1.7 TYPES OF DATA NEEDED TO IDENTIFY AND EVALUATE POTENTIAL IMPACT OF CLIMATE CHANGE ON PG&E'S HYDROPOWER OPERATIONS

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1. ABSTRACT

Pacific Gas and Electric Company (PG&E) forecasts and schedules seasonal runoff for it's 68 hydroelectric powerhouses (includes one pump storage facility) and an additional 19 powerhouses that belong to it's Partnership Irrigation Districts and Water Agencies. These powerhouses are located in California's Sierra Nevada and southern Cascade mountain ranges, which extend from the Kern River east of Bakersfield, north to the Pit River with headwater drainage just south of the Oregon border. A single PG&E powerhouse is located in the coast range east of Ukiah. Historically during the past 30 years, hydro generation has been derived from the following sources of runoff with an approximate averaged percentage of each source: 1) groundwater-38%, 2) snowpack-37%, and 3) rainfall-25% (Freeman, 2001). The PG&E hydroelectric system was mostly designed prior to the 1970's and built to accommodate a specific mix-ratio of rainfall- and snowmelt produced runoff with assumed 'design' timing and quantity of runoff along specific river reaches derived from the prior 'known' historical data period. The year-to-year variance was specific for that time series. Design and placement of seasonal storage reservoirs and diversion dams likely took elevation into consideration as it relates to precipitation type and timing of runoff. The anticipated proportion or ratio of rain and snowfall, as a factor that influenced runoff quantity and timing of inflow, was important for best determining reservoir size and location. However, a recent review of PG&E's water and climate data indicates that a change in runoff timing has taken place with a decrease in snowmelt-produced runoff during the past 50 years as compared with the first half of the 20^{th} century. This change appears to be continuing in a trend-like manner toward decreasing runoff from snowmelt. The reduction in snowmelt runoff appears to be the result of a decreasing trend in the low elevation snowpack, with a corresponding increase in rain-produced runoff from the low elevation contributing drainage. The result is larger and more variable winter and early spring runoff with increased risk for reservoir filling from snowmelt alone. This paper will present some preliminary findings and discuss types of data needed, including data analysis that would be most useful to identify and further evaluate change in runoff timing and quantity. Some of the types of commonly collected hydrometeorological data and data calculations, which seem to best describe and track timing shift of unimpaired runoff for our hydroelectric system in California are: 1) aquifer outflow rates from northeastern California's volcanic drainages, 2) the winter and spring ratio of compiled subbasin unimpaired flows between diversion dams, including ratio variance, 3) the ratio of low to mid- elevation snowpack compared with high elevation snowpack, and 4) air temperatures. For all types of commonly collected hydrometeorological data, increased emphasis on improving data quality as it relates to the watershed in its entirety is needed. Improved data quality would likely lead to increased confidence in utilizing this data to identify climate change and to calculate possible impact on future hydroelectric generation production.

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2. INTRODUCTION

Hydroelectric scheduling and the runoff forecasting, which supports the process at PG&E is dependent on utilizing a historical climate and runoff time series that best represents and supports expectations for a given season's remaining weather uncertainty.

If the climate and runoff time series is not stationary, but instead its mean and variance changes significantly with time, then forecasters may need to identify and account for the change. In the case of runoff forecasting, a climate change is likely to also affect vegetative succession and possibly change evapotranspiration rate, with potential to further affect runoff over a period of time. The response of the watershed as a whole is increasingly complicated by climate change since it involves an overall water balance between vegetation transpiration, groundwater net transfer rates, infiltration capacity, interception losses, and other various type responses. Millar, et al (2001) for example has studied the effects of a changed snowline and melt timing in the Sierra on tree growth and invasion into formerly persistent snow-covered slopes. A change in forest vegetation type and distribution, as a result of climate change, may significantly change a basin's water balance with consequent runoff effect. In addition to long-term trend change in observed runoff, possible oscillation in wetness may also be taking place with grouped years in terms of relative wetness (Freeman, 2002).

Since seasonal runoff forecast schemes at PG&E continue to rely on utilizing a regression-based approach and a historic time series of climate and runoff variables, a review of possible effects on PG&E's hydroelectric system that included identifying data needs to identify and track climate change seemed appropriate. Others have performed similar type analysis on hydroelectric systems with regard to possible effects on hydroelectric systems in response to climate change. (Harrison, 1998, 2002).

