CLIMATE CHANGE AND CALIFORNIA'S DIMINISHING LOW ELEVATION SNOWPACK - A HYDROELECTRIC SCHEDULING PERSPECTIVE

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ABSTRACT

Pacific Gas and Electric Company's (PG&E) Water Management Team did a review to identify possible effects on PG&E's hydro generation production of an increase in winter runoff from rainfall and a decrease in spring runoff from snowmelt. There are many indications that the reduced snowpack in the low-elevation Sierra snow zone, which has been observed in recent years, is a likely consequence of climate change. Climate change appears to be affecting runoff timing and flow quantities most significantly for those relatively low-elevation watersheds, which are situated from the Yuba River north. For PG&E, both the Feather River and the Yuba River Basins have large portions of their drainages at relatively low elevation and appear most sensitive in terms of potential to affect future hydro generation schedules. The November-through-February winter runoff quantities, which are mostly rainfall-produced, appear to have increased both in intensity and monthly quantity; and the spring snowmelt in the low elevations, from a somewhat diminished snowpack, appears to be taking place almost a month early for some portions of the Feather River. One possible outcome of a lowered April 1 snowpack expectation in early winter may be a hedging tendency by hydro schedulers to enter the winter period in late December with higher than historic reservoir storages as the planned end-of-the-year winter-minimums. With remaining seasonal weather uncertainty and a reduced snowpack accumulation expectation during the remaining winter months, an operating strategy, which plans for higher end-of-year reservoir carryovers, would increase the likelihood for filling in late spring. Full reservoirs near the end of the snowmelt period are a desirable outcome for meeting critical summer and fall electric load demands. However, the effect of carrying increased reservoir storage into the uncertain winter period, while increasing assurance for filling, would also increase the historical likelihood for spills from diversion dams and seasonal storage reservoirs due to increased amounts of winter rain in years that turn out to be wetter than expected.

INTRODUCTION

PG&E's Water Management team has observed a significant reduction in the low to mid-elevation April 1 snowpack during the second half of the 20th century. This appears to be most noticeable within the PG&E headwater drainage from the Yuba River in the central Sierra north into the McCloud and Pit Rivers in the southern Cascades. This downward shift appears balanced among increased frequency of both precipitation occurring as rainfall and earlier snowmelt. The effect has been an overall shift in runoff timing and quantity from the spring into the winter period. The shift in timing of runoff affects the stationary stochastic nature of the historical time series. As a consequence, it influences the decision for utilizing a representative time period to forecast both seasonal and daily runoff and producing probabilistic hydroelectric schedules. PG&E utilizes both a seasonal regression-based forecast model and a daily mixed statistical-conceptual model in the spring for topping off reservoirs from snowmelt (Grygier, 1997). The extended streamflow ensemble and its probability assumptions may be subject to bias for historical years, which are possibly no longer representative of the current climate and hydrology (Freeman, 2003). There was also concern that the possible effect on PG&E's hydroelectric production should be better understood both as to possible impact on future hydroelectric production and for identifying what some of the early response may likely be if climate change continues toward increased warming.

PG&E'S HYDROELECTRIC SYSTEM

PG&E has 99 reservoirs and 68 powerhouses; its Partnerships include another 25 reservoirs and 19 powerhouses. Its watersheds extend along the Sierra north from the Kern River to the Pit and McCloud Rivers in the southern Cascade Range near the Oregon Border. A single powerhouse is located in the Eel River drainage

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along the north coast. Historical long-term average sources of generation from runoff for the PG&E hydroelectric system are: 1) rainfall - 25%, 2) snowmelt - 37%, and 3)groundwater - 38% (Freeman, 2003). While the annual variance among successive years is large and reasonably uncertain for precipitation, the annual groundwater contribution is significantly more predictable. Groundwater flow from springs varies over a period of years and reflects an accumulated net balance of recharge and discharge to the aquifers (Freeman, 2001). This balance in turn affects the pressure and thus flow rates from the springs that overlay the northern California volcanic basalts. The hydroelectric system was designed with hydrometeorological data mostly prior to the 1970's. The system facilities were built to accommodate a specific mixture of rainfall and snowmelt produced runoff with historical timing and quantity statistics, but with a large variance in terms of timing and quantity. It was designed for California's highly variable year-to-year climate and within-the-year weather fronts and freezing levels. Many of the watersheds have diversion dams and powerhouses positioned in a manner somewhat similar to a staircase with seasonal storage reservoirs often located in mid- and higher elevation reaches of the drainage. The timing of discretionary seasonal water releases from the upstream storage reservoirs are highly dependent on uncontrolled sidewater contribution to the downstream lower elevation reaches between successive diversion dams. The sidewater reach contributions have mean drainages at varying mean elevations. Runoff for those elevations which contribute along the lower watershed reaches are temperature-elevation dependent in terms of precipitation form and snow fall elevation levels. Changes in precipitation form from the historic normal ratios have potential to change spill frequency and magnitude compared to data utilized in the historical design of the system.

