ANALYZING THE IMPACT OF CLIMATE CHANGE ON MONTHLY RIVER FLOWS IN CALIFORNIA'S SIERRA NEVADA AND SOUTHERN CASCADE MOUNTAIN RANGES

Gary J. Freeman[1]

ABSTRACT

The impact of climate change on monthly river flows in California's Sierra Nevada and southern Cascade Mountain Ranges and its potential to impact hydroelectric production was analyzed to determine changes that have taken place in two successive 35-year periods during the past 70 years. Unimpaired monthly flows from both California's Department of Water Resources' (CDWR) Data Exchange Center's (CDEC) files and from Pacific Gas and Electric Company's (PG&E) operational subbasin runoff forecasting files for the Feather River were analyzed for comparison of the two periods. A notable change was the shift of snowmelt runoff from the April through July period into the month of March. March flows were larger for the more recent 35-year period for all of the flow points analyzed in the Sierra and southern Cascades including two subbasins on the upper North Fork Feather River where rain shadowed climate change impact has significantly reduced both snowmelt and water year runoff in the more recent 35-year period. The increase in March runoff appears to be a combination of mostly earlier snowmelt due to warming temperatures and from an increase in proportion of March precipitation that now occurs as rainfall. In northern California both the shift of snowmelt into March and the reduction of snowpack overall has resulted in reduced late spring and summer flows during the months of April through June. Subbasins south of the Yuba River have for the most part increased overall snowmelt runoff for the March 1 through July 31 period, while subbasins from the Yuba River north have remained either equal or declined in snowmelt runoff in recent years. Both increased elevation and orographic cooling seem to be critical for delaying the impacts of climate change on affecting spring and early summer runoff. For a rain-shadowed subbasin such as Lake Almanor, the recent 35-year period shows a 22% decline in the April through July runoff caused primarily from a combination of: 1) earlier snowmelt, 2) increased proportion of precipitation occurring as rainfall in recent years with less snowfall overall, and 3) reduced aquifer outflow from springs. (KEYWORDS: climate change, subbasin, unimpaired flow, orographic, hydroelectric)

INTRODUCTION

The warming climate has changed the timing of spring runoff in the mountainous areas of California. Large watershed unimpaired flows were analyzed and compared throughout the Sierra and southern Cascades for two successive 35-year periods. Utilizing the same two periods for comparison, an analysis was also performed for several subbasins on the Feather River, a large river in northern California. In a comparison of the two periods, the more recent period shows a shift of snowmelt runoff into March. Also a greater percentage of the March precipitation now typically occurs as rainfall in recent years which results in an increase in rainfall-generated runoff during the month of March. This climate related change is supported by the findings of Knowles et al., (2006) and Mote et al., (2005). Shifting the spring freshet to earlier in the year typically results in less runoff being available for summer and fall flows. For PG&E, a large investor owned California gas and electric utility that manages its reservoirs to fill in late spring and early summer to meet its summer and fall hydroelectric needs for peaking power, the combination of a decline in the April 1 snowpack (Freeman, 2010), filling mountain reservoirs from snowmelt earlier in the year, and an increasing dependence on rainfall for filling is anticipated to eventually lead to increased likelihood for spill from PG&E's relatively small mountain reservoirs. The higher elevation subbasins in the southern Sierra are less influenced from climate change with regard to getting precipitation in the form of rainfall in March. However the March average for the 1977-2011 35-year period still shows an increase in runoff for the more recent of the two 35-year periods. This observed increase in March inflow seems to occur universally throughout the Sierra and southern Cascades. The earlier spring snowmelt runoff period may also be negatively impacting aquifer recharge on northern California's porous volcanic watersheds (Freeman, 2008, 2010, and 2011). This loss of recharge opportunity may be revealing itself in the observation that aquifer outflow of springs for the upper North Fork Feather River @ Lake Almanor has steadily declined during the past three decades. A similar effect has been shown for the McKenzie River in Oregon by Jefferson et al., (2008).

Paper presented Western Snow Conference 2012

[1]Power Generation Department, Pacific Gas &Electric Co., Mail Code N13A, P.O. Box 770000, San Francisco, CA 94177, GJF2@pge.com

Snowmelt results in a slow somewhat steady infiltration downward into the soils, which eventually reaches the water table and helps recharge groundwater. Increased runoff into mountain reservoirs during the January through March period has some potential to reduce the historical snowmelt pulse that typically occurred in April through July on many watersheds. For hydroelectric operators such as PG&E, getting some runoff into reservoirs prior to April 1 provides reservoir operators with an opportunity to run the water through powerhouses rather than wait for the historical April through July runoff from snowmelt. Historically prior to 1977, a larger proportion of the January through March precipitation came as snowfall. Beginning in mid-to-late April in years prior to 1977, the runoff from snowmelt during years of average or greater wetness would take place beginning in early April , quickly filling the relatively small mountain reservoirs, with excess snowmelt runoff often spilling at diversion dams and bypassing powerhouses. The pricing for hydroelectric energy produced in February and March is often fairly good and is always valued higher than zero dollars, which is the consequent value of water spilling past powerhouse diversion dams. However the down side of a declining snowpack is that there is increasing risk from supply uncertainty when relying on an increasing proportion of precipitation occurring as rainfall. Snowpack is frozen water in storage and can be accounted for with reasonably high certainty; however the uncertainty of remaining weather and increasing dependence on future precipitation for filling reservoirs greatly increases operational risk for both spill and for not filling. Faced with the uncertainty of whether or not there will be sufficient precipitation in the spring for filling reservoirs, reservoir operators often find themselves holding onto or storing additional water in attempt to increase assurance for filling the seasonal reservoirs. If in late March, the reservoir operator has mostly full reservoirs, and March turns out to be wetter than normal with most precipitation occurring in the form of rainfall, the reservoirs can quickly fill and spill past the powerhouse's diversion dam with consequent hydroelectric generation loss. The water release planning period is decreased from the historically longer, mostly gradual snowmelt duration of 2-3 months, to a few days. Receiving short notice of a warm storm's arrival in the form of a weather forecast and the consequent filling of a small reservoir of 62 hm^3-148 hm^3 in size (50 TAF-120 TAF) is typically not more than a few days to a week. There is often inadequate time to increase powerhouse flows and utilize the water efficiently for hydroelectric production, especially for large rain producing storms. For PG&E during storm periods, the flumes and canals are typically operated with increased freeboard during storm periods to reduce the likelihood for storm related damage to the facilities such as sometimes occurs from falling trees and debris slides. If a water carrying conduit becomes damaged from storm related incidents, the consequent snowpack and winter mountain conditions may increase the time that it will take to complete a repair. In the meantime the canal downstream of a break or damaged area may not be able to carry water. In the high country, lack of sufficient water in an open conduit may result in the canal or flume filling with snow, or in some cases, the empty structure 'floating' or being buoyed upward due to lack of having sufficient weight for the water being displaced by the structure's base within the soil.

