RUNOFF IMPACTS OF CLIMATE CHANGE ON NORTHERN CALIFORNIA'S WATERSHEDS AS INFLUENCED BY GEOLOGY AND ELEVATION – A MOUNTAIN HYDROELECTRIC SYSTEM PERSPECTIVE

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ABSTRACT

Northern California's Pit, McCloud, Feather, Yuba, and American Rivers each have regional differences that set them apart from the higher elevation, less porous Sierra watersheds to the south. The watersheds from Lake Almanor north are primarily characterized by relatively porous volcanic basalt rock flows with several large springs that provide a large sustained base flow component into the McCloud, Pit, and North Fork Feather Rivers. High infiltration capacity supports a large proportion of any given year's precipitation moving downward through the vadose zone contributing to aquifer recharge and is characteristic of the mostly volcanic southern Cascade and Modoc Plateau watersheds that overlay the High Cascade and flood basalts. Relatively low overall elevation sets these northern California mountain watersheds apart as some of the first watersheds in California anticipated to be affected from climate-induced change to snowpack. During an average water year, for much of the Pit and McCloud Rivers, approximately 80-90 percent of river runoff is water from past years that emerge from springs as aquifer outflow. For those rivers that overlay large volcanic aquifers, in spite of their relatively low elevation and increase in winter rainfall, the form of precipitation has much less significance on runoff timing than watersheds south of Lake Almanor. Climate change is not anticipated to significantly affect timing and quantity of runoff for the basalts, but it will likely have relatively large timing and quantity changes for the Yuba, American, and some reaches of the North Fork Feather River. The Yuba River Basin which has a relatively large proportion of exposed granite in its headwaters is revealing a significant timing shift in runoff into earlier months. In terms of operating a mountain hydroelectric system, adaptation to climate change specific to a given watershed will likely include a combination of operating changes that may include, but are not limited to the following: higher winter carryover reservoir storage levels, reduced conveyance flows in canals and flumes during winter storm periods, reduced reservoir releases during the late spring and summer period, and increased sediment sluicing releases from diversion dams.

INTRODUCTION

The watersheds that contribute to Pacific Gas and Electric Company's (PG&E's) hydroelectric production are located primarily in the Sierra and southern Cascade Mountain ranges. A single powerhouse is located in the California coastal range at Potter Valley near Ukiah, California. The regional geology varies greatly. The Sierra headwater drainage is characterized largely by exposed, hard, mostly impervious granite that supports only a relatively small quantity of late summer and fall base flow runoff. North of the Sierra granites, the mostly volcanic southern Cascade mountain range starts at Lake Almanor near the town of Chester in northern California (Freeman, 2007). Watersheds in the coastal mountain range east of Ukiah, California that provide water for the Potter Valley Project are characterized primarily by the late Mesozoic Franciscan Complex, with both mélange and coherent types, along with non-Franciscan units that comprise generally mildly deformed coherent sequences of graywacke, shale, conglomerate, and limestone (Etter, 1979). Elevations likewise vary for watersheds in the PG&E hydroelectric system. The median elevation for the McCloud River Watershed above McCloud Reservoir near Mt. Shasta is approximately 1,400 m (4,600 ft), while at the southern end of PG&E's hydroelectric system, the median elevation for the upper North Fk Kings River above Lake Wishon (excluding the Courtright Reservoir subbasin) is approximately 2,800 m (9,200 ft) elevation – a difference of 200%. Both the geology and elevation significantly affect the impact of climate change on runoff timing. Area-elevation curves typically appear hyposometric in form when plotted. The watershed area most likely to be currently influenced in timing of runoff from climate change is the historical low elevation snow zone below about 1,829 m (6,000 ft). If the low elevation zone encompasses a relatively large portion of the watershed then the potential for affecting runoff timing can be significant. The PG&E watersheds from the Feather River north typically have a significant portion of their drainages in or below the low elevation snow zone. At the opposite end of the spectrum, a PG&E watershed with headwater contribution to its seasonal storage reservoirs in the southern Sierra, such as the North Fork Kings River

