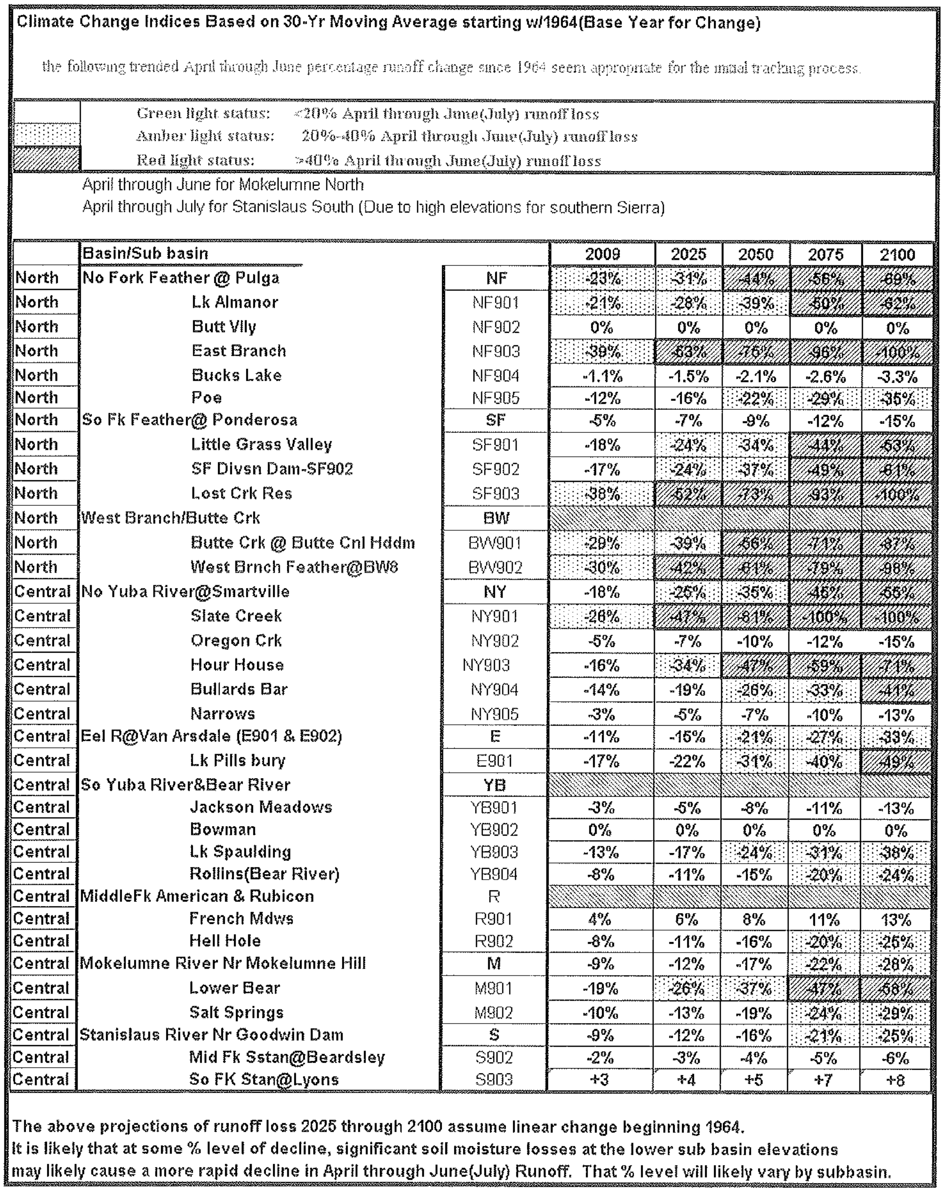
Estimates of 2075 and 2100 have limited usefulness for long range planning because with additional scientific research the approximation will likely turn out to be non-linear. These longer term estimates listed in Table 1 will continue to be compared with and are anticipated to eventually be modified utilizing the more comprehensive downscaled GCM output as such information becomes available at the subbasin level of detail. However the relatively simple procedural approach described here provides the immediate benefit of being available now for the planner's increasing awareness and for providing a rough indicator of current subbasin impact on runoff and possibly some approximate indication of future state. New approaches can be applied to the data compilations and the procedure revised as they become available from the science community. Meanwhile first steps toward meaningful adaptation can proceed with a focused approach for those hydroelectric subbasins in the central and northern Sierra that are most impacted by a decline in spring snowmelt runoff.

## COMPARISON OF FINDINGS

The results of the subbasin comparison are shown in Table 1. Table 1 lists the subbasins for which meaningful data exists and for which data has been compiled. The starting year 1964 was chosen for subbasins that range from the Feather River in the north to the Stanislaus River in the south. Three trend-loss color coded classifications were created: Green light status <20% April through June (July) runoff loss, Amber light status 20%-40% April through June (July) runoff loss, Red light status >40% April through June (July) runoff loss. The table which will be updated and revised annually along with a review of the latest science findings for climate change will be part of PG&E's standard work procedures. The annual comments and evaluations of recent science updates and other climate change related information will be shared with PG&E's leadership. This approach provides a standardized methodology to increase awareness and to focus adaptation efforts on the highest priority subbasin drainage units. Generation impacts, reservoir filling and operational implications will be evaluated for those reaching red or greater than 40% runoff loss. While most concern will likely focus on those subbasins that currently are approaching 40% or more loss and those already in red light status, other subbasins with less losses may also be important depending upon facility constraints, contract commitments, instream flow releases, or other water related operating criteria.