SPRING SNOWMELT RUNOFF TIMING AND AMOUNT

In recent years, PG&E had an increased focus on the effects of a reduced snowpack in the relatively low elevation snow zone. Roos, (1991) and others have described the reduction in snowpack for northern California during recent years. Figure 1 reveals a 19 percent , or 21.3 cm (8.4 inches) decrease in snow water equivalent for the Lake Spaulding snow course #85 at the 1,585 m (5,200 feet) elevation in California's central Sierra from the earlier 37-year period. Precipitation that had historically been stored in the snowpack reservoir for spring runoff from melt must now be accommodated as inflow to the reservoir from rainfall-produced winter runoff and earlier melt-produced runoff, which now occurs in March rather than April. On the same watershed and about 16 miles away, the Meadow Lake snow course, located 671 m (2,200 feet) higher at the 2,195 m (7,200 feet) elevation, shows a 3 percent increase for the more recent of the same two 37-year periods (Figure 2). This 19 percent difference readily reveals the sensitivity of the low elevation snow zone to the earlier melt and the lack of seasonal snow accumulation in recent years. Figure 3 illustrates the effect of reduced low elevation snowpack on the April through July seasonal runoff for central California's Yuba River. The second 50-year period has declined 9 percent from the earlier period. This change in runoff timing of California's Sierra is similar to findings of Cayan et al. (2001); and the projections of Snyder et al. (2001).

Winter Rainfall Runoff

The winter period runoff, as shown in Figure 4, has increased over 7 percent due to an increased amount of runoff taking place from precipitation that fell as rain rather than snowfall. In addition to a shift in runoff timing, precipitation falling as rainfall also produces runoff at a much more rapid rate then snowmelt. Increased winter rainfall has also significantly increased the frequency of large accumulated winter runoff totals for the November through February period. Figure 5 shows this increased frequency of the winter period runoff that occurred in the second half of the 20^{th} century.

CLIMATE CHANGE AND POSSIBLE IMPACT ON HYDROELECTRIC PRODUCTION

No effect of climate change on PG&E's hydroelectric production has been identified at this time. PG&E's hydroelectric system was designed to accommodate large seasonal and within-the-season variance. PG&E utilizes an optimizing scheduling process (Jacobs et al. 1995) that dampens and minimizes the impact of runoff variance on energy production. If climate change continues and results in a significantly increased variance shift, then it is possible that the scheduling models used will hedge operations sufficiently to impact average long-term energy value and generation. A possible effect of climate change may be on the winter reservoir carryover storage decision. Historically, the relatively small mountain seasonal storage reservoirs are taken to minimum storage by December 31, preparing them to receive the spring snowmelt runoff, and some winter rainfall-produced runoff.