COMPARING TWO EQUAL LENGTH PERIODS OF RUNOFF DATA

In order to detect possible effects of climate change, two successive 35-year periods were selected and their means and standard deviations compared for differences. PG&E maintains unimpaired natural runoff for over 100 locations in the Sierra, southern Cascade, and the Coastal Mountain Ranges of California. Nearly all of these points are computed daily and kept current for the purpose of forecasting runoff and performing water studies in connection with the operation of PG&E's hydroelectric system. The two periods selected for comparison were 1942 through 1976 (35-years) and 1977 through 2011 (35-years). The 1976 and 1977 water years were selected as the dividing point for the two 35-year periods because both years were very dry with 1977 being a second consecutive year of drought and drier than 1976 in terms of both precipitation and surface runoff. Much of the change that has occurred in recent years appears to have begun in the mid-1970's. CDWR likewise computes unimpaired monthly natural flows for most of the major rivers that drain the Sierra and southern Cascades, but typically do so for the entire river to a point at or close to a large multipurpose reservoir near the floor of the Central Valley. These large multipurpose reservoirs are typically referred to as the 'rim' reservoirs as they are situated along the rim of California's Central Valley. While the study was mostly performed at the subbasin level of detail within the upper reaches of the large rivers, for the sake of simplicity many of the table and chart comparisons in this paper compare the monthly runoff for 13 of the large rivers which range from the Klamath River near the Oregon Border to the Kern River near Bakersfield. In many ways this relatively low resolution analysis summarizes the overall findings that were observed at the operational subbasin level of detail. Compared with the other large rivers, a primary difference was observed for the Feather River where rain shadowed operational subbasins lack the orographic cooling condition and the runoff is much more impacted from climate change than for the Feather River as a whole. For the Feather River Basin, some of the subbasins are analyzed for their somewhat unique climate change response. For these few rain shadowed cases, the winter minimum air temperatures have warmed significantly above the surrounding, more orographically influenced subbasins. The rain shadowed subbasins indicate a relatively large water year loss for the more recent of the two 35-year periods. In both cases this surface runoff loss appears to have resulted mostly from increased evapotranspiration.

THE WATER YEAR

Figure 1 indicates an overall linear trend in water year change in runoff for the more recent 35-year period compared with the earlier period that ranges from -10.6 percent for the Klamath River at Orleans near the Oregon border to +17.2% for the Kern River near Bakersfield. This increasing trend needed to be removed to evaluate the monthly flows. For the two time periods analyzed, the rivers show a gain in water year runoff for the more recent period from the American River southward. This increase may in part be related to increased elevation and relatively strong orographic cooling associated with the central and southern Sierra. While there is some tendency

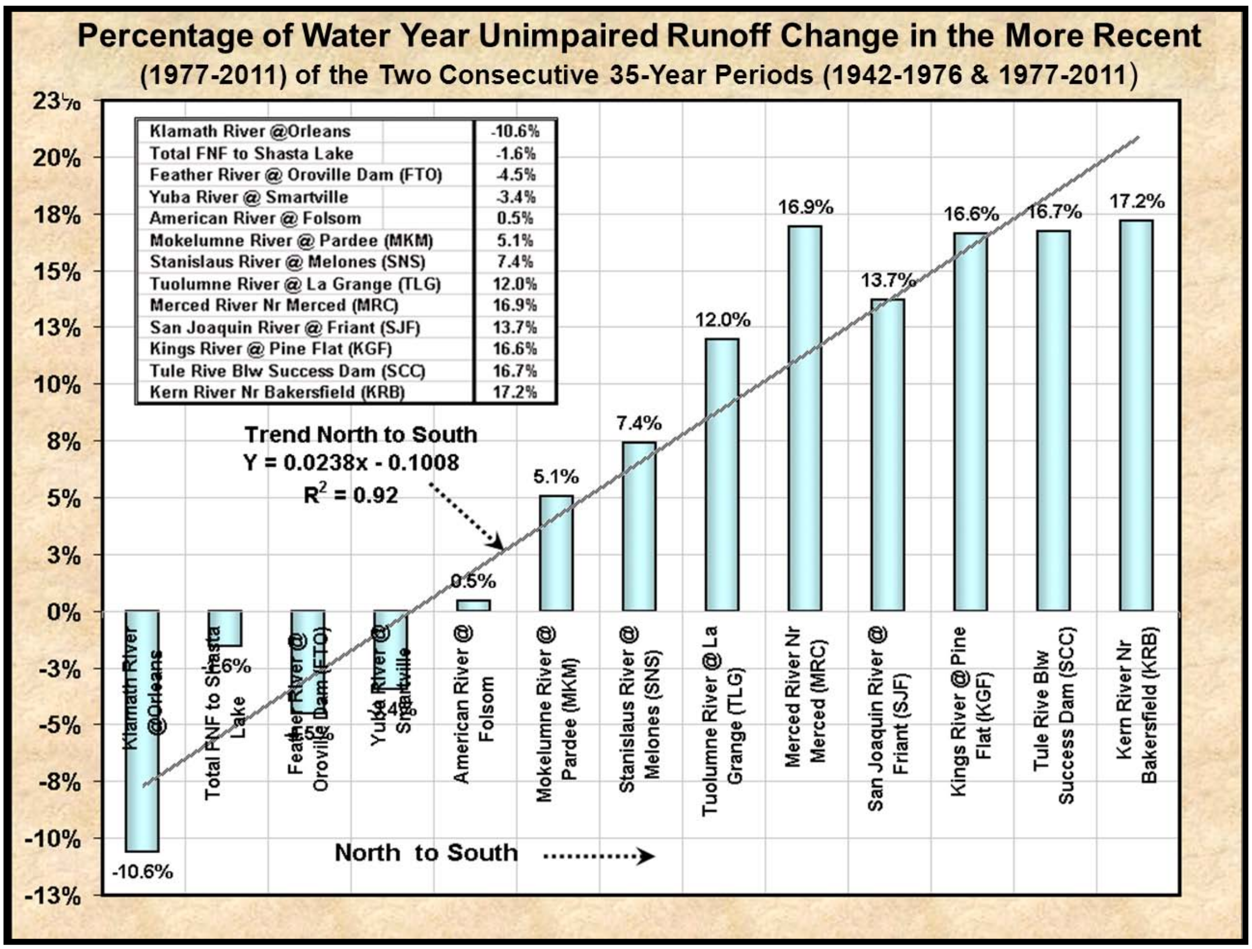

Figure 1. Water year runoff quantities for the American River southward generally increase in the more recent 1977-2011 period compared with the earlier 1942-1976 period.

for precipitation to increase in the north to south direction, the percent increase has a lot of variance. The northern Sierra is much lower in elevation overall, has several rain shadowed subbasins, and as such does not overall have the extent of orographic cooling effect. Orographic cooling is more common for subbasins along the west facing side of the Sierra Nevada, which encounter the eastward frontal flow from storms onto the relatively steep inclined windward slopes. For PG&E with its hydroelectric system distributed over the Sierra Nevada and southern Cascades, the overall impact from climate change has been somewhat of a "no net impact" at least during the past couple decades and this situation will likely continue to be the case for at least the near future. The increased runoff for the southern Sierra watersheds and the benefits of increased hydroelectric generation that results from an earlier snowmelt with increased rainfall overall leads to an earlier filling of the relatively small mountain reservoirs. Rather than waiting for snowmelt, which has historically started in April with high likelihood for spill in years with above average late spring snowmelt runoff, beginning in mid- January stored water is now increasingly released from the reservoirs with decreased risk for spill past the powerhouses. The downside risk for the operator is that with this earlier rainfall-caused inflow, reservoir planners are now becoming increasingly dependent on the uncertainty of remaining weather, often in the form of rainfall for filling reservoirs.