The Lake Almanor subbasin on the North Fork Feather River is currently showing a 21% April through June trend loss of runoff up through 2009. However there is increased concern for this subbasin beyond the loss of spring snowmelt runoff. The late spring and early summer flows are in large part from aquifer outflow of springs, and these groundwater inflows to Lake Almanor during the snowmelt period as well as throughout the year have dropped significantly since 1964. In this case, the loss of snowpack may be related to loss of groundwater recharge opportunity. For the water year as a whole approximately 30% of this subbasin's groundwater inflow to Lake Almanor has disappeared since the early 1960's. This has significantly impacted the April through June unimpaired inflows to Lake Almanor. Utilizing the 30-year moving average index procedure, most subbasins in the higher southern Sierra from about the Tuolumne River southward reveal a positive increase in the April through July runoff index. This in part is a characteristic of the index methodology used and in part also due to the relatively high topographic barrier effect of the mountain subbasins of the southern Sierra. Orographically active precipitation areas in northern California such as Battle Creek, where Mt. Lassen is located on its eastern headwater area and the Bucks Creek subbasin in the relatively steep walled Feather River Canyon seem to have localized adiabatic cooling that has at least for the present time period slowed the impacts of declining spring runoff from climate change. In the case of Battle Creek, a distinct increase in the April through June runoff was found. This watershed has nearly a 50% contribution from springs throughout the year, unlike Lake Almanor, which is somewhat blocked by mountain barriers, the Battle Creek subbasin is apparently not experiencing a decline in spring runoff from climate change. Subbasins such as the East Branch North Fork Feather River and Lost Creek of the South Fork Feather River are characterized by topography that blocks frontal storm movement by mountains on the windward side that creates a topographic blocking barrier. Air that descends into these two subbasins is likely affected by compressional heating, which may affect the dew point temperature and result in reduced annual snowfall and precipitation. The East Branch of the North Fork Feather River has a relatively large evapotranspiration quantity compared with other northern California subbasins. It receives much less precipitation and the runoff recovery efficiency is poor. Snowpack from this subbasin is rapidly declining. At the current rate of decline, it's highly likely that by 2065-2070, the snowpack may be almost nonexistent on this 2,655 km$^2$ (1,025 sq mi) subbasin in most years. However, even on this severely impacted subbasin some snow may continue to fall on the highest peaks at century-end. As snowpack disappears from these subbasins in northern California it can likely be anticipated that the Bowen ratio (sensible heating/latent heating) will increase possibly causing increased land surface heating to take place. That heating effect has potential to accelerate soil drying and lead to increased vegetative stress during progressively longer periods of spring, summer, and fall dryness. Figure 3 shows that March runoff has increased on the East Branch of the North Fork Feather River as a result of earlier snowmelt. While it is intuitive that some of the April through June runoff has declined as a result of earlier snowmelt, shifting increased runoff into the month of March, as mentioned above, the water year runoff has also declined. For the Feather River Bain at Lake Oroville, in addition to the April-June runoff decrease from a declining snowpack, there has been a water year decrease as well. Figure 4 illustrates the concept of the western facing windward slopes of Mt. Lassen serving as a topographic barrier for Battle Creek, and also shows an area of wider spaced isohyetal lines that would likely be characterized by less adiabatic cooling influence and have an active land surface, which is

Table 1. Summary status table of climate change indices based on 30-yr moving average



**Climate Change Indices Based on 30-Yr Moving Average starting w/1964(Base Year for Change)**

the following trended April through June percentage runoff change since 1964 seem appropriate for the initial tracking process.

| | |
|---|---|
| | Green light status: <20% April through June(July) runoff loss |
| ░ | Amber light status: 20%-40% April through June(July) runoff loss |
| ▨ | Red light status: >40% April through June(July) runoff loss |

April through June for Mokelumne North
April through July for Stanislaus South (Due to high elevations for southern Sierra)