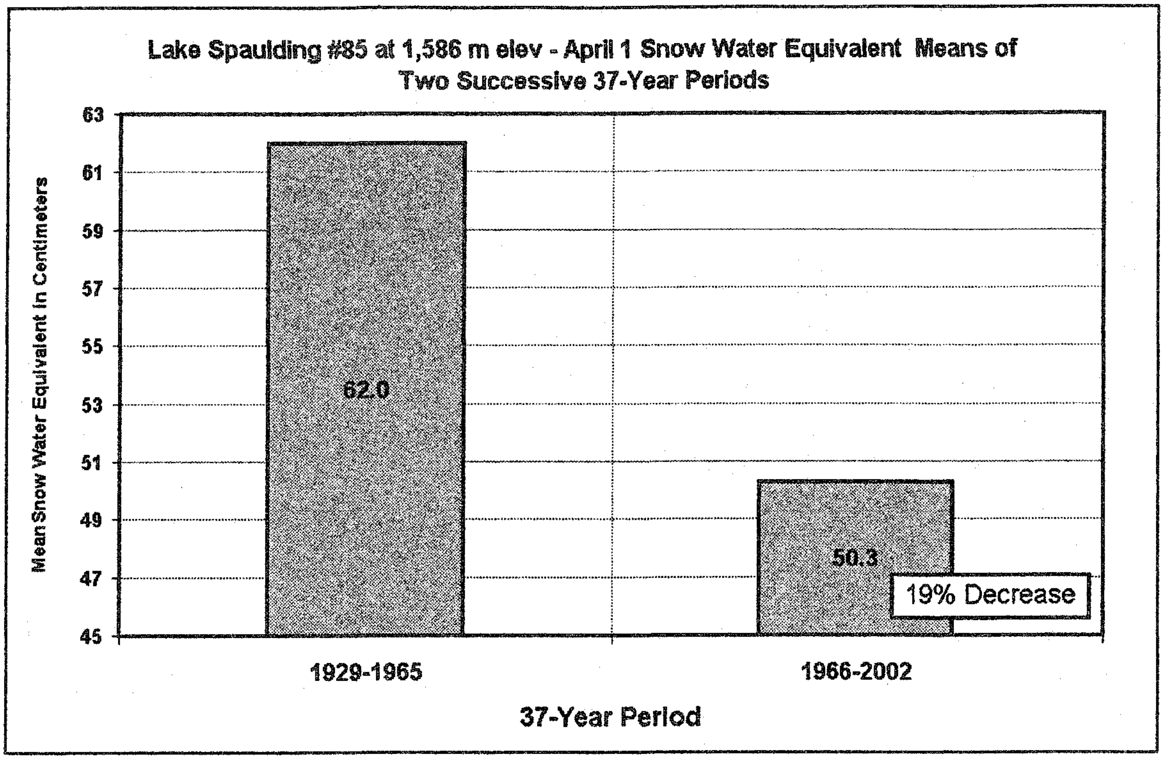

Figure 1. A comparison of April 1 snow water equivalent for Lake Spaulding snow course on the central California's Yuba River for two successive equal length periods.

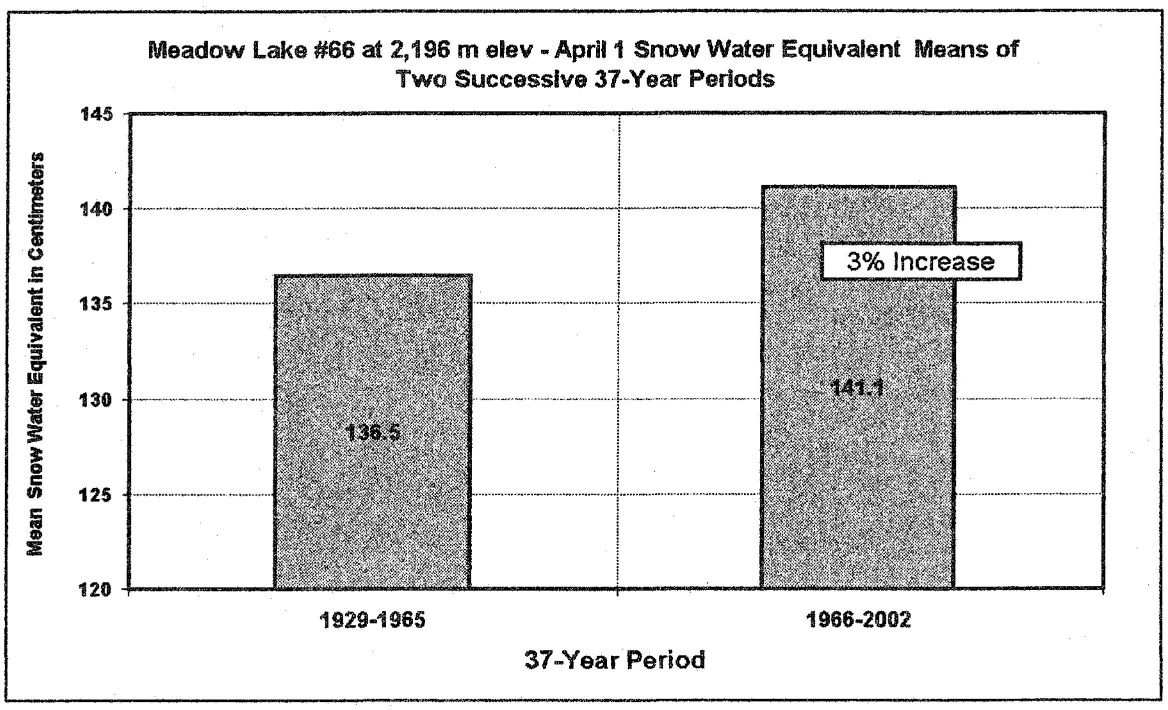

Figure 2. A comparison of April 1 snow water equivalent for the Meadow Lake snow course on the central California's Yuba River for two successive equal length periods.