SUB-PERIODS WITHIN THE WATER YEAR

In order to remove the trending change in water year runoff for the 13 rivers analyzed in this study, the average monthly runoff for each of the subbasins and watersheds for the two comparative periods were divided by that period's water year total runoff. Converting the two successive 35-year periods into a monthly percentage of the water year totals produced a relatively trend-free set of monthly ratios to use in comparing the two periods irrespective of differing average water year totals. The watersheds were then compared from north to south along the Sierra and southern Cascades. The PG&E hydroelectric system is primarily divided into operational subbasins based on a combination of both diversion dams and the larger seasonal storage reservoirs. Runoff is forecasted and accounted for at each diversion dam. Some rivers such as the Feather River above Lake Oroville is forecasted with water release planning taking place at PG&E for approximately 20 operational subbasin diversion points. Each of these diversion points have sidewater unimpaired inflows associated with them, which allows for a fairly detailed elevation-based climate analysis that utilizes

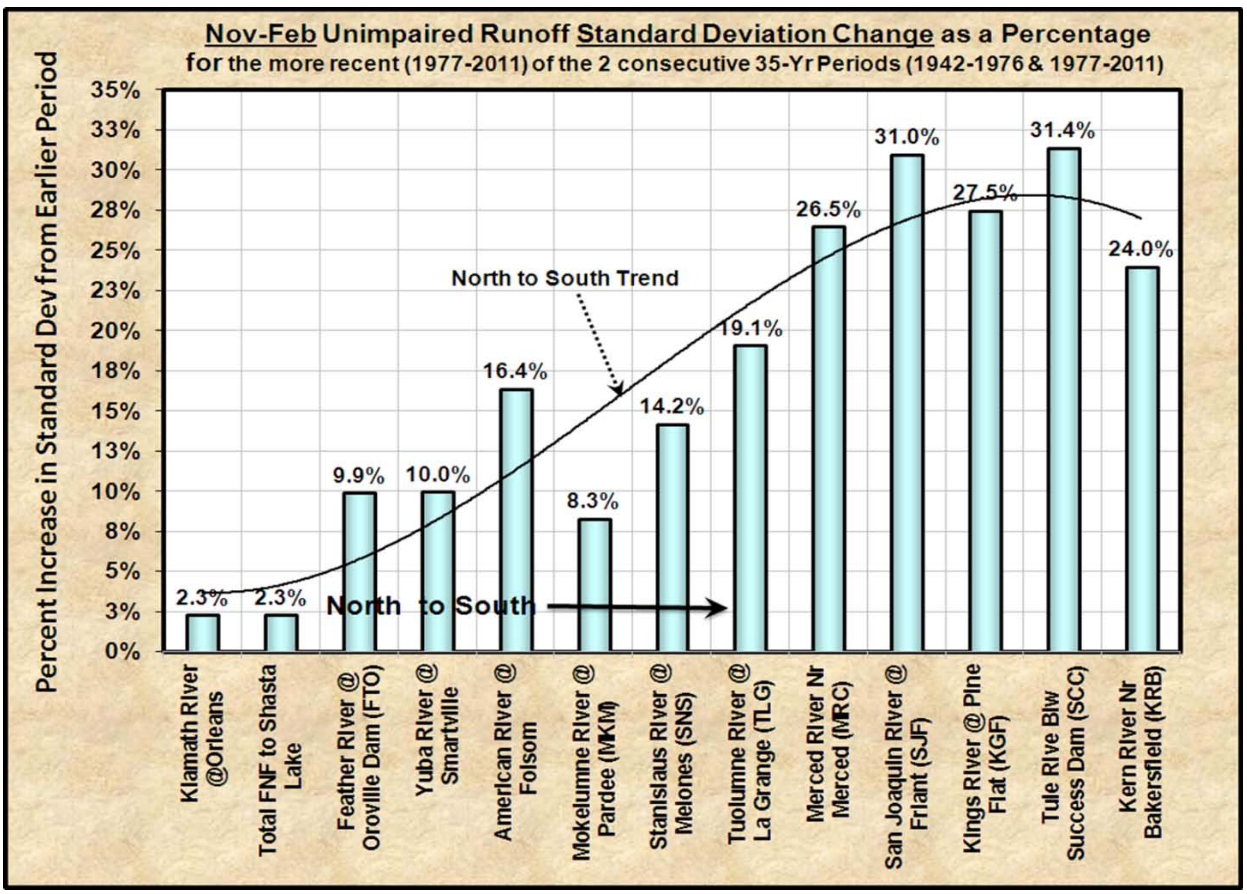

Figure 2. The percentage increase in standard deviation for the November through February runoff in the more recent (1977-2011) of the two 35-year periods.

calculated and daily compiled subbasin and river reach runoffs. An analysis of the Feather River subbasins was done to identify the runoff impact of climate change on orographic and rain shadowed subbasins.

Standard Deviation increase in the More Recent Period

The standard deviation for both the water year and the November through February 4-month sub-period increased in the more recent of the two 35-year periods. For the November through February 4-month sub-period, the trend in general increased from north to south, with somewhat of a leveling off for the Merced River southward. For the water year period, the standard deviation tended to decrease on both sides of the Merced River. It's fairly characteristic for the rivers that flow over the exposed granites, that they have historically had a large variance in flows in which either being very dry or very wet is almost the norm. What is observed is that with climate change the variance and related standard deviation increases in the more recent period with standard deviation increasing as much as much as 31 percent for the November through February period and up to 47 percent for the 12-month October 1 through September 30 water year period. Figure 2 and Figure 3 show the standard deviations for both the November through February and the water year periods for the thirteen major rivers.