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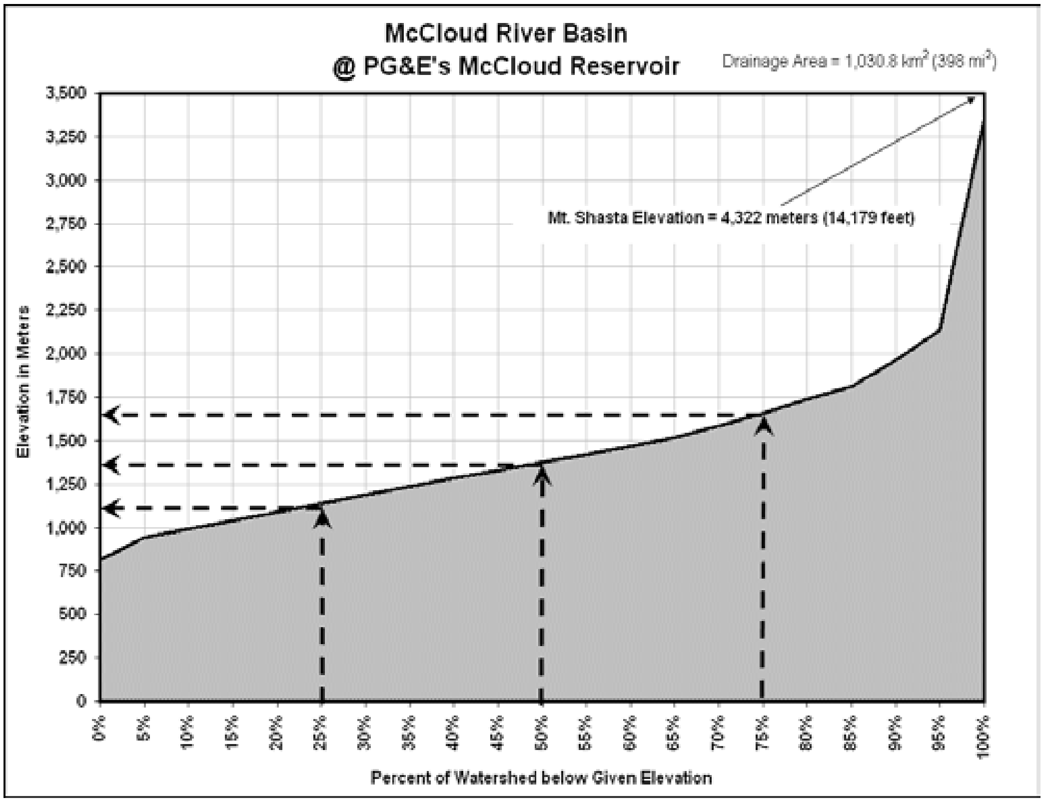

Figure 1. Area-elevation curve for the McCloud River Watershed above McCloud Reservoir. This is a relatively low elevation watershed on the High Cascade volcanics in northern California, which is experiencing a large decrease in the April 1 snow water equivalent.

typically has a large proportion and in some cases all of its drainage above the 1,829 m (6,000 ft) elevation. Runoff timing for high elevation watersheds is not as likely at this time and possibly for the next 20-35 years to be significantly affected from an increasingly higher snowline. Figure 1 illustrates the large area of the 1,031 km^2 (398 mi^2) McCloud River Watershed above McCloud Reservoir in northern California that is likely to be affected from climate change. Approximately 88 percent of the McCloud River watershed is below the 1,829 m (6,000 ft) elevation.

The impact of climate change on runoff timing is reduced if infiltration capacity is sufficiently large to dampen the effect of a change in precipitation phase from snow to rainfall. While a significant reduction in the April 1 snow water equivalent along with increased rainfall and an earlier melt is observed for snow courses in northern California on the volcanic basalts, the overall observed impact on runoff timing has been relatively small compared with the nearby Feather River Basin. This relatively small impact on runoff timing response observed for the volcanic basalts reveals that in terms of hydroelectric generation there is not likely to be a significant change in future years even if climate change continues to increase rainfall at the expense of losing snowpack. That will be a good outcome as reservoir storage is relatively small on the McCloud and Pit Rivers, a PG&E hydroelectric system which was engineered and built mostly in the 1960's before engineers anticipated the changes now being brought about from climate change.