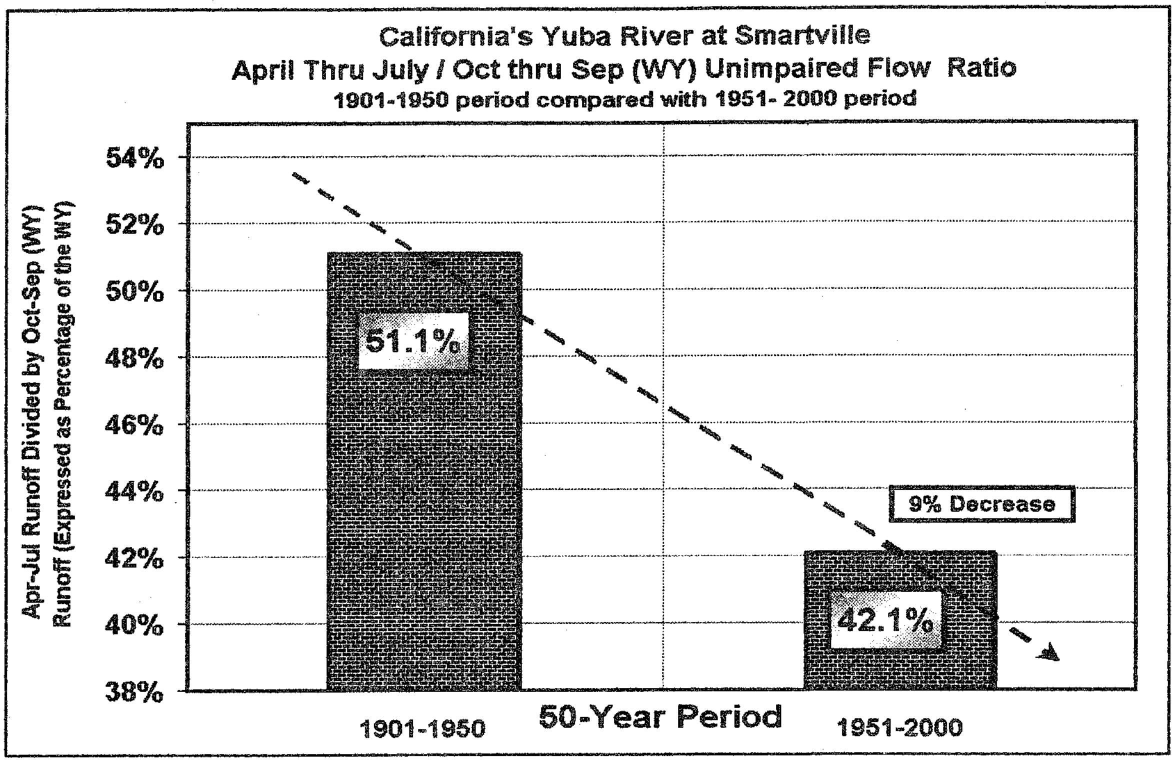

Figure 3. Runoff for California's Yuba River for the 4-month April through July period has declined in the second half of the 20th century. The most likely reason appears to be a loss of the relatively low-elevation snowpack from both a higher freeze line and an earlier melt.