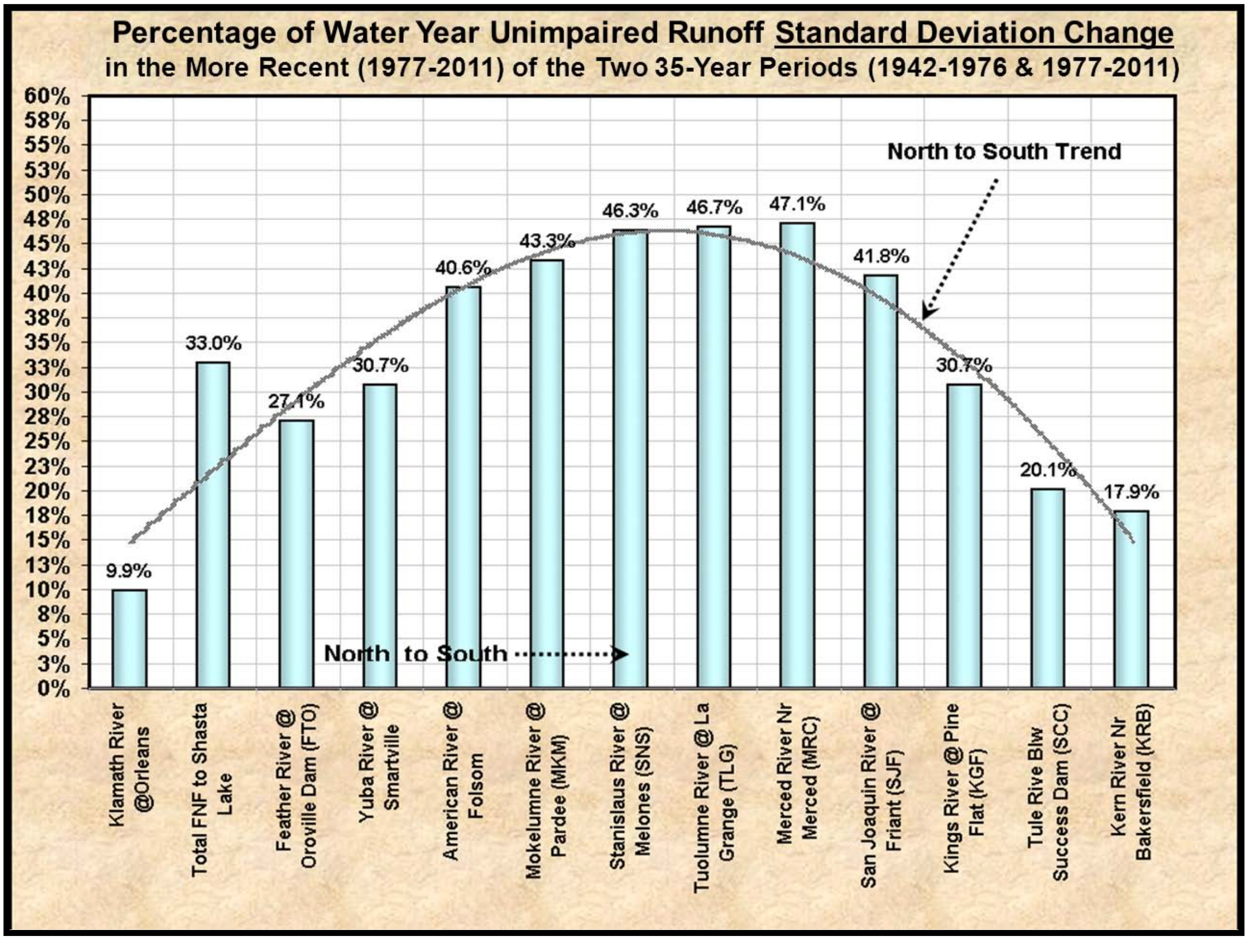

Figure 3. The percentage increase in standard deviation for the water year runoff in the more recent (1977-2011) of the two 35-year periods. The Merced River has the greatest increase in standard deviation.

Shift of the April through July into Earlier Months

Figure 4 illustrates the impact that climate change has on each of several large river basins that range in location from north to south from Northern California's Klamath River south to the Kern River near Bakersfield. A large portion of the April through July runoff has shifted into March and a lesser amount into February. The largest shift into March from the April through July period is 4.4% for the Feather River at Oroville Dam. Both north and south of the Feather River, the trend shifts downward. The Kern River, which is at the far right of the Figure 4 chart shows a slight increase of runoff shift into March. Due to the Kern River's upper basin, which drains distinctly southward behind the initial Sierra Crest, the Kern River as shown in Figure 5 does not have the same basin orographic orientation as the drainages to the north, but instead has a somewhat rain-shadowed configuration. In spite of the position of its downstream reach which empties into the San Joaquin Valley near Bakersfield; its headwater drainage has a somewhat blocked configuration giving it a more northern characteristic equivalent to that of the San Joaquin River in terms of the March ratio.

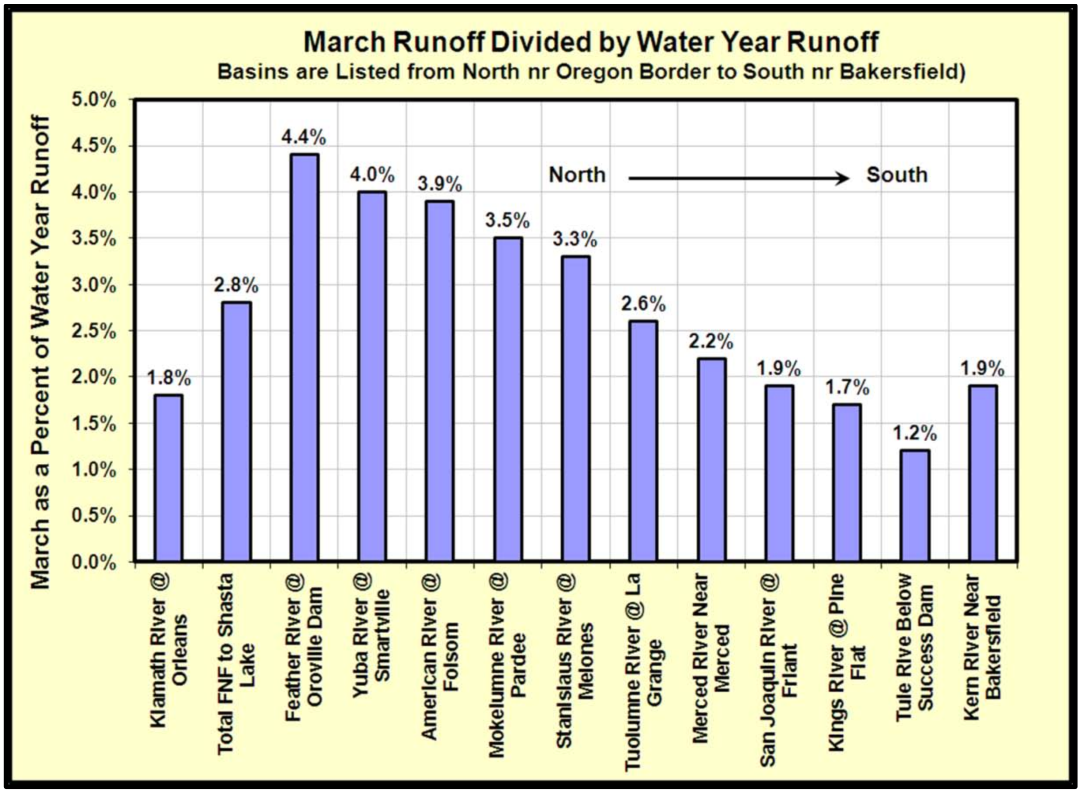

Figure 4. March runoff divided by water year runoff. Left to right order corresponds to north to south orientation.

Figure 5. The Kern Headwaters differs from most Sierra Rivers by turning northward along the Sierra's southern block's Kern Canyon Fault behind the blocking influence of the Sierra Nevada's Great Western Divide sub range.