| | Basin/Sub basin | | 2009 | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|---|---|
| North | No Fork Feather @ Pulga | NF | -23% | -31% | -44% | -56% | -69% |
| North | Lk Almanor | NF901 | -21% | -28% | -39% | -50% | -62% |
| North | Butt Vlly | NF902 | 0% | 0% | 0% | 0% | 0% |
| North | East Branch | NF903 | -39% | -63% | -76% | -96% | -100% |
| North | Bucks Lake | NF904 | -1.1% | -1.5% | -2.1% | -2.6% | -3.3% |
| North | Poe | NF905 | -12% | -16% | -22% | -29% | -35% |
| North | So Fk Feather@ Ponderosa | SF | -5% | -7% | -9% | -12% | -15% |
| North | Little Grass Valley | SF901 | -18% | -24% | -34% | -44% | -53% |
| North | SF Divsn Dam-SF902 | SF902 | -17% | -24% | -37% | -49% | -61% |
| North | Lost Crk Res | SF903 | -38% | -52% | -73% | -93% | -100% |
| North | West Branch/Butte Crk | BW | | | | | |
| North | Butte Crk @ Butte Cnl Hddm | BW901 | -29% | -39% | -56% | -71% | -87% |
| North | West Brnch Feather@BW8 | BW902 | -30% | -42% | -61% | -79% | -98% |
| Central | No Yuba River@Smartville | NY | -18% | -25% | -35% | -45% | -55% |
| Central | Slate Creek | NY901 | -26% | -47% | -81% | -100% | -100% |
| Central | Oregon Crk | NY902 | -5% | -7% | -10% | -12% | -15% |
| Central | Hour House | NY903 | -16% | -34% | -47% | -59% | -71% |
| Central | Bullards Bar | NY904 | -14% | -19% | -26% | -33% | -41% |
| Central | Narrows | NY905 | -3% | -5% | -7% | -10% | -13% |
| Central | Eel R@Van Arsdale (E901 & E902) | E | -11% | -15% | -21% | -27% | -33% |
| Central | Lk Pills bury | E901 | -17% | -22% | -31% | -40% | -49% |
| Central | So Yuba River&Bear River | YB | | | | | |
| Central | Jackson Meadows | YB901 | -3% | -5% | -8% | -11% | -13% |
| Central | Bowman | YB902 | 0% | 0% | 0% | 0% | 0% |
| Central | Lk Spaulding | YB903 | -13% | -17% | -24% | -31% | -38% |
| Central | Rollins(Bear River) | YB904 | -8% | -11% | -15% | -20% | -24% |
| Central | MiddleFk American & Rubicon | R | | | | | |
| Central | French Mdws | R901 | 4% | 6% | 8% | 11% | 13% |
| Central | Hell Hole | R902 | -8% | -11% | -16% | -20% | -25% |
| Central | Mokelumne River Nr Mokelumne Hill | M | -9% | -12% | -17% | -22% | -28% |
| Central | Lower Bear | M901 | -19% | -26% | -37% | -47% | -58% |
| Central | Salt Springs | M902 | -10% | -13% | -19% | -24% | -29% |
| Central | Stanislaus River Nr Goodwin Dam | S | -9% | -12% | -16% | -21% | -25% |
| Central | Mid Fk Sstan@Beardsley | S902 | -2% | -3% | -4% | -5% | -6% |
| Central | So FK Stan@Lyons | S903 | +3 | +4 | +5 | +7 | +8 |

**The above projections of runoff loss 2025 through 2100 assume linear change beginning 1964.**
**It is likely that at some % level of decline, significant soil moisture losses at the lower sub basin elevations**
**may likely cause a more rapid decline in April through June(July) Runoff. That % level will likely vary by subbasin.**

likely to exhibit a slightly higher Bowen ratio than the surrounding rising watershed. Figure 5 shows the trended April through June increase through 2009. Bucks Creek subbasin on the North Fork Feather River likewise is a high precipitation area that benefits greatly from orographic cooling. This subbasin shows only a slight decrease in spring runoff from climate change. While more study is needed, it appears that subbasin areas with significant orographic cooling and relatively high annual precipitation, are at least for the near term, not being significantly impacted from climate change while nearby areas with much less precipitation and which have a blocking topographic feature are exhibiting significant climate change impacts leading to a decrease in the April through June (July) snowmelt runoff. This effect may help explain why there are existing reports of glaciers increasing in size on Mt. Shasta (Howat et al., 2007). A warming Pacific Ocean may result in wetter winter frontal systems. While in recent years, the snow line in general has risen in elevation, exposed topographic barriers to frontal storms such as Mt. Lassen and Mt. Shasta offer topographic blocking opportunity for the moister, somewhat warmer air to rise upward, expand, and orographically cool, bringing increased snowfall onto the windward edge of high elevation steep mountains. This may also help explain why some of the high elevation southern Sierra subbasins also show increased spring and water year runoff in recent years. For some exposed high elevation mountain areas climate change may actually facilitate and slightly enhance snowfall. Utilizing the 30-year index and the methodology described in this paper, nearly all subbasins south of the Tuolumne River reveal an increase in the April through July runoff in recent years. While it may be only a short term effect, it is sufficient for PG&E to focus its attention on watersheds north of the Tuolumne Basin. It's important to realize that a shorter term moving average or other metric may give different results. The purpose of this approach utilizing the 30-year moving average of spring runoff was one that at least initially proved well suited for identifying hydroelectric operation subbasins to focus on for developing and planning adaptation alternatives. As an example of one such alternative, PG&E is currently adding the US Geological Survey's Precipitation Runoff Modeling System (PRMS) to the Feather River and eventually to the Yuba River as an additional forecasting tool that can be utilized along with PG&E's existing statistical regression forecasting tools. PRMS is a physically conceptual hydrological modeling tool that utilizes hydrologic response units. The Feather River appears to be the most impacted basin overall in PG&E's hydroelectric system, a system which has facilities that exist on 16 Rivers in California from the Pit River near the Oregon border south to the Kern River with a single powerhouse on the Eel River in the coastal mountains.