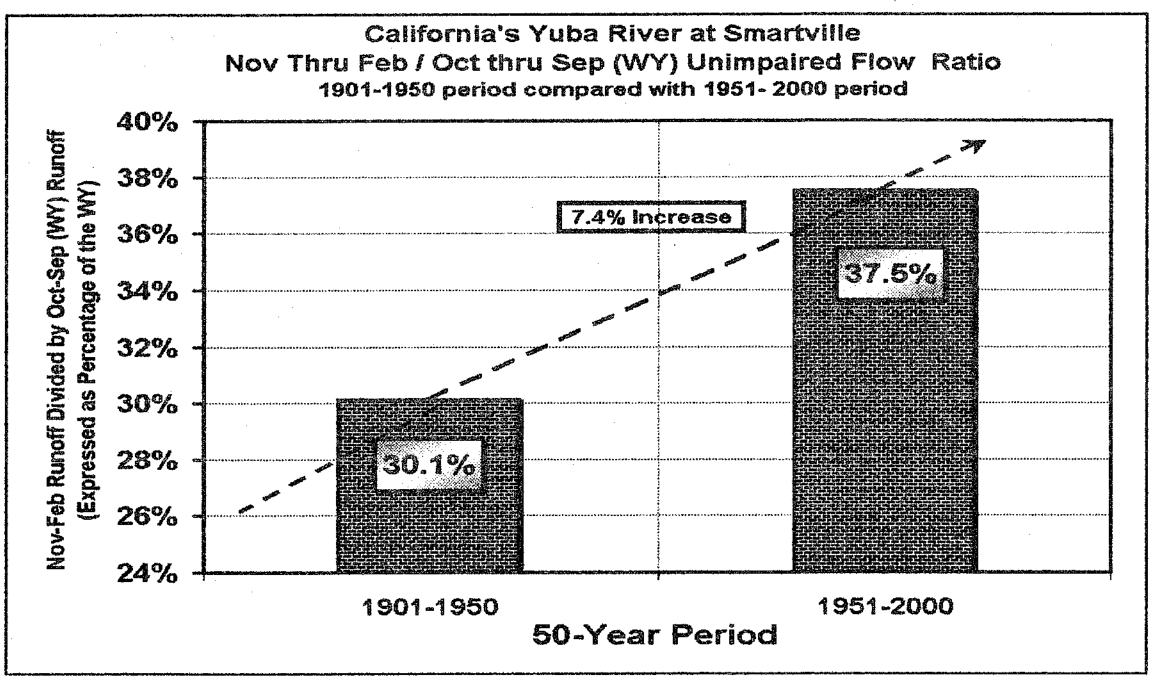

Figure 4. Runoff for California's Yuba River for the 4-month period November through February has increased in the second half of the 20th century.

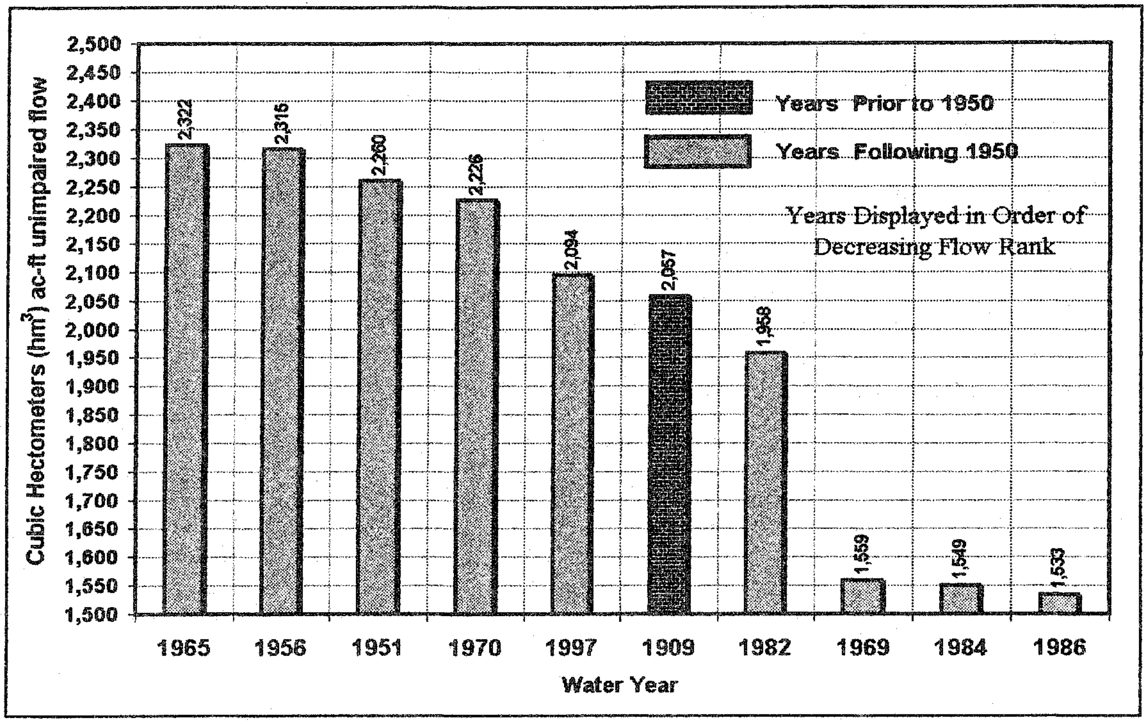

Figure 5. For unimpaired runoff of the North Yuba River @ Smartville, nine out of ten November-through-February winter runoff periods, which exceeded 1,850 hm^3 (1,500,000 ac-ft) for the 4-month November through February period, occurred in years beginning after 1950.