In terms of analyzing the effects of climate change on runoff, orographic effect seems to have major implications on how runoff in the Sierra and southern Cascades is impacted. Both the Klamath River and the combined Sacramento, McCloud, and Pit Rivers @ Shasta appear to likely have greater orographic cooling overall compared with the Feather River. Elevation overall appears to provide a benefit against the effects of climate change providing that the elevation has the windward benefits from steep upward cooling. In the case of the Kern River those windward benefits appear to have been slightly dampened by the Kern Basin's shape as it cuts behind and becomes somewhat blocked by a portion of the Sierra crest. The Kern River is the only major Sierra River to flow north to south. It runs nearly a straight line down the 87-mile long Kern Canyon Fault from the highest Sierra peaks including Mt. Whitney and south in two main forks that have carved dramatic canyons along their paths bordered to the west by the Great Western Divide, one of the largest and highest mountain sub ranges in the Sierra Nevada Mountains. The Kern River, the result of the Kern Fault is located on the southern block, which 60-20 million years ago emptied into the Colorado River to the East, but during the past 20 million years has shifted its outlet westward into the San Joaquin Basin, and within the past 12 million years shifted its outlet toward the city of Bakersfield (Hill, 2006; Nadin, 2007). Because of it not being a part the main Sierra block that tilted toward the west, the effect of orographic cooling from winter storm activity is likely slightly less than for much the more exposed west-facing, windward slopes of the Kings and Tule Rivers just north of Bakersfield. Freeman (2011) discusses the importance that subbasin and basin orientation has in minimizing and buffering the impacts from climate change.

MONTHLY CHANGES

Table 1 lists as a percent the monthly runoff divided by the water year runoff ratios for the more recent 35-year period for the 13 rivers studied. Table 2 lists the actual average monthly flows for October through September for the same 13 rivers. Unimpaired runoff data utilized for both Tables 1 and 2 was taken from the California Department of Water Resource's Data Exchange Center (CDEC). Creating monthly ratios such as was done for Table 1 helped remove the effect of some watersheds having had an increasing 35-year water year average and others a decreasing water year average for the more recent period. In addition to March having increased runoff in every basin and subbasin analyzed, February likewise gained runoff for several subbasins. A few cases showed a small January increase. Somewhat surprisingly October through December showed a general decrease in runoff percent of the water year for the more recent period. It was almost as if the months of February and March increased at the cost of the October through December period' increase and in some cases the fall runoff as well. Figure 6 shows the two 35-year periods with a monthly comparison of the month/water year flow ratios as percentages of the water year for the North Fork of the Feather River at Poe Diversion Dam. When the actual monthly flows were reviewed, the second 35-year period has a much changed water balance with significantly more water entering into evapotranspiration rather than surface runoff. The mean surface runoff for the 1977-2011 water

Table 1. Monthly water year ratios* for the two successive 35-year periods: 1942-1976 and 1977-2011. Thirteen large rivers are listed.

***Monthly Percentages = Monthly Runoff/Water Year Runoff** — **General Increase** (Feb–Mar) — **General Decrease** (Apr–Jun)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Klamath River @Orleans	-0.3%	-0.7%	-0.2%	-1.4%	0.9%	1.8%	0.0%	-0.3%	-0.1%	0.3%	0.1%	-0.1%
Total FNF to Shasta Lake	-0.5%	-1.0%	-1.1%	-0.4%	1.0%	2.8%	-1.2%	0.4%	0.2%	0.0%	-0.1%	0.0%
Feather River @ Oroville Dam (FTO)	-0.5%	-0.2%	-0.8%	-0.4%	1.5%	4.4%	-1.4%	-1.5%	-0.6%	-0.2%	-0.2%	0.1%
Yuba River @ Smartville	-0.5%	-0.7%	-1.1%	-0.6%	1.6%	4.0%	-0.4%	-1.2%	-0.9%	0.2%	-0.2%	-0.1%
American River @ Folsom	-0.2%	-0.7%	-1.2%	-0.4%	2.3%	3.9%	-0.6%	-1.9%	-1.1%	0.0%	-0.1%	0.0%
Mokelumne River @ Pardee (MKM)	0.1%	-0.9%	-1.8%	0.7%	1.5%	3.5%	-0.3%	-2.6%	-1.4%	1.1%	0.1%	0.2%
Stanislaus River @ Melones (SNS)	0.3%	-0.5%	-1.5%	1.4%	2.5%	3.3%	-0.7%	-3.5%	-1.7%	0.2%	0.0%	0.2%
Tuolumne River @ La Grange (TLG)	0.3%	-0.8%	-1.7%	0.9%	1.1%	2.6%	-0.5%	-2.3%	-1.6%	1.0%	0.6%	0.4%
Merced River Nr Merced (MRC)	0.3%	-0.9%	-2.0%	1.4%	1.5%	2.2%	-0.5%	-3.1%	-1.3%	1.5%	0.6%	0.4%
San Joaquin River @ Friant (SJF)	0.2%	-0.4%	-1.2%	0.8%	0.7%	1.9%	-0.2%	-2.2%	-1.1%	1.0%	0.3%	0.3%
Kings River @ Pine Flat (KGF)	0.3%	-0.2%	-1.1%	0.6%	0.7%	1.7%	0.0%	-2.6%	-1.2%	0.9%	0.3%	0.5%
Tule Rive Blw Success Dam (SCC)	0.3%	-0.4%	-2.6%	0.2%	2.1%	1.2%	-1.3%	-2.2%	0.9%	1.0%	0.5%	0.3%
Kern River Nr Bakersfield (KRB)	-0.1%	-0.3%	-1.5%	-0.1%	0.8%	1.9%	0.1%	-0.9%	-0.5%	0.3%	0.1%	0.1%

Table 2. Actual runoff listed for each of the 13 river basins. In general basins and their subbasin components for the American River southward showed an increase in their water year averages for the more recent 35-year period.