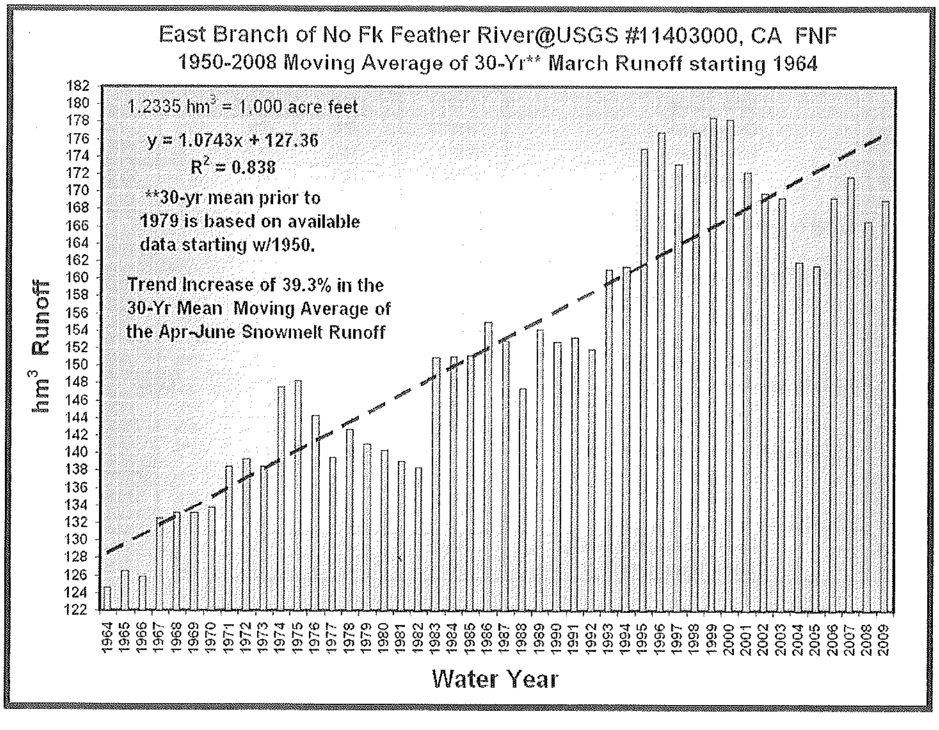


Figure 3. March Runoff for the East Branch of the North Fork Feather River has a trend increase of 39% since 1964.

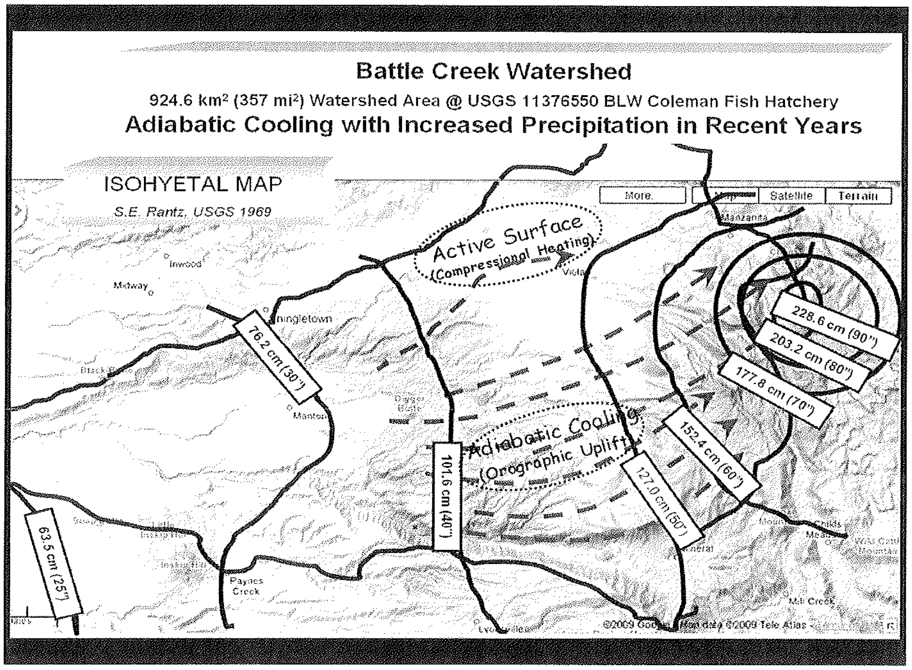


Figure 4. The Battle Creek subbasin showing superimposed isohyetal lines taken from Rantz's statewide Isohyetal map and the author's drawing of likely air flows against both the slopes of Mt. Lassen and the high plateau near the town of Viola.