Full reservoirs near the end of the snowmelt runoff period are a desirable outcome for meeting critical summer and fall electric loads (Freeman, 1997).

A future possible outcome of continued climate change may be to hedge the probabilistic scheduling model toward increasing the winter carryover storage. This would increase assurance for filling the reservoirs in the late spring-early summer period to meet the high value, heavy load summer and fall energy period. However, storing additional water in the reservoirs during the winter period will leave them increasingly vulnerable to spill from more increased rainfall generated runoff. Runoff from rainfall is much less controllable than the less flashy snowmelt runoff. Because California's Division of Safety of Dams (State of Calif., 1995) requires that spill gates remain open at most mountain reservoirs during the winter, rainfall produced runoff can quickly fill remaining reservoir space, especially if the additional water is carried into the winter period to assure reservoir filling in late spring.

Accounting correctly for climate change to produce accurate seasonal and monthly runoff forecasts based on historical data will be another challenge added to the error uncertainty already inherent in utilizing historical climate data and compiling unimpaired natural flow data (Freeman, 1999). Data streams may need to be checked for stability over time. PG&E currently utilizes a seasonal disaggregation model to produce monthly streamflow ensembles (Grygier, et al, 1993). This is primarily a regression process, which utilizes historical streamflow series to forecast monthly streamflow quantities from the seasonal runoff forecast. A climate shift may bias the historical probabilities toward a non-representative distribution.

Some contracts between the utility and Irrigation Districts were written many years ago with what appeared to be a stable historical ratio of rainfall to snowfall. It was a historical period that seemed more certain in terms of runoff timing from rainfall and snowmelt. A shift in runoff timing may lead to a need to renegotiate some contracts and agreements and may focus on the need for a more adaptive type of verbiage for accommodating possible additional climate change.

Currently California's Division of Safety of Dams (DSOD) requires operators for most Sierra mountain reservoirs to leave the gates open between November 1 and March 31 to pass floodwaters. In future years, a reduced spring snowpack may lead to increased requests to DSOD for early gate closures. Early gate closures would increase assurance for filling reservoirs with an increased frequency of a diminished snowpack and less spring snowmelt produced runoff than now occurs.

Harrison, et al. (1998) discusses developing models for specific watersheds and studying possible impacts. PG&E's experience is that at the present rate of observed change, the net effect of hydroelectric production would be hard to quantify. For some years for some watersheds, there would be increased production from winter rainfall increases which provide runoff into the reservoirs at a time when historically the water was frozen in the form of snow and not available for generation. At other times the quantity and intensity of winter runoff may increase winter spills reducing hydroelectric generation for specific watersheds and situations.

Increased Availability of Water During High-Value Winter Periods

While contrary to common belief, hydroelectric energy often does have relatively high value during the winter months. With continued climate change, there have been reports of possibly less water available for hydroelectric production from northern California watersheds (Edwards, 1991). PG&E has not observed this to be the case and currently does not anticipate any reduction of hydroelectric production during periods of high-energy value. The PG&E hydroelectric system is characterized by many relatively small seasonal reservoirs. Many of these seasonal storage reservoirs have historically spilled snowmelt in late May or in June during average to above average precipitation years. Increased winter runoff, which occurs at a time when the water has historically been locked up in the form of snow often provides opportunity potential for additional generation being produced during the year, and at a time when runoff had historically been much less. For PG&E's hydroelectric projects located in California's Sierra Nevada, some of the years with the largest generation have been years with both winter snowmelt and an increased proportion of winter precipitation falling in the form of rain.

(Harrison, et al, 2002) performed a sensitivity analysis for a planned hydro scheme in Sub-Saharan Africa. He reports that changing climate may have proportionately more effect on low flows during dry conditions than for flows during wet years. It is possible that there will be negative generation impacts for PG&E during dry years and positive generation impacts during average and wet years. If one considers that many of the mountain seasonal storage reservoirs do not normally spill in below average precipitation years, then it is somewhat likely that during drier years, with a reduced snowpack, the reservoirs would enter the high-value summer energy use period with less water in storage compared to historical times