RIVER		All Water Values are in Cubic Hectometers (1 hm3 = 810.71 Acre Feet)												
Klamath River @Orleans (KLO)		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	WY
	1942-1976 (35-Yrs)	118.7	342.9	746.6	1,034.9	859.3	843.5	810.4	781.7	450.4	159.8	88.5	71.3	6,308.0
	1977-2011 (35 Yrs)	91.4	264.6	658.7	845.9	818.9	853.4	722.9	682.4	399.1	160.1	82.7	60.0	5,640.1
														-10.6%
Total FNF to Shasta Lake (SHA)		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
	1942-1976 (35-Yrs)	337.7	464.7	769.5	1,004.3	1,004.4	992.7	915.1	674.5	429.3	309.4	277.9	270.3	7,449.8
	1977-2011 (35 Yrs)	293.3	383.1	673.5	960.5	1,060.2	1,181.4	812.5	692.8	438.8	306.3	266.9	264.3	7,333.4
														-1.6%
Feather River @ Oroville Dam (FTO)		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
	1942-1976 (35-Yrs)	156.3	256.7	533.7	706.0	670.5	740.4	906.8	866.1	453.9	208.8	136.8	111.9	5,747.8
	1977-2011 (35 Yrs)	120.8	233.4	467.4	649.6	722.1	945.6	789.6	743.4	397.7	187.0	120.6	110.5	5,487.8
														-4.5%
Yuba River @ Smartville (YRS)		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
	1942-1976 (35-Yrs)	51.1	128.9	294.1	377.3	344.0	362.7	455.6	538.5	283.1	74.1	34.3	26.1	2,969.7
	1977-2011 (35 Yrs)	35.7	104.6	251.7	347.7	378.1	465.6	427.5	484.4	247.4	76.2	26.3	22.4	2,867.7
														-3.4%
American River @ Folsom (FOL)		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
	1942-1976 (35-Yrs)	38.2	126.8	300.0	417.4	361.2	423.9	551.1	655.4	358.2	90.9	24.4	14.7	3,362.4
	1977-2011 (35 Yrs)	30.9	104.7	262.3	404.8	439.4	557.0	535.0	592.9	323.3	91.1	20.2	16.0	3,377.8
														0.5%
Mokelumne River @ Pardee (MKM)		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
	1942-1976 (35-Yrs)	7.4	29.1	58.9	68.7	67.6	87.1	152.7	245.5	154.3	31.2	6.4	3.2	912.0
	1977-2011 (35 Yrs)	8.6	22.3	44.3	78.6	85.1	124.8	157.7	232.7	148.6	43.4	7.4	4.8	958.3
														5.1%
Stanislaus River @ Melones (SNS)		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
	1942-1976 (35-Yrs)	11.3	40.3	83.4	102.3	98.0	137.4	236.6	364.7	228.3	67.0	15.7	6.8	1,391.8
	1977-2011 (35 Yrs)	16.0	35.3	66.7	130.1	142.4	197.5	244.1	339.4	219.3	75.7	17.5	10.8	1,494.7
														7.4%
Tuolumne River @ La Grange (TLG)		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
	1942-1976 (35-Yrs)	18.3	71.3	136.1	153.4	154.0	200.8	327.3	556.2	441.6	143.5	26.9	10.9	2,240.4
	1977-2011 (35 Yrs)	29.2	59.4	108.6	194.3	200.2	290.7	353.4	564.9	453.3	186.9	45.1	22.8	2,508.8
														12.0%
Merced River Nr Merced (MRC)		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
	1942-1976 (35-Yrs)	7.8	30.1	65.8	77.6	82.1	107.2	171.7	297.9	209.8	61.1	13.0	5.2	1,129.1
	1977-2011 (35 Yrs)	12.7	23.7	50.4	109.3	116.1	154.6	194.0	306.7	228.2	90.9	22.7	10.9	1,320.1
														16.9%
San Joaquin River @ Friant (SJF)		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
	1942-1976 (35-Yrs)	22.2	46.6	88.9	100.3	110.6	152.8	279.9	533.7	459.8	197.7	61.5	27.3	2,081.4
	1977-2011 (35 Yrs)	31.2	43.6	71.5	133.4	143.1	217.7	313.8	555.4	496.6	247.4	75.9	37.1	2,366.6
														13.7%
Kings River @ Pine Flat (KGF)		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
	1942-1976 (35-Yrs)	21.1	39.6	75.4	83.1	86.1	121.2	248.6	529.7	455.4	186.5	55.7	23.7	1,926.2
	1977-2011 (35 Yrs)	31.5	40.8	62.9	111.4	116.8	180.0	289.0	558.5	505.1	238.5	72.0	39.9	2,246.3
														16.6%
Tule Rive Blw Success Dam (SCC)		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
	1942-1976 (35-Yrs)	1.5	5.9	14.8	19.4	19.1	28.1	28.9	27.1	12.6	3.8	1.4	0.9	163.5
	1977-2011 (35 Yrs)	2.3	6.0	12.3	23.0	26.3	35.0	31.3	27.5	16.5	6.4	2.6	1.7	190.9
														16.7%
Kern River Nr Bakersfield (KRB)		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
	1942-1976 (35-Yrs)	20.4	26.1	44.1	46.9	47.0	67.0	111.1	183.6	158.6	81.1	36.5	21.2	843.7
	1977-2011 (35 Yrs)	22.9	27.7	36.9	54.2	63.4	97.5	131.2	206.2	180.5	98.4	43.9	26.0	988.7
														17.2%

year period is 215.6 hm^3 (174.8 TAF) or approximately 7.5 percent less than the earlier period. The April through December months all declined while the February and March runoff increased. For the American River south as seen in Figure 1, water year flows increase in the more recent period and decrease for watersheds north of the American River. Freeman (2011) hypothesizes that this increase for the major River Basins that include the American River southward may be attributable to an increase of available moisture in frontal systems for the most recent 35-year period. The orientation and elevation of the Sierra south of the Yuba River may provide sufficient orographic cooling to capture the additional moisture as precipitation, which in turn appears to be resulting in increased surface runoff for the Sierra's central and southern Sierra watersheds south of the Yuba River, which is the case at least for the two periods analyzed.

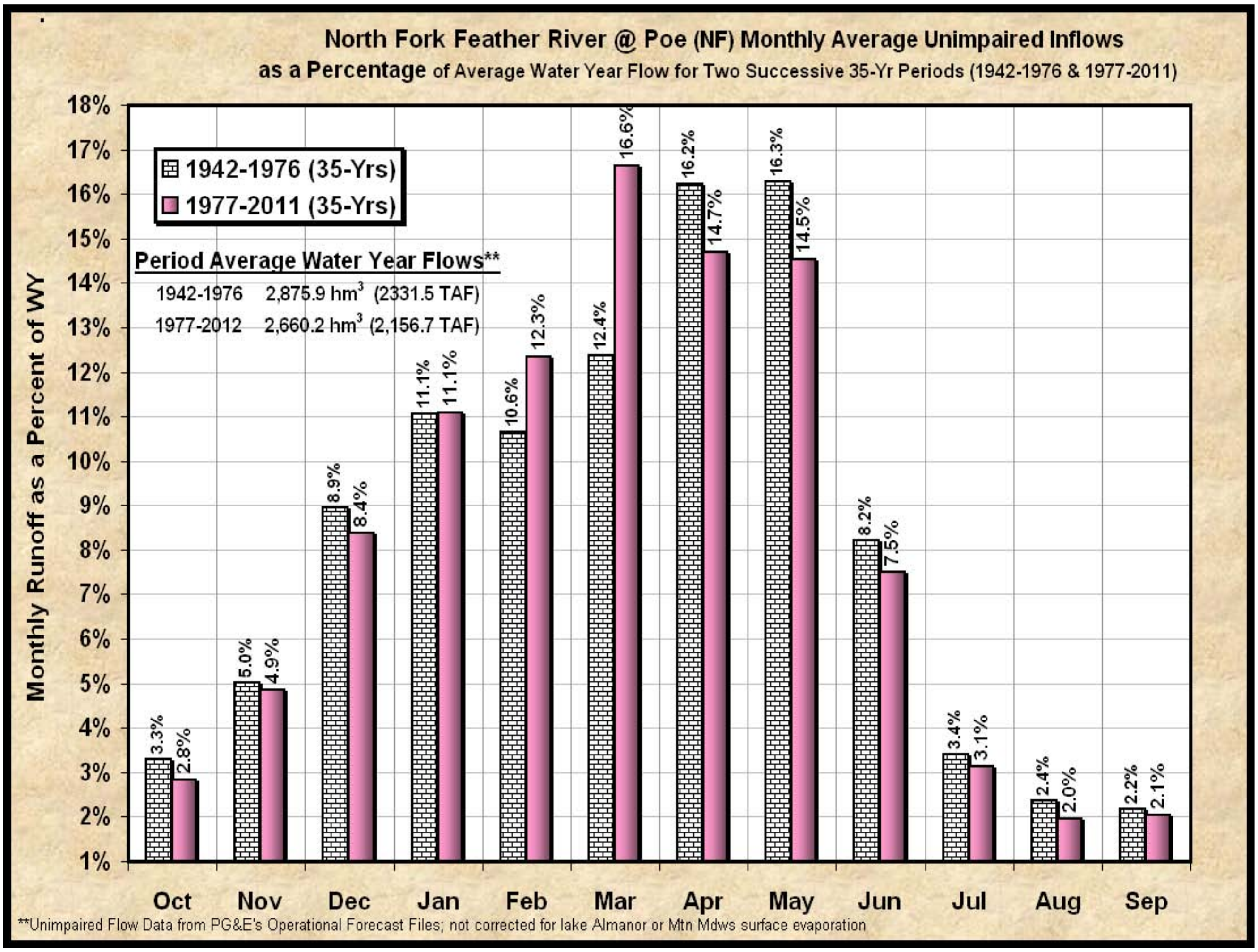

Figure 6. A comparison of the monthly/water year runoff ratios for the two consecutive 35-year periods for the North Fork of the Feather River @ Poe Diversion Dam.