3. THE CURRENT OBSERVED CLIMATE CHANGE SITUATION

Recent analysis at PG&E reveals that changes in the longer-term monthly distribution in mountain runoff for California's central and northern Sierra have occurred during the past century, most noticeably beginning about 1950 (Freeman, 2002). This agrees with findings of Cayan, et al, (2001). The effect appears likely to be the result of a change in precipitation form in response to warmer temperatures with a greater portion of the annual precipitation taking place in the form of rain. This seems to be a likely cause for the observed increase in rainfall-generated runoff during the November through March period and a consequent declining proportion of runoff from snowmelt during the April through July period (Snyder, et al, 2001;Roos, 1991). Figures 1 and 2 shows these unimpaired runoff trends for the central Sierra's Yuba River @ Smartville. A possible contributor to the observed shift in runoff timing may be an increased frequency of warmer temperatures, which possibly accompany winter storm fronts, with a consequent decrease in snow accumulation in the low elevation snow zone as illustrated with Figures 3 and 4. An increased proportion of winter precipitation in the form of rainfall seems a likely cause for the observed increase in runoff during the November through February Period since about 1950.

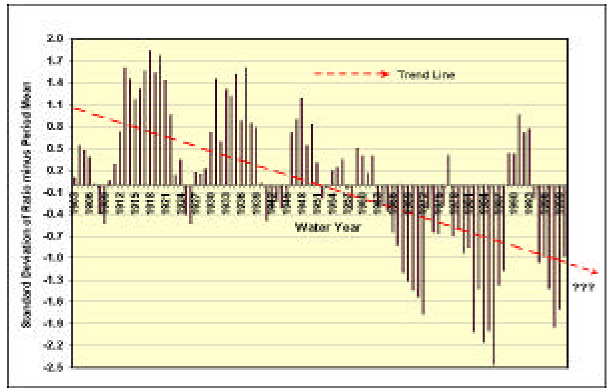

Figure 1. A declining trend in flow for the unimpaired April through July runoff of the Yuba River @ Smartville. Centered 5-yr moving average applied to the 1900-2002 data. Ratio of April through July period divided by sum of same period plus the November through February period.

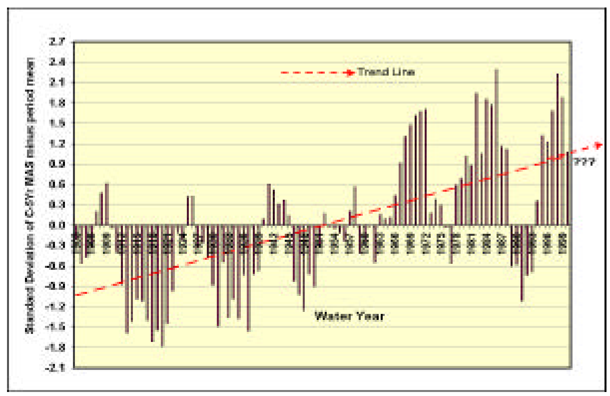

Figure 2. An increasing trend in flow for the unimpaired November through February runoff of the Yuba River @ Smartville. Centered 5-yr moving average applied to the 1900-2002 data. Ratio of November though February subtotal divided by sum of same period plus the April through July period.

4. POTENTIAL IMPACT ON PG&E's HYDROELECTRIC PRODUCTION

At this time PG&E's water management team has not observed any significant change in hydroelectric production that can be directly attributed to global warming or climate change. A review of current trends indicates that no significant generation impact is anticipated for the near future. Preliminary findings reveal that each of the watersheds, where PG&E hydroelectric projects are located, and the elevation bands within those basins react slightly different to climate change as observed to date. While the hydroelectric system was optimally designed with historical climate data, mostly prior to the mid-1960's, the system was designed to operate for large wetness variance, which included single year, weekly, and daily storage cycles type operation for 98 of its 99 reservoirs.

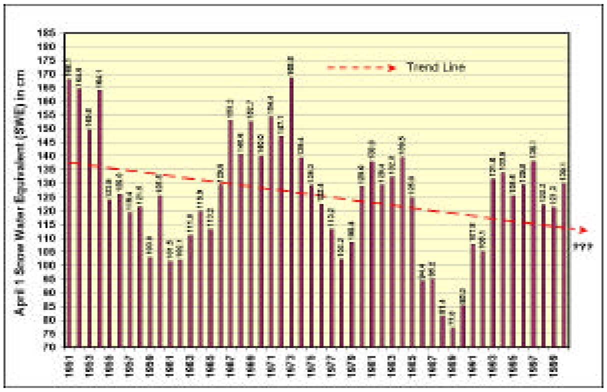

Figure 3. Letterbox snow course #49 (Elevation 1,707m) April 1 snow water equivalent (SWE). North Fork Feather River headwaters near Bucks Lake. Centered 5-Yr moving average smoother applied.