SOME GENERAL TRENDS NOTED FOR THE SIERRA AND SOUTHERN CASCADES

Before focusing on the effects of climate change specific to PG&E's upstream mountain sub basin drainages and facilities, an analysis was performed to note some general runoff timing trends for several of the Sierra and southern Cascades' watersheds above the many large multipurpose 'rim' reservoirs. These are the major flood control and water supply reservoirs near California's Central Valley Floor, and are mostly operated by State and Federal Agencies. The drainage areas for these foothill reservoirs are significantly larger than for PG&E's mountain hydroelectric systems. PG&E has upstream facilities on many of the rivers that flow into these large 'rim' reservoirs. The full river unimpaired flows to these large reservoirs have been compiled and reviewed for data quality by various State and Federal Agencies and for purposes of this study would provide a general verification of overall runoff timing trend for various regions of the Sierra and southern Cascades. The author believes that

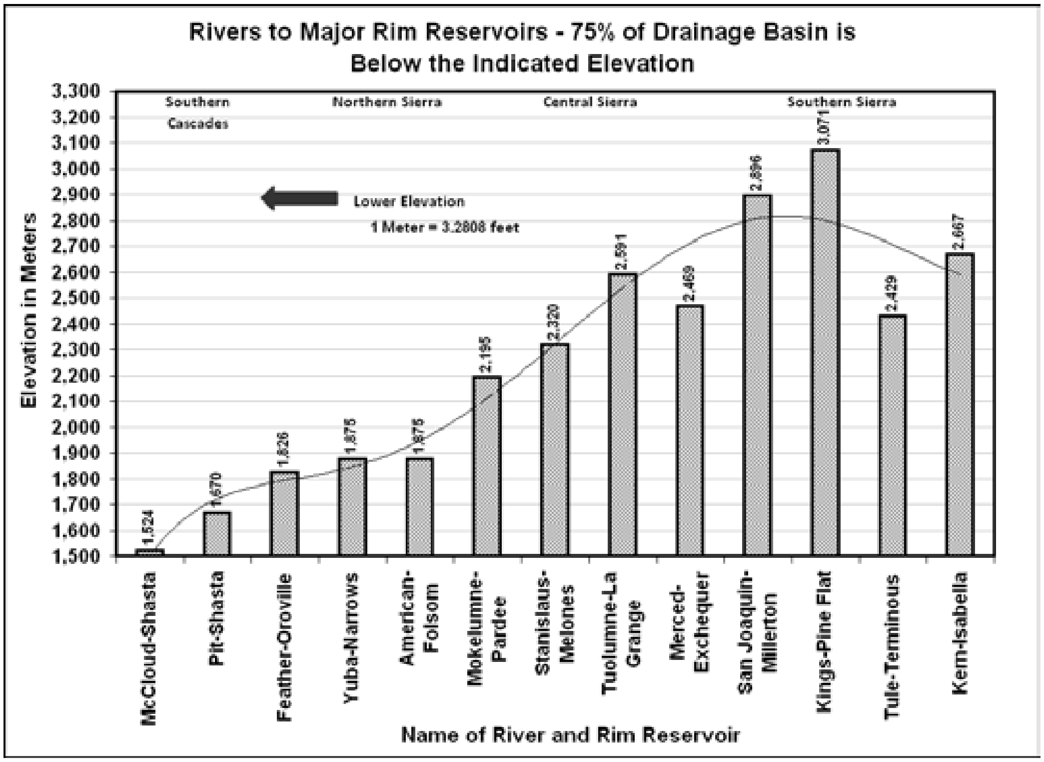

Figure 2. A north to south area-elevation plot for several rivers in the southern Cascades and Sierra with inflow to either a large 'rim' reservoir or to a principal river forecast point near the Central Valley Floor. The chart reveals the relatively low watershed area-elevation characteristic for northern California.