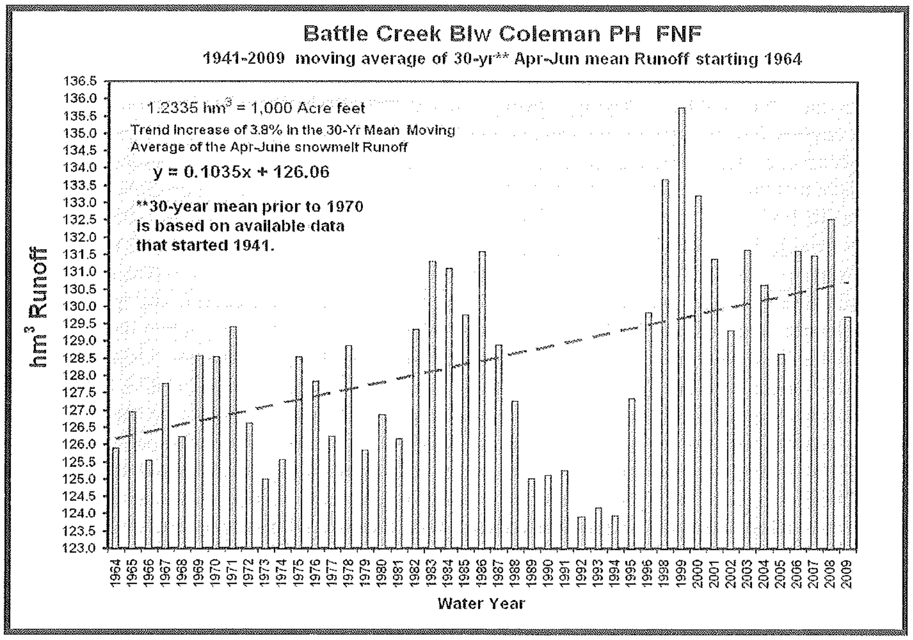


Figure 5. The increase in spring runoff from the Battle Creek subbasin indicates that with very active orographic adiabatic cooling such as occurs along the west facing slopes of Mt. Lassen (3,444m (11,300') elevation); there may be a slight increase in enhanced snowfall and increased spring runoff from climate change at least for the near term.

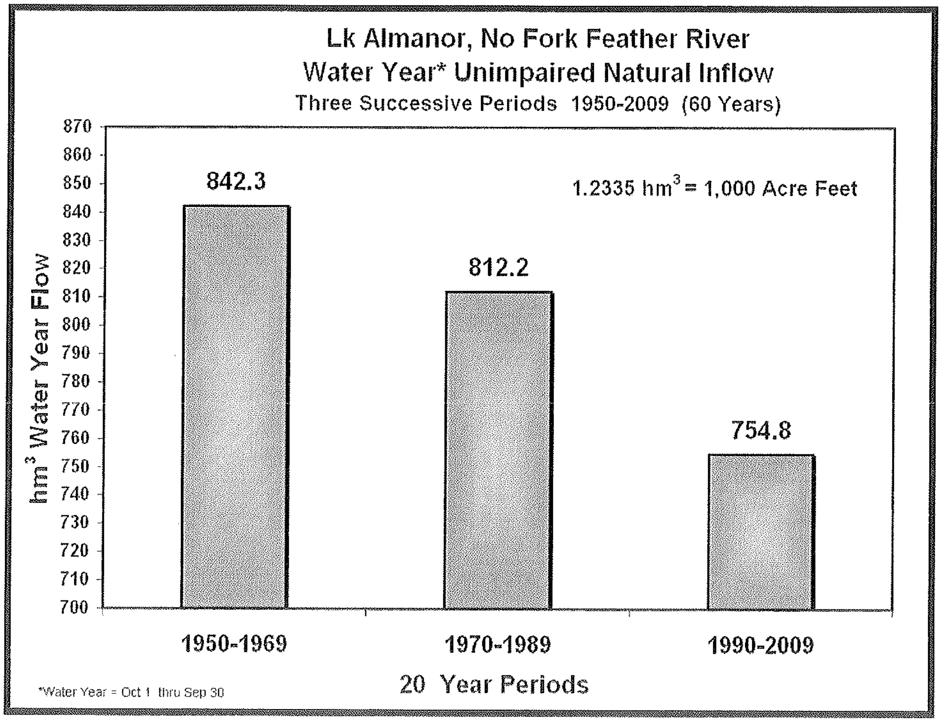


Figure 6. Three successive 20-year periods of water year runoff decline from the decrease in aquifer outflow rate of the contributing springs to Lake Almanor on the North Fork Feather River.

## THE VOLCANIC LOW ELEVATION WATERSHEDS

Both the Pit and McCloud River basins in northern California are losing low elevation snowpack similar in magnitude to the Feather River; however the impact on spring runoff from the declining snowpack is difficult to identify. The high level of dependence on large springs as a source for the majority of stream flow (Davisson and Rose, 1997) tends to obscure the impact of annual snowfall decline. For example, approximately 88% of the annual surface for the Fall River at PG&E's Pit PH #1 is from aquifer outflow (Freeman, 2007). The aquifer outflow is mostly from precipitation of past years and experiences the impacts and characteristics of dry and wet periods such as from the early 20th century's five decade long groundwater drought in the southern Cascades. The multilayer volcanic flows are very porous and are in several areas composed of dozens and in some cases hundreds of very porous volcanic layers of basalts. The flows for these two rivers which are largely dependent on groundwater are difficult to analyze in terms of the impacts of a diminishing snowpack. However the loss of snowpack will likely result in a loss of soil moisture with increased likelihood for vegetative stress, disease, and an increase in the frequency and intensity of fires on these watersheds. At Lake Almanor on the upper North Fork Feather River, the aquifer outflow of the relatively shallow layers of volcanics has resulted in approximately 105 $hm^3$-123 $hm^3$ (85-100 TAF) per year loss of runoff from the springs surrounding and under the Lake. Research by Jefferson et al., (2008) suggests that a loss of aquifer recharge opportunity on porous volcanic rock may result from a diminishing low elevation snowpack in the headwaters. How this area of relatively shallow volcanics differs from those of the much deeper layered Pit and McCloud River volcanics will require additional research. Figure 6, which shows water year loss also indirectly reveals the loss of aquifer outflow that has occurred since the mid-20th century. Nearly all of the water year loss is from the decline in aquifer outflow of large volcanic springs.