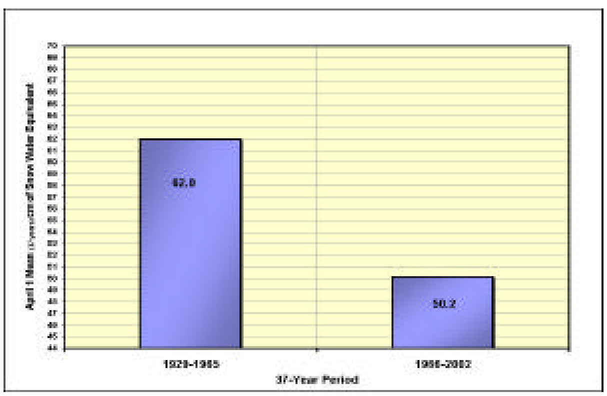

Figure 4. Lake Spaulding snow course #85 (Elevation 1,609m) - Yuba River headwaters in California's central Sierra near Highway 80. The April 1 snow water equivalent (SWE) means for two successive 37-year periods.

There is a single multi-year reservoir, Lake Almanor, located on the Feather River. Lake Almanor with $1{,}409.3\times10^{6}\ m^{3}$ storage capacity has approximately ten times the storage capacity compared with PG&E's next largest storage reservoir. The year-to-year annual- and monthly flow variance for the North Fork Feather River, in terms of flow quantity, greatly exceeds the anticipated effect of a shift of runoff from the spring snowmelt period into the November through February precipitation period or an earlier snowmelt starting in March rather than April. There is a long-term variance shift in runoff timing and quantity, but for the most part it does not exceed the expected short time-step variance that may exist for or within a given year. In addition, most of PG&E's reservoirs are located at relatively mid-to high elevations, which are mostly above the current influence of possible recent warming on snowpack accumulation.

PG&E's two most northern systems, the Pit-McCloud and North Fork Feather River Projects comprise approximately 55% of PG&E's average-year hydroelectric generation. A large area of low elevation headwater terrain characterizes these two northern California watersheds. For these two northern California drainages, a relatively large portion of the total watershed area would be affected from a slight elevation shift in freezing level. Watersheds further south with relatively higher elevation drainage would likely be less affected from climate change, which includes warming. The Pit-McCloud Rivers, which overlay volcanic flows have a substantial portion of the annual flow attributable to aquifer outflow from springs consisting primarily of prior year's precipitation, a portion of which may extend back in time several years.(Manga, 1999). With baseflow being a prime driver of flow timing and quantity for the Pit-McCloud Rivers, hydro operations for that system are less likely to be greatly affected from a shifting precipitation pattern compared with other low lying basins such as the North Fork Feather River, which has significantly less volcanic drainage. With nearly 90 percent of the north Fork Feather River Basin at or under 1,829 meters elevation, it can be expected that spills past diversion dams, especially along the lower elevation reaches of that river, from uncontrolled sidewater during the winter wet season, may possibly increase in frequency and quantity in the future if climate change continues with increased warming.

Since approximately 2/3 of the water year runoff from the North Fork Feather River is from uncontrolled sidewater which overlay non-volcanic drainage, the potential for an increase in winter rainfall-produced-runoff as a cause for more frequent spills from increased rainfall on the low elevation snow-zone seems likely. At this time No detailed type studies have been made at PG&E to determine the potential generation impact from long-term ongoing continuation of climate change. Operational response to future climate change would most likely first take place in probabilistic decision-making during the mid-November through March period, a time when most precipitation normally occurs each year. Probabilistic hydro scheduling based on remaining weather uncertainty would likely assume a gradual change over a period of years in probabilistic tradeoffs for deciding storage and release of water from reservoirs (Freeman, 1997). PG&E's seasonal runoff forecasting methodology utilizes a disaggregation routine as described by Grygier, et al, (1993) to subdivide the seasonal runoff forecast into monthly flows. If the historical monthly distribution of runoff has changed with time, then for the regression routine to work as originally intended, the routine should likely utilize a relatively recent, possibly weighted time series of monthly data, with heavier weighting for recent years.