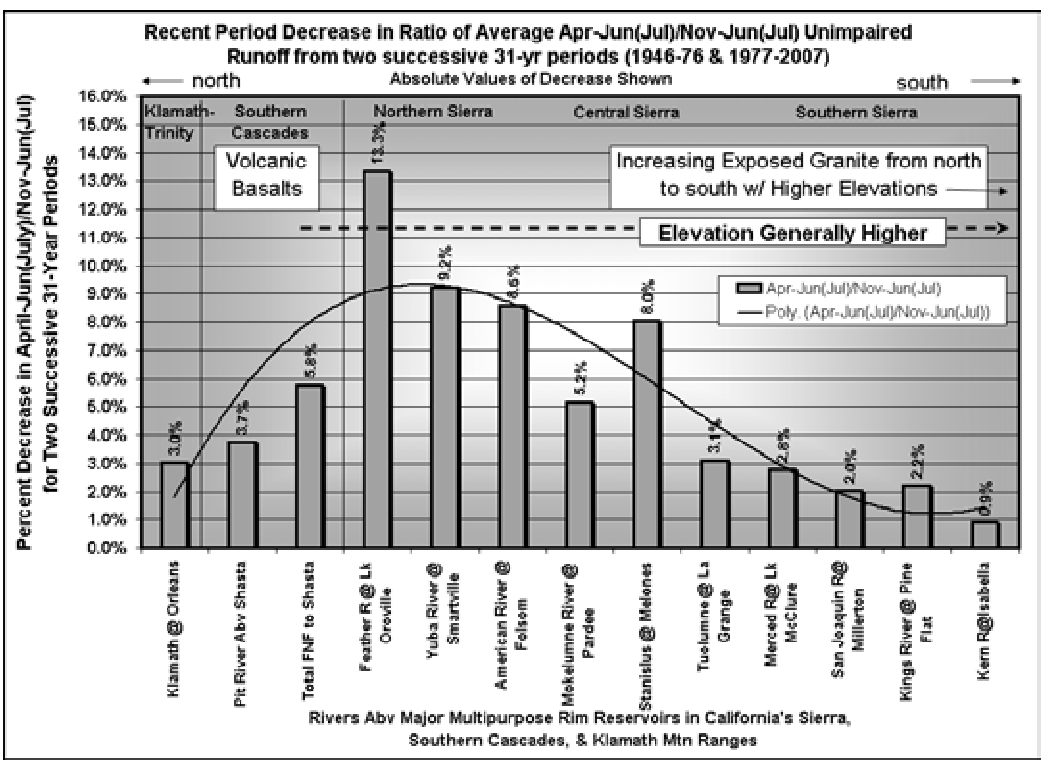

Figure 3. The percent decrease in the Apr-Jun (Jul) snowmelt runoff in the more recent 31-Year period (1977-2007) compared with the earlier period (1946-1976). Some of the largest shifts in timing of snowmelt runoff into the winter period occur for the relatively low elevation Feather, Yuba, and American Rivers.

these full river unimpaired flow calculations to the large multipurpose ‘rim’ reservoirs are significantly more accurate than those that are compiled utilizing relatively small sub basin reach computations between diversion dams (Freeman, 1999, 2003). Figure 2 and 3 reveal that as expected the relatively low elevation Feather River at Lake Oroville followed by the slightly higher Yuba River at Smartville, both being in the northern Sierra reveal the largest shift in runoff timing from the late spring into the winter period. Also as expected the high elevation San Joaquin, Kings, and Kern Rivers showed the least evidence of climate change in terms of runoff timing change. The average ratio of the April through June period divided by the November through June period was utilized for the Mokelumne River north for the two successive 31-year periods: 1946-1976 and 1977-2007. South of the Mokelumne River, for the higher elevation watersheds, the November through July period was divided by the April through July period for the same two periods. July was included for the southern Sierra, which seemed appropriate to better account for the higher elevation characteristic of the southern Sierra and its increased delay in snowmelt.