## LOW ELEVATION SNOWPACK LOSS IN NORTHERN CALIFORNIA'S LAKE ALMANOR SUBBASIN

Both Lake Almanor and the East Branch of the North Fork Feather River are two subbasins in which winter frontal cells are topographically blocked by mountain ridges. This effect is reflected in the reduced historical precipitation averages for both of these subbasins as compared with the much wetter Feather River Canyon along Highway 70, which experiences significant orographic precipitation enhancement. Figure 7 shows the declining April 1 snowpack in terms of snow water equivalent for Mt. Stover above Lake Almanor. While there is considerable year-to-year variance, the trend shows a relatively steep decline in the April 1 snowpack since 1949. The author believes that this loss of low elevation snowpack may have impacted groundwater recharge opportunity for Lake Almanor. The snowpack while in the process of ablation provides a relatively evenly distributed contribution to the soil surface generally lasting 60-70 days historically. The extended contribution of water for infiltration provided soil moisture and groundwater recharge opportunity may have been shortened by several days in recent years. Currently Mt. Stover as shown in figure 7, receives less snow than 60-70 years ago and its snowpack melts earlier. In addition to a longer dry period for soils in summer, the absence of soil moisture and snowpack may have potential for increased heating at the soil surface leading to increased vegetative stress.

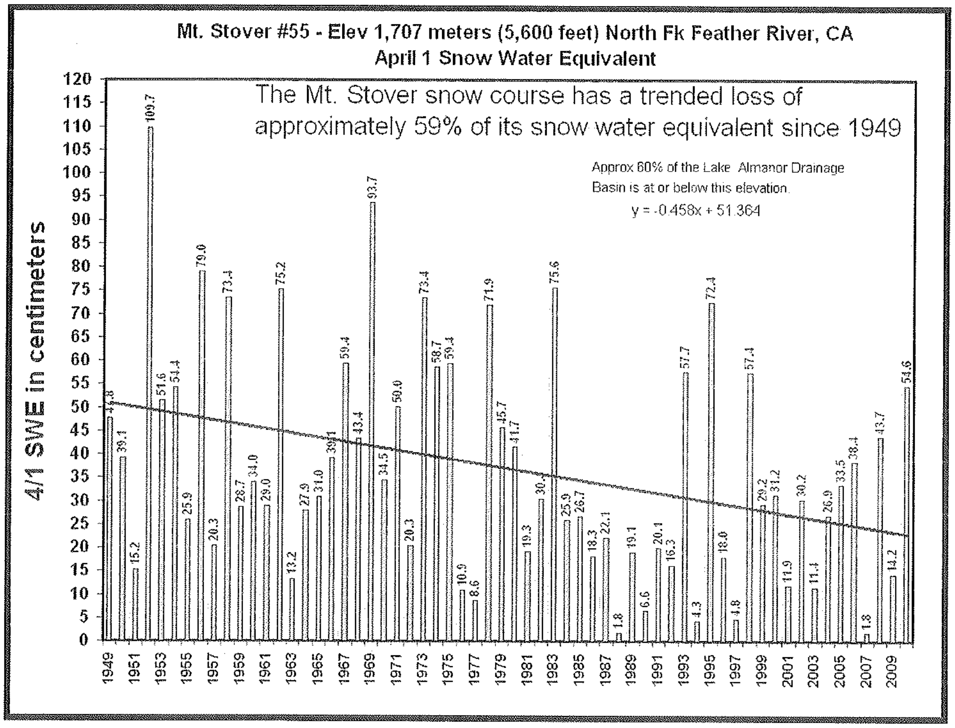


Figure 7. Mt. Stover April 1 snow water equivalent with declining trend line. Mt. Stover is located in the Lake Almanor subbasin on the North Fork Feather River.