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5. TYPES OF DATA BEING UTILIZED AT PG&E TO DESCRIBE AND TRACK THE RUNOFF TIMING SHIFT

5.1 RUNOFF

An early focus at PG&E was to track aquifer outflow rates on the Pit-McCloud Rivers in northern California. About 38 percent of PG&E's annual hydrogeneration is from aquifer outflow, a large portion that is from precipitation of past years. The springs, which contribute to flows in the McCloud and Pit Rivers are some of the world's largest, provide a natural lag of past climate revealing the effect of long-term pressure changes in the aquifer from net recharge and discharge. Trend over time can be revealed as well as a shorter-term subtle oscillation effect of grouped year variance (Freeman, 2001). Other analysis of runoff, precipitation, and snowpack trends and cycles (Freeman, 2002) revealed both long term trending and a shorter somewhat subtle 14-16 year wetness oscillation. The shift of runoff monthly runoff averages into the winter months during the last half of the 20^{th} century posed the most concern as it may have possible potential to affect the hydroelectric scheduling value optimization process.

5.2 SNOWPACK

An analysis of the April 1 Snow water equivalent for the Lake Spaulding snow course in the central Sierra at the 1,609 meter elevation shows a significant decrease during the second half of the 20^{th} century. This decrease in the April 1 SWE mean represents a 19-percent drop from the earlier period. No significant decline was observed to have occurred in a nearby snow course at Meadow Lake, which is 610 meters higher in elevation. The decline in low elevation snow in recent years may be indicative of a higher snowfall line with winter storm systems.

Likewise the Letterbox snow course #49 on the North Fork Feather River at the 1,707 meter elevation likewise reveals a significant decline in April 1 snow water equivalent during the past 50 years.

6. DATA QUALITY - ITS IMPORTANCE FOR TRACKING AND RESPONDING TO CLIMATE CHANGE.

Among the types of data which would likely be most indicative of accurately defining trends in climate change are compiled subbasin unimpaired natural flows from successive reaches of increasing drainage elevation or in other words the subbasin reaches between existing diversion dams as one moves upstream along the river. While the unimpaired flows for the entire river can be compiled reasonably accurately immediately below the large multipurpose reservoirs such as at Shasta, Oroville, Melones, Bullards Bar/Englebright, Millerton, and Pine Flat, it is much more difficult to provide accurate definition of upper subbasin reaches moving upstream in the watershed (Freeman, 1995).

PG&E computes daily and in some cases hourly subbasin reach flows for nearly 80 reaches in the Sierra as part of it's normal forecasting and hydro scheduling process. However, the calculation of reasonably accurate subbasin unimpaired flows for the lower reaches of the rivers, which have hydroelectric projects remains a challenge. The problem is primarily one of cumulative error uncertainty and the existing standards of how gaging flows are currently evaluated for revision.. Currently stream gaging is rated as excellent or good based on the "stand-alone" station record. Powerhouses remain for the most part un-reviewed by the US Geological Survey. However, accurate powerhouse flows synchronized in a manner that one powerhouse is aligned in terms of error uncertainty with an adjacent powerhouses is one of the largest obstacles in currently compiling reasonably accurate subbasin unimpaired sidewater flows between upstream diversion dams (Freeman, 1999). In order to compute a subbasin unimpaired flow between diversion dams, one generally needs a combination of: change in storage at the intervening pondage(s) (forebay or afterbay), 2 powerhouses, 2 diversion dam spills, 2 leakage and instream flows, and occasionally an import or export gage if water is entering or leaving the reach to or from elsewhere. At the minimum, there may be 5 gages within the calculation, but normally 7, and sometimes more measuring points are required for the computation of subbasin unimpaired inflow. The two Powerhouses and spills, when they occur, from the two diversion dams represent the largest sources of unaligned error uncertainty and noise in attempting to define intervening subbasin flow contribution. It is important that the time in which the readings are read is consistent and if there is significant time of travel between diversion dams, it is important to account for travel time accordingly.