GEOLOGY

Volcanic Basalts

The McCloud, Pit River, and upper North Fork Feather River above Lake Almanor are characterized by volcanic basalts of both the High Cascade volcanics in the vicinity of the McCloud River and a large area of flood basalts that cover much of the Modoc Lava Plateau and contribute to the upper and middle reaches of the middle Pit River (Figure 4). Interspersed are localized areas of Cenozoic nonmarine (continental) sedimentary and alluvial lake deposits in areas such as make up the Fall River Valley. Relatively shallow volcanic basalts along with some Mesozoic sedimentary and older metamorphosed volcanic rock are located along the southern edge of the Mountain Meadows drainage. A significant portion of groundwater accumulation for Fall River which is tributary to the Pit River has its headwater source on the eastern slopes of the Medicine Mountains that form the perimeter of the Medicine Lake Caldera. Scattered large aquifers exist along various headwater reaches that flow into the Pit and McCloud Rivers. Some of these contribute to Fall River, Hat Creek, and the McCloud Rivers in the form of large springs (Calif Dept of Conservation, 1966, Meinzer, O.E. 1927). Water that emerges from springs such as from Hat Creek (Rising River) has likely been in transit for up to 100 years or more (Davisson, Rose, and Criss, 1996).

Figure 4. The southern Cascade volcanic-rock aquifers in northern California (Planert and Williams, 1995).

The springs, however, reflect a much more rapid response to annual precipitation amount that reveals itself within 3-4 years at most springs (Freeman, 2001). While the actual infiltrated water itself that enters into the aquifer may have a long transfer time (Freeman, 2007), depending on where it falls, the response to pressure change within the aquifer appears relatively quickly as evidenced by outflow of the springs. Hydroelectric operators at Pacific Gas and Electric can therefore forecast future runoff from the large base flow component several years in advance (Freeman, 2002). This base flow component for large tributaries such as Fall River makes up a long term average of approximately 88-89 percent of flow through PG&E's Pit No. 1 Powerhouse before entering into the Pit River. For the North Fork Feather River at Lake Almanor, the main North Fork tributary contributes approximately 45-50 percent of the annual inflow to Lake Almanor. The combined flow from the Hamilton Branch Powerhouse and channel contribute approximately 25 percent of the inflow to Lake Almanor. Submerged springs were found to contribute between 8,500-14,160 L/s (300 cfs-500 cfs), depending on water year type, to Lake Almanor. Springs are located in the southern end of Lake Almanor. Pratt Springs is located near the Prattville Intake and Dotta Springs is located approximately one mile north of Canyon Dam. The Big Spring complex was the largest of the inundated springs; it is located near the confluence of Hamilton Branch with Lake Almanor (PG&E, 2002). The southern portion of the Lake Almanor watershed is located along the divide between the Sierra Nevada Range and Cascade Range, where the older Sierra rocks are buried by younger volcanic rocks of the Cascades (Durrell, 1987). Much of the Sierra Nevada mountains have increasing amounts of exposed relatively impervious granite from Lake Almanor south. The East Branch and Feather River Canyon (along Hwy 70) reaches of the North Fork Feather River and much of the Yuba River basin have sufficient drainage areas on relatively impervious granite, metasedimentary marine , and other rock types that climate change in the form of increased rainfall will have an effect in terms of causing a timing change. South of the Feather River, exposed granite becomes increasingly common, with relatively rapid runoff from rainfall or snowmelt. PG&E's Potter Valley Project, which is located in the Coast Range, is characterized primarily by the Franciscan Complex formation with relatively deep soils that when saturated beyond field soil moisture capacity, promote relatively rapid surface runoff and interflow that leads to flood flows in wet years accompanied by high sediment rates.