## MONTHLY DISTRIBUTION OF RUNOFF CHANGES

One of the most impacted subbasins identified in Table 1 is the East Branch of the North Fork Feather River, a 2,655 km$^2$ (1,025 mi$^2$) subbasin above Lake Oroville. In addition to a large trended decline of 39% in the April through June runoff, the 12 month water year has declined 23% in the more recent period compared with the earlier 1950-1975 26-year period of record. This subbasin, which is located in a relatively low elevation and low rainfall area, is topographically blocked from the cooling, orographic effect of winter storms by the relatively steep Bucks-Grizzly Ridge. Figure 8 shows that while March runoff has increased over the earlier period, reflecting the effects of an earlier snowmelt, the April through June period has declined significantly in the more recent period. Analysis of the two successive periods also revealed a 221 hm$^3$ (179 TAF) or 23% decline in the more recent water year period compared with the earlier period. In contrast to the East Branch of the North Fork Feather subbasin, which is located in the rain shadow or leeward, east side of the Bucks- Grizzly Ridge, the Bucks Lake NF904 subbasin is located on the windward, west side of the Bucks- Grizzly Ridge. This orographically influenced Bucks Lake NF904 subbasin had only a 1.1% decline in the April through June runoff for 2009 and revealed no change in water year runoff from the earlier period. The Bucks Lake NF904 subbasin which is 74.1 km$^2$ (28.6 mi$^2$) is a small, steep storm facing watershed that experiences significantly more annual precipitation than surrounding subbasins on the Feather River. Figure 9 shows its monthly distribution for the two periods. While for the more recent period May and June show a decline, the preceding months have increased sufficiently to retain the overall water year runoff quantity. Bucks Lake precipitation is approximately 3.5 times that of Quincy on the East Branch of the North Fork Feather River. Air that rises over blocking mountain ridges and descends into these subbasins likely loses benefit of orographic cooling. With recent period warming since the mid-1970's, the snowline for the blocked relatively low elevation subbasins may have risen much more than for orographically influenced subbasins such as occurs on the Bucks Lake NF904 subbasin. Subbasins near the bottom of Table 1 are located in higher southern Sierra subbasins and appear much less impacted from loss of the spring runoff. The cooling effect of the higher southern subbasins may be similar to those northern California subbasins that experience orographic cooling. For orographically cooled subbasins, isohyetal maps may be helpful for identifying which subbasins are likely to be most impacted from the effects of climate change. When 'rain shadowed' subbasins such as the East Branch of the North Fork Feather River receive less snowfall, the spring and summer water balance may possibly shift a greater proportion of available precipitation into maintaining vegetation and a higher rate of evapotranspiration to compensate for increased soil surface heating. Future studies are needed to increase our understanding as to why the water year runoff from such subbasins has declined in recent years.

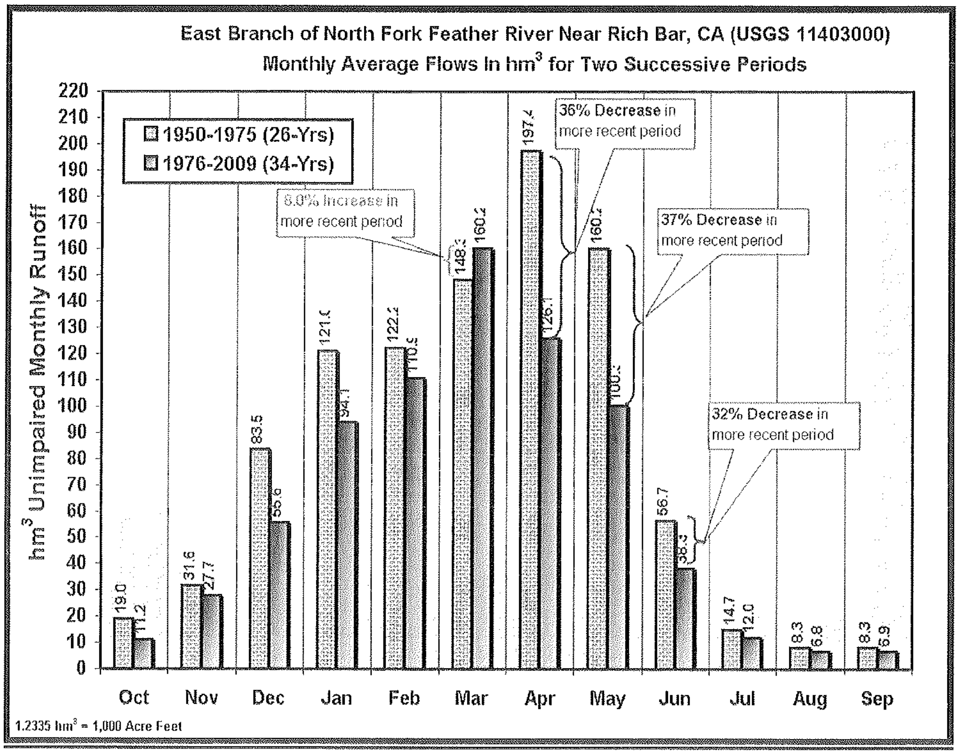


Figure 8. East Branch of North Fork Feather River monthly distribution for two successive water year periods. Analysis of the two successive periods also revealed 221 $hm^3$ (179 TAF) or 23% decline in the more recent water year period compared w/earlier period.