A needed approach to identify and track the rate of flow regimen change with elevation requires that the current "stand-alone" gage station data quality review be expanded to include error alignment procedures with adjacent gages. All of the gages within a reach that have water flowing into and water leaving as well as the all successive reaches on a river must have error uncertainty alignment to successfully identify and track timing and quantity changes of flow contribution by elevation zone. Powerhouse flows require accurate flow monitoring on the individual units and accurate measuring of spills are needed at many locations. Currently the level of monitoring described above and data review which always includes adjacent gages is not a required standard and does not exist for nearly all dammed reaches of California's mountain rivers upstream of the large multi-purpose federal flood control facilities which are mostly located in or near the foothills rising from the Central Valley floor. Stream gages and Powerhouse flows define the total flow response between elevation bands from climate change including changing evapotranspiration demand with vegetation succession and response to climate change. Currently the flow measurement process for stream gages and powerhouses along the lower reaches of many Sierra Rivers, including the Pit and McCloud Rivers is inadequate for accurately compiling subbasin unimpaired flows between diversion dams. This current process of water data collection and review limits accurately determining the effect of successive reach increments of flow, and limits accurately tracking runoff changes by elevation band.

7. MONITORING SNOWPACK AND AIR TEMPERATURE DURING STORM EVENTS

There is currently a lack of relatively high elevation snow sensors in northern California. This part of California which transitions from the Sierra into the southern Cascades in the vicinity of Lake Almanor is characterized by much lower elevation headwater drainage than occurs further south in the central and southern Sierra. These northern California watersheds, particularly the Feather River drainage are likely to be the most impacted from snowpack declines in the low elevation snow zone. PG&E in cooperation with the National Park Service and the California Department of Water Resources are currently exploring the feasibility for installing a cosmic gamma snow sensor with temperature and solar radiation monitor at Helen Lake (2,499 meters elevation) to reference winter snow accumulation. With a unique pattern of orographic effects, Helen Lake on the south side of Mount Lassen has a reputation for being one of the deepest monitored snowpacks in California. It is hoped that if installed, the additional instrumentation and monitoring at this site, will provide a relatively well instrumented high elevation northern California reference benchmark for evaluating snow zone change in the Feather River, Cow-Battle Creeks, and Hat Creek drainages. In the central and southern Sierra, limited snow sensor monitoring in the high elevation headwater drainages, already exists..

8. CLIMATE STATIONS

In years prior to the changeover of high elevation, manually read climate stations that were utilized to gather precipitation and air temperature data to remote automated, non-visited stations, station data was cooperatively shared with the National Weather Service (NWS). An NWS cooperator visited the stations daily and standards for data collection in terms of both equipment and data collection quality were for the most part assured with regularly scheduled visits by the NWS station network specialists. Today that situation is changed with the removal of most lake tenders and powerhouse personnel from many of PG&E's mountain climate station sites. Automation and the ease of satellite telemetry have changed how climate data is collected at many mountain station sites. This change in methodology has contributed to additional uncertainty as to what is believable in terms of having significance for identifying and tracking climate change.

9. CONCLUSIONS

PG&E's water management team is aware that climate change is occurring and is planning for how to best work with runoff change in terms of best hydroelectric scheduling practice.

PG&E's hydroelectric system with its many relatively small reservoirs was designed during an era with less winter runoff and more spring and early summer snowmelt runoff. With about 55 percent of it's average annual hydroelectric production coming from the relatively low elevation drainage of the Pit and Feather Rivers hydroelectric systems, there is a need to understand how anticipated change in runoff timing will affect overall hydroelectric energy production. For the Feather River, it will likely increase winter high water events, both in frequency and magnitude with possible increased frequency of diversion dam spill and shut-down of hydroelectric facilities during high water to avoid damage. Sedimentation of powerhouse forebays is likely to occur at an increased rate compared with the past. At this time there is not a good understanding as to how aquifer outflow rates such as those, which contribute to the Pit and McCloud Rivers and to Lake Almanor, may be impacted by a rising snowline. Precipitation in the form of increased rainfall rather than snowfall may possibly affect overall infiltration capacity on the volcanics. Types of data needed to best monitor and track this change require improved methods of data quality collection and analysis. For flows, it will likely require moving beyond the current stand-alone station type analysis and possibly improvement in measurement of powerhouse flows. Data from multiple flow and storage gages needs to be analyzed as a group rather than as stand-alone stations to align water data in terms of error uncertainty such that while some error is unavoidable, the unimpaired flows of subbasin reaches can be reasonably defined for elevation bands within the watershed. Improvements in terms of standardizing the continuously increasing number of automated mountain climate station seems needed, and possibly locating additional snow sensors at some key locations would be helpful in defining relative change for specific locals in northern California.

At this time PG&E's water management team has not observed any significant change in hydroelectric production that can be directly attributed to global warming or climate change.

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