In order to accurately forecast runoff for hydroelectric scheduling, PG&E utilizes a two pass regression approach in a system named PRM (Precip Recovery Method) developed at PG&E. The first pass contains a relatively long historical period of approximately 25-35 years to determine whether or not the forecast is for an average, wet, or dry period. Once the program has chosen the basic wetness type, the forecasting tool then performs a second pass regression on a much more limited set of years to improve its fit with the independent variables such as snow water equivalent, precipitation, and aquifer outflow of springs. In the face of changing seasonal runoff with climate change, PG&E's runoff forecasts handle the growing issue of runoff time series loss of stationarity, by utilizing relatively recent water years only with attention to the runoff changes such as shown in Table 2 for the larger river. Runoff for the April through July period has decreased for those watersheds north of the American River, and that decrease in spring runoff is anticipated to continue well into the mid-21st century as the climate continues to warm. Hydrologists can forecast the spring runoff with that fact in mind, which helps bias operating decisions toward less spring runoff than is being indicated by the long term historical data set. Likewise for the southern Sierra watersheds, a slight bias is given to expecting an increase in April through July and water year runoff. In all cases larger March runoff is anticipated than has historically occurred prior to 1977. In order to effectively deal with the changes being observed, PG&E is currently calibrating subbasins on the Feather River with the PRMS model (USGS Precipitation Runoff Modeling System), working in partnership with both the California Department of Water Resources and the US Geological Survey. PRMS, a distributed conceptual modeling tool that utilizes hydrological response units as described by Koczot et al., (2005) will help assist PG&E's forecasting hydrologists with an alternative physically based model that can more effectively handle temperature, evapotranspiration, soil moisture, and groundwater than the seasonal regression model by itself.

POTENTIAL IMPACT ON PG&E'S HYDROELECTRIC PRODUCTION

If the current trends in monthly and water year runoff continue, hydroelectric generation for PG&E's conventional hydroelectric system is anticipated to show little if any decline overall up through about 2025. Beyond 2025 the system overall may then likely begin a gradual net decline in hydropower production as the benefits of an earlier runoff into the mountain reservoirs likely begins to be outweighed by a number of other risk factors. Historically, the typical spring runoff quantity from snowmelt resulted in frequent spring spills as the runoff quantity exceeded both the available usable capacity of the seasonal reservoirs and the capacity of releasing snowmelt inflow through powerhouses. May and June spill at many of the mountain reservoirs occurred with a frequency of 1 in 2 to 1 in 3 years for many of PG&E's 98 reservoirs. Some of the smaller seasonal reservoirs spill every year even during very dry years. As the April through July snowmelt increasingly shifts into March and February as a result of both an increased frequency of earlier snowmelt and the change in physical form from snowfall to rainfall, the opportunity to move the inflow earlier has increased hydroelectric generation for some rivers especially for the Yuba River southward. The value for energy in February and March is typically less than for summer and fall, however it is still better than waiting for the snowmelt to start April 1 or later and then end up spilling much of the inflow from snowmelt in late May and early June after both the reservoir and powerhouse capacities have been exceeded. The energy value for water bypassing the powerhouses is often zero depending whether or not there are some downstream powerhouses that have sufficient capacity to utilize the water which is spilled past upstream lower capacity powerhouses. The overall benefit from earlier runoff in a large diverse system such as PG&E's is currently being balanced by hydroelectric losses such as are taking place on the Feather River that when balanced together appear to have at this time little or no net gains or losses in conventional hydroelectric generation. This net zero overall impact for the PG&E hydro system may possibly continue for another 12-15 years.

Balancing Energy Gains with Energy Losses Including Increased Risk for Spill

Figure 7 conceptually illustrates the impact that climate change is currently having on PG&E's hydroelectric production including increased risk for maintaining current levels of hydroelectric production being anticipated beyond 2025. Because PG&E's hydroelectric system has both Company and Partnership Projects that extend from the McCloud and Pit Rivers in northern California to the high elevation Kern River in the southern Sierra on approximately 16 major rivers in the Sierra, southern Cascade, and Coastal Mountain ranges, the operational subbasin response to current and anticipated climate change is highly diverse. In addition to subbasin diversity, historically approximately 38% of PG&E conventional hydroelectric generation comes from large springs in northern California (Freeman, 2007). This source of water is multidecadal in terms of quantitative water year supply and not necessarily dependent on a given year's precipitation, but instead depends on relatively long lag times that involve both long term increases and decreases in aquifer storage and the accumulated effect of the past 3-5 years of accumulated wetness including recharge opportunity. Some of the current identified losses include the impact of climate change for the upper North Fork Feather River rain shadowed subbasins where the water balance has increasingly resulted in increased evapotranspiration and declining outflows of the springs. For the North Fork Feather River, the runoff losses average about 308 hm^3 (250 TAF)/year. As the effects of warming continues and the snowpack continues to decline and that decline moves increasingly southward along the Sierra in extent, increasing planning uncertainty begins to increasingly take its toll on energy production. As the frozen snowpack continues to decline in an increasing number of years, the relatively small mountain reservoirs must be held higher and higher in the December through February period to help assure filling and to maximize their storage capacity for meeting summer recreation expectations and for meeting summer and fall hydroelectric peaking needs. The probabilistic opportunity cost for keeping reservoirs low beyond about mid-January is the rising uncertainty of depending increasingly on remaining weather for filling the reservoirs and less on the much easier forecast frozen snowpack for filling (Freeman, 2003). The inevitability of increasing spill in February and March comes with reduced assurance for 'filling reservoirs'. Historically the mountain reservoirs were reduced to minimum operating levels on or about Dec 31 and reservoir planners then relied on the building snowpack to fill and in many cases spill. But the historical balance had higher probability for spill than for not filling. With a declining snowpack, planners will have to begin holding additional water in storage in the reservoirs beyond mid-January or at least until a sufficient snowpack develops to help cope with the increased risk of increasingly having to rely on future weather rather than having both a snowpack and the expectation of remaining weather.