## HYDROELECTRIC OPERATIONS

For those subbasins in central and northern California where climate change has reduced spring runoff from the loss of low elevation snowpack, an important part of the water storage system is lost. In order to compensate for the loss of water storage in the snowpack, surface reservoirs will need to retain higher water levels over the winter period to increase the likelihood to fill reservoirs during drier than normal springs. The uncertainty of remaining precipitation and rainfall-caused runoff from winter and early spring weather for filling reservoirs increases the operational planning risk for winter and early spring spills. Increased spill from mountain reservoirs leads to increased likelihood for lost hydroelectric generation. Also if the spring remains dry in terms of precipitation, reservoirs for certain subbasins may not fill. This can have negative impact on recreation, hydroelectric, water supply, contractual commitments, etc. It's important to realize that the runoff impacts of climate change are subbasin specific, and that for any successive reach moving downstream, subbasin impacts are cumulative. In terms of overall hydroelectric generation, the current climate change impacts are not yet significantly impacting PG&E's average annual generation. Increased rainfall-generated runoff during the December through February time period decreases the likelihood for spring snowmelt spills, and provides runoff during a period that historically received very little runoff. Winter and spring generation prices are largely dependent on natural gas pricing. In current years, generation prices have been sufficient to welcome the opportunity for winter hydroelectric generation during a period that historically had experienced relatively little runoff with much of the precipitation being in the form of snowfall. It is anticipated that if the current climate change impacts continue to raise the snowline elevation, than a negative impact to overall hydroelectric generation from PG&E's mountain hydroelectric system may become significant after about 2020-2025. An increase in the rainfall proportion of precipitation that leads to larger winter-rainfall runoff events will likely cause increased erosion potential, resulting in increased sediment movement. This has the potential to fill both diversion dam pondages and seasonal storage reservoirs.

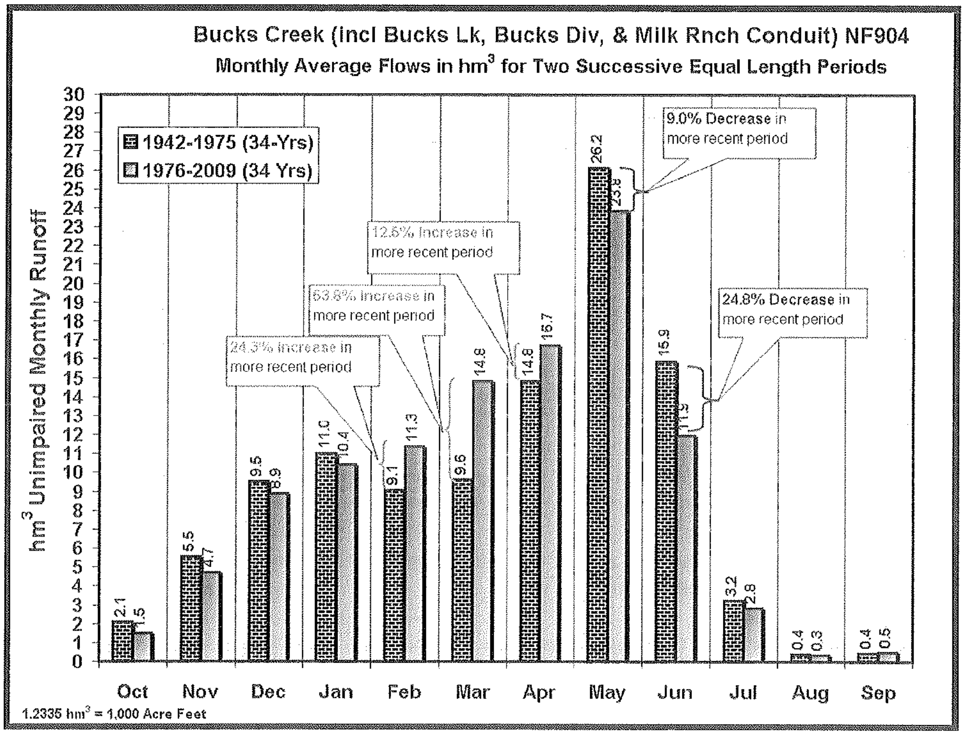


Figure 9. Bucks Lake (Creek) NF904 monthly distribution for two successive water year periods. Analysis of the two successive periods for this strongly orographic affected subbasin shows only a 1.1% decline in the more recent water year period compared with the earlier period.

## CONCLUSIONS

A procedure utilizing the spring snowmelt runoff for the months April through June (July) to access the impact of climate change was developed for a number of operational hydroelectric subbasins in central and northern California. While California as a whole is experiencing the impact of a low elevation snowfall decline and an earlier snowmelt overall from climate change, the Feather and Yuba River watersheds are experiencing some of the largest impacts at the current time with specific subbasins being impacted more than others. A 30-Year moving average that starts in 1964 was utilized in this study as a trended index for comparing the response of various subbasins and identifying those that may require an adaptative water management approach. A shift of winter and spring precipitation from snowfall to rainfall and an earlier snowmelt explains a lot of the spring runoff decline, however for some subbasins and watersheds; the water year runoff is also revealing a decline, possibly due to increased evapotranspiration, increased Bowen ratio and other hydrological changes. It was discovered during this study that some subbasins are able to resist the impact of climate change from diminishing snowfall due to a combination of topography, geology, and aquifers that can combine in unique ways to maintain and in some cases even increase spring snowmelt runoff. At Lake Almanor, groundwater recharge opportunity appears to be declining due to loss of the low elevation snowpack over the relatively shallow layers of relatively recent volcanic flows. While climate change does not at the present time and during the next 10-15 years appear to represent any significant negative impact on hydroelectric production overall for PG&E, it is anticipated that if climate change impacts on the diminishing snowpack continue, associated impacts of climate change to hydroelectric operations are likely to eventually occur and must be planned for in terms of developing additional adaptation alternatives.

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