Small Mountain Reservoirs and Valuing Stored Water

PG&E schedules reservoir releases from its reservoirs based on 1) hydrological state, which includes current reservoir storage, snowpack, and current streamflows including baseflows, 2) remaining seasonal weather uncertainty, and 3) a price forecast for energy replacement based on weekday/weekend, and peaking/non-peaking classification. Water in storage is valued inversely to its likelihood for spill and loss of generation value. As the reservoir fills during the winter period from rainfall-generated runoff, there are value tradeoffs. Such tradeoffs include the value associated with the increased assurance of filling the reservoir by late spring for capturing high value summer and fall generation, especially should a snowpack not develop as anticipated, balanced against utilizing the water now with possible reduced generation value at a time when energy demand is relatively low and value is less than it would be in summer and fall, but avoiding the uncertainty of spill. This has to do with opportunity cost in terms of value tradeoffs under uncertainty. While there appears high opportunity cost for taking the water now for generation at reduced value, that opportunity cost of foregoing future assurance of high value must be balanced with a increased likelihood for spill if water is held in the reservoir through the winter period. The greater the amount of water to be held over the winter period to assure late spring filling, the higher the likelihood that winter runoff will force a spill of that water or cause the operator to release the water for less than optimal value. Conceptually since the water which occupies the highest reservoir levels spills first, it by nature of its position to occupy space is valued the least. Water, which theoretically resides at a lower position in the reservoir, has higher value in that it is less likely to spill or prompt an operator to make a release during a period of low generation value.

Watersheds with large contributing drainage in the low-elevation snow zone are most likely to be most impacted first from ongoing climate change. For California, and more specifically for watersheds which provide runoff for PG&E's hydroelectric system, the McCloud, Pit, Feather, and to a lesser extent, the Yuba Rivers are most likely to be impacted. From the Mokelumne River south, the Sierra is topographically steeper with less total contributing drainage in the low-elevation snow zone, especially in comparison with the Feather and Pit Rivers. A projected continuation of climate change for the North Fork Feather River, a watershed that contributes about 25 percent of PG&E's annual hydroelectric production, will shift a significant portion of runoff from the spring months into the winter storm period. The magnitude of the shift will likely be larger in these low-elevation watersheds than for higher-elevation, steeper watersheds in the southern Sierra. Compared with the Feather River, the Pit and McCloud Rivers also have relatively low-elevation drainages and are not anticipated to have as large an increase in winter flows from a decrease in snowpack. For the Pit and McCloud Rivers, nearly 75% of the annual runoff is from aquifer outflow. The unanswered question is the uncertainty as to recharge rates from rainfall versus snowmelt. The infiltration rate for potential groundwater recharge may be lower from rainfall than the slower release of water typical of snowmelt. If infiltration and recharge over time becomes less, then the recharge rate would decline and likewise be reflected with reduced baseflows of springs into the Pit River during the drier months.

The Feather River Basin above Lake Oroville has about 51 percent of its drainage basin between the 1,372 m (4,500 feet) to 1,829 m (6,000 feet) elevation band. A slight increase in the daily mean temperatures and the freezing level for winter storm fronts may have significant impact on runoff timing for a large portion of this basin. Figure 6 illustrates the large portion of the Feather River Watershed, which lies between the 1,372 m (4,500 feet) to 1,829 m (6,000 feet) elevation zone.