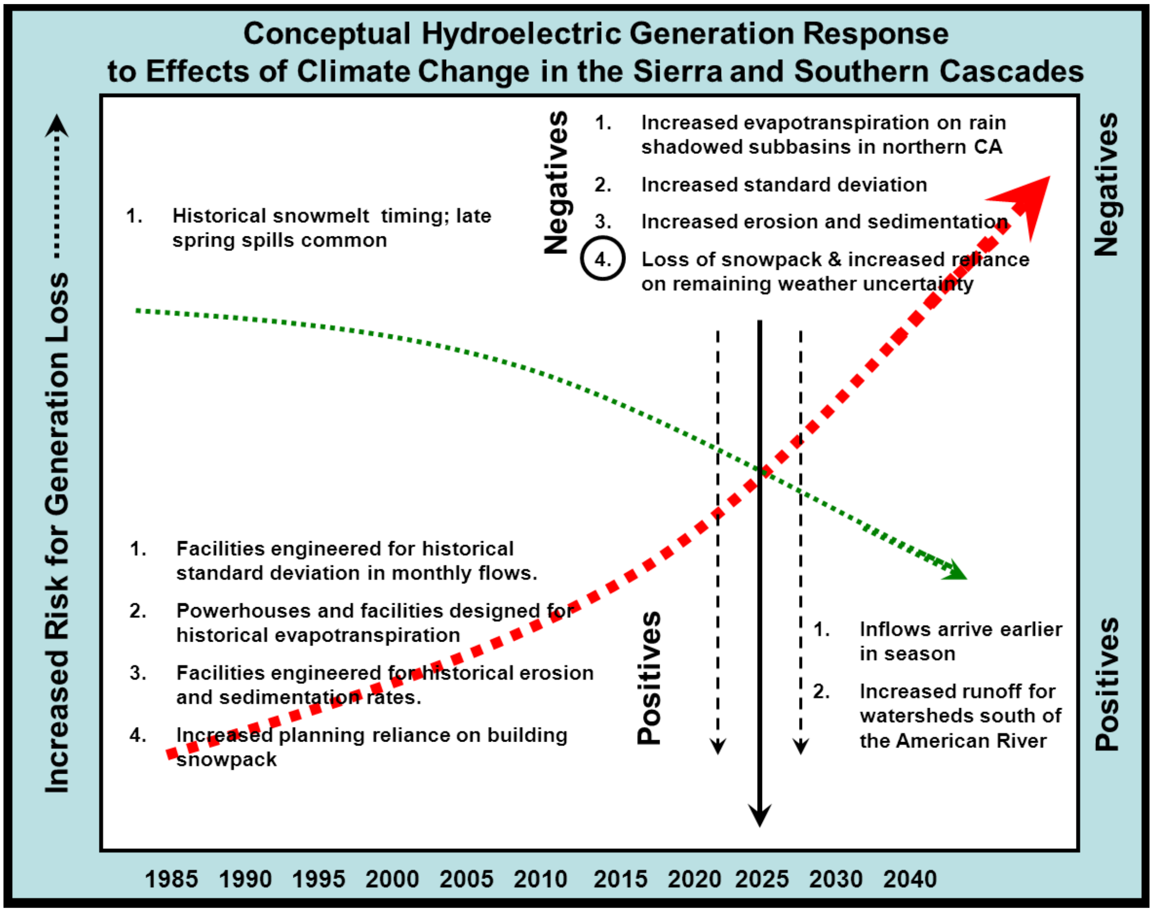

Figure 7. A likely generation response for mountain hydroelectric generation based on the two 35-year period analyzed.

CONCLUSIONS

When a number of large California rivers are compared for two successive 35-year periods, 1942-1976 and 1977-2011, it is apparent that changes indicative of climate change have occurred. In addition to an increasing standard deviation and overall variance in their water year and winter flows, there are trends that indicate a shift in spring flows into earlier months of the year, namely March and February. When grouped into two consecutive 35-year periods beginning in 1942, water year flows from the American River southward have increased since the mid-1970's. There are indications from earlier studies (Freeman, 2011) that warmer air may be capable of holding additional moisture, which when sufficiently cooled as it ascends the windward west facing side of the Sierra may be providing additional opportunity for precipitation increase, much of it in the form of snowfall. It should be noted that from the Yuba River north, the Sierra is lower elevation and less steep. Compared with the Sierra to its south, the Feather River on the northern end of the Sierra is more representative of the older ancestral Sierra. The Feather has maintained its more ancient cut though the Sierra crest eastward well into the Basin and Range Province near Honey Lake. The decline in April through July flow, with consequent increase in March and even February is likely the result of both an earlier snowmelt and an increase in the amount of precipitation which now occurs as rainfall during those two months. Freeman, (2010) showed that on the Feather River in rain shadowed subbasins, minimum winter temperature during storms have increased approximately 6-9 degrees Fahrenheit since 1976. For PG&E with its mountain hydroelectric system in the Sierra, southern Cascade, and Coastal Mountain ranges, its hydro system is sufficiently diverse across different topographic relief and geology that when comparing the two successive 35-year periods, PG&E is currently not seeing any overall change in its system's hydroelectric production that can be directly attributed to climate change. Water year losses in runoff that are occurring from rain shadowed subbasins in northern California, are currently being balanced by earlier inflows to the reservoirs along with an increase in water year runoff from the American River southward in the Sierra. The current "no net change" is anticipated to change in the near future with assumed continued warming. For the relatively small operational subbasin drainages above mountain reservoirs or between diversion dams, orographic cooling of winter and spring storm systems appear to have sufficient cooling effect to slow and somewhat buffer the warming impacts that are otherwise currently being observed on the northern Sierra rain shadowed subbasins such as Lake Almanor and East Branch of the North Fork Feather River.

REFERENCES

Freeman, G.J. 2003. Climate change and California's diminishing low elevation snowpack – a hydroelectric scheduling perspective. Western Snow Conference 71:39-47.

Freeman, G. J. 2007. A program to increase aquifer outflow in northern California's McCloud and Pit River watersheds. Western Snow Conference 75:31-42.

Freeman, G.J. 2008. Runoff impacts of climate change on northern California's watersheds as influenced by geology and elevation – a mountain hydroelectric system perspective. Western Snow Conference 76:23-34

Freeman, G. J. 2010. Tracking the impact of climate change on central and northern California's spring snowmelt subbasin runoff. Western Snow Conference 78:107-118.

Freeman, G. J. 2011. Climate change and the changing water balance for California's North Fork Feather River. Western Snow Conference 79:71-82.

Hill, M. 2006. Geology of the Sierra Nevada. California Natural History Guide Series No. 80. 453 p.

Jefferson, A., A. Nolin, S. Lewis, and C. Tague, 2008. Hydrogeologic controls on streamflow sensitivity to climatic variability, Hydrological Processes, 22: 4371–4385 DOI: 10.1002/hyp.7041 (accessed 7 April 2009).

Koczot, K.M., A.E. Jeton, B.J. McGurk, and M.D. Dettinger, 2005, Precipitation-runoff processes in the Feather River Basin, northeastern California, with prospects for streamflow predictability, water years 1971–97: U.S. Geological Survey Scientific Investigations Report 2004–5202, 82 p.

Knowles, N., M.D. Dettinger and D.R. Cayan, 2006. Trends in snowfall versus rainfall in the western United States, Journal of Climate, 4545-4559.

Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier. 2005. Declining mountain snowpack in western North America. American Meteorological Society. January 2005, 39-49

Nadin, E. S. (2007) Structure and history of the Kern Canyon fault system, southern Sierra Nevada, California. Dissertation (Ph.D.), California Institute of Technology.