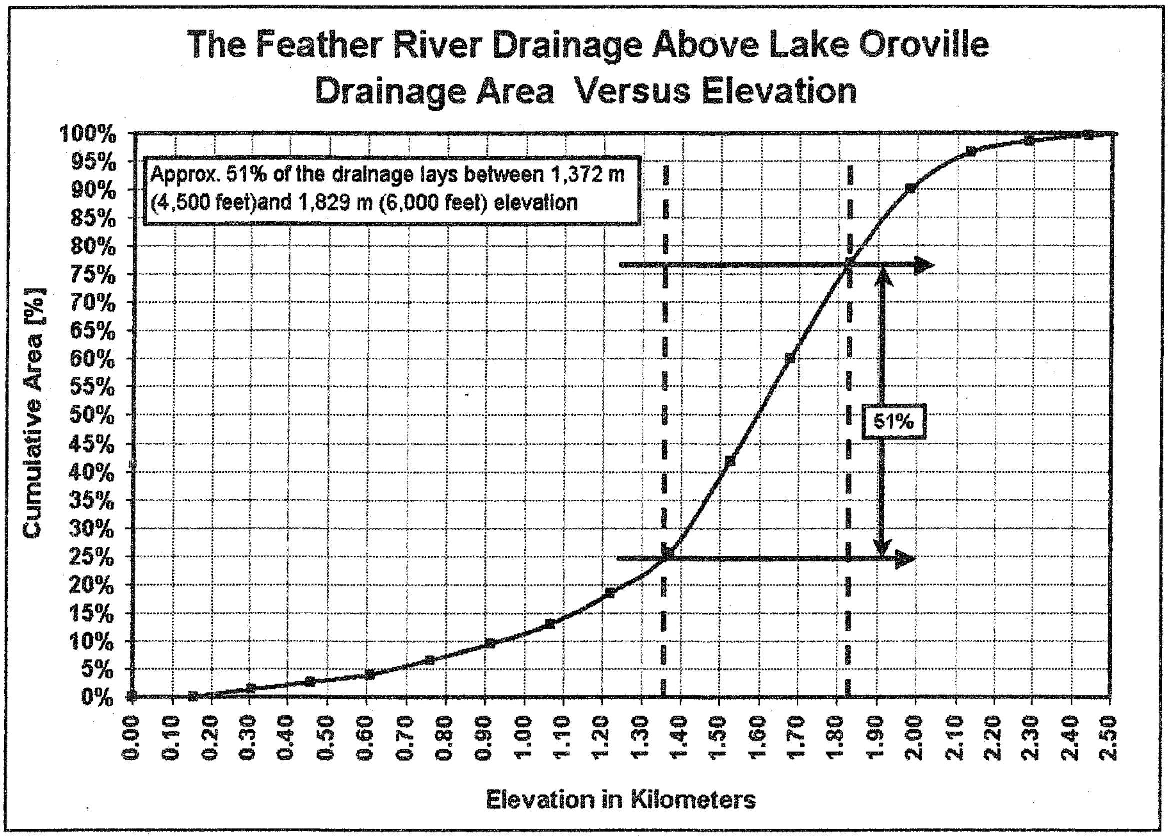

Figure 6. The Feather River Above Lake Oroville. Approximately 51 Percent of the Feather River Drainage Area above Lake Oroville is located in the 1,372 m (4,500 feet) to 1,829 m (6,000 feet) elevation band.

WEATHER MODIFICATION PROGRAM FOR NORTH FORK FEATHER RIVER

Currently PG&E operates a large weather modification program on the North Fork Feather River for the watershed above Lake Almanor. A key seeding criteria is that storm fronts are sufficiently cold for effective seeding to take place. If there becomes a continued trend for warmer storm fronts, then effective seeding opportunities may become increasingly limited. Currently it is estimated the there is a 3-6% annual increase in runoff into Lake Almanor from weather modification. If temperatures warm sufficiently that an increased number of storm fronts no longer meet the established seeding criteria, there may be an impact on runoff and a reduction in annual generation from the Feather River. It is largely unknown at this time what magnitude of impact if any to the weather modification program to expect from possible continued climate change

CONCLUSIONS

There has been an overall decline in the low-elevation snowpack seasonal accumulation since about mid-twentieth century. This decline seems mostly limited to the mid- to lower elevation snow zone where a slight temperature increase during winter storms will result in rainfall rather than snowfall. This effect has changed the runoff timing for the Sierra, most easily identified in the relatively low elevation characteristic of the central Sierra north. The Feather and Pit Rivers have substantial contributing mountain drainage below the 1,829 m (6,000 feet) elevation. A slight change in the snowline over time can affect hundreds of square miles for these northern watersheds. Nearly 55 percent of PG&E's hydroelectric production is from the Pit and Feather River watersheds.

If climate change continues, these watersheds, characterized by their relatively low elevation drainage, would be the most likely to first reflect change in the form of precipitation and surface runoff. Since the Pit and McCloud Rivers are primarily groundwater driven, with between 75-80 percent of the historical annual runoff from springs, unless the recharge balance should change substantially, the near constant daily contribution of the aquifers during a given year is unlikely to affect hydroelectric production even with significant change in precipitation form. The Feather River however has much less groundwater contribution. Continuing climate change on the Feather River has potential in the future, to possibly impact the hydroelectric picture, form both the weather modification perspective and from continued runoff timing change.

The first compensating strategies by hydroelectric operators would likely be to hold additional water in the reservoirs through the winter period to increase assurance of full reservoirs in late May following snowmelt from a snowpack, which is becoming increasingly reduced in the low elevation snow zone. It is likely that with reduced spring runoff from snowmelt, there would be an increased number of occasions when requests would be made to the California State Division of Dam Safety to lower the spill gates prior to their historical April 1 date. With increased rainfall generated runoff during the winter period, there would likely be increased spills from storms compared with historical operations. If the snowpack continues to become less in the low-to-mid elevation snow zone, it is anticipated that the spring runoff recovery from a much-reduced snowpack may decline, as an increased proportion of soil moisture is likely to be held to satisfy late spring evapotranspiration needs.

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