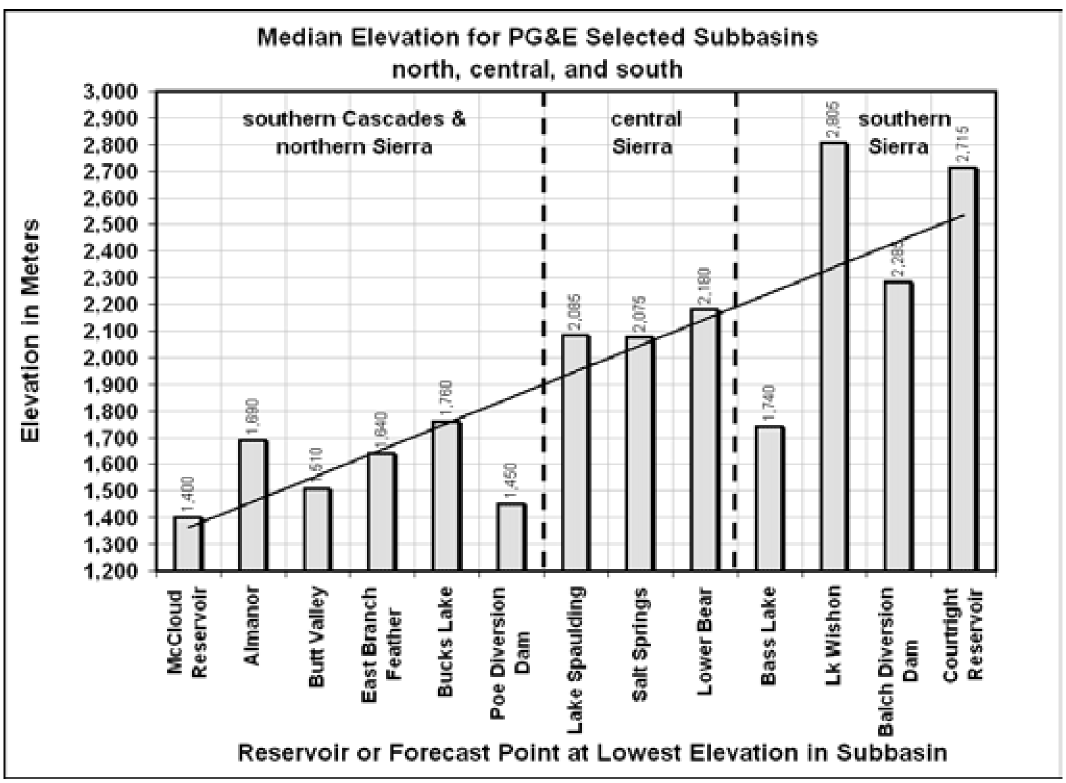

Figure 5. Median elevations for some representative PG&E subbasins arranged from north to south. The elevations vary for each subbasin within river basins, but in general the subbasins and their headwaters trend higher in elevation from north to south.

ELEVATION

In general the crest of the Sierra Nevada Mountain Range lowers northward in elevation from relatively high in the Kern River to medium-low elevation in the North Fork Feather River. The southern Cascades are relatively low elevation in comparison with the southern Sierra and likewise PG&E's headwater drainage for Lake Pillsbury in the coastal mountain range is relatively medium to low relative the southern Sierra. Snow Mountain above Lake Pillsbury peaks at 2,145 m (7,038 ft) elevation, with Lake Pillsbury below at 558 m (1,832 ft). Elevation has an important role in evaluating effects of climate change on runoff. A partial list of median elevations for PG&E sub basins is shown in Figure 5. The subbasins are listed from north to south. Watershed subbasins in the low elevation snow zone south of the volcanic basalts already reveal significant change in runoff timing. Medium and higher elevation snow courses show significantly less impact of climate change in terms of the April 1 snow water equivalent. If the current trend of snowpack reduction on April 1 continues due to climate warming, it is likely only a matter of time before the effects now being experienced at the lower elevation snow courses begin to take place at higher elevations. For most operational subbasins, between hydroelectric diversion dams, the lowest elevation bands have an almost equal or greater area compared with the next higher elevation band within a given subbasin. Many of PG&E's diversion dams and their pondages (forebays & afterbays) are relatively small, incapable of storing significant quantities of rainfall generated runoff. The middle 50% elevation band between the area-elevation proportions for area that equals or exceeds a given elevation is likely to have increasingly less elevational difference south to north.

REGIONAL IMPACTS OF CLIMATE CHANGE ON RUNOFF TIMING TO PG&E's MOUNTAIN RESERVOIRS

McCloud and Pit Rivers

While some of the lowest elevation watersheds occur in northern California's Pit and McCloud Rivers, The impact on runoff timing observed in the past have remained essentially unchanged. While the April 1 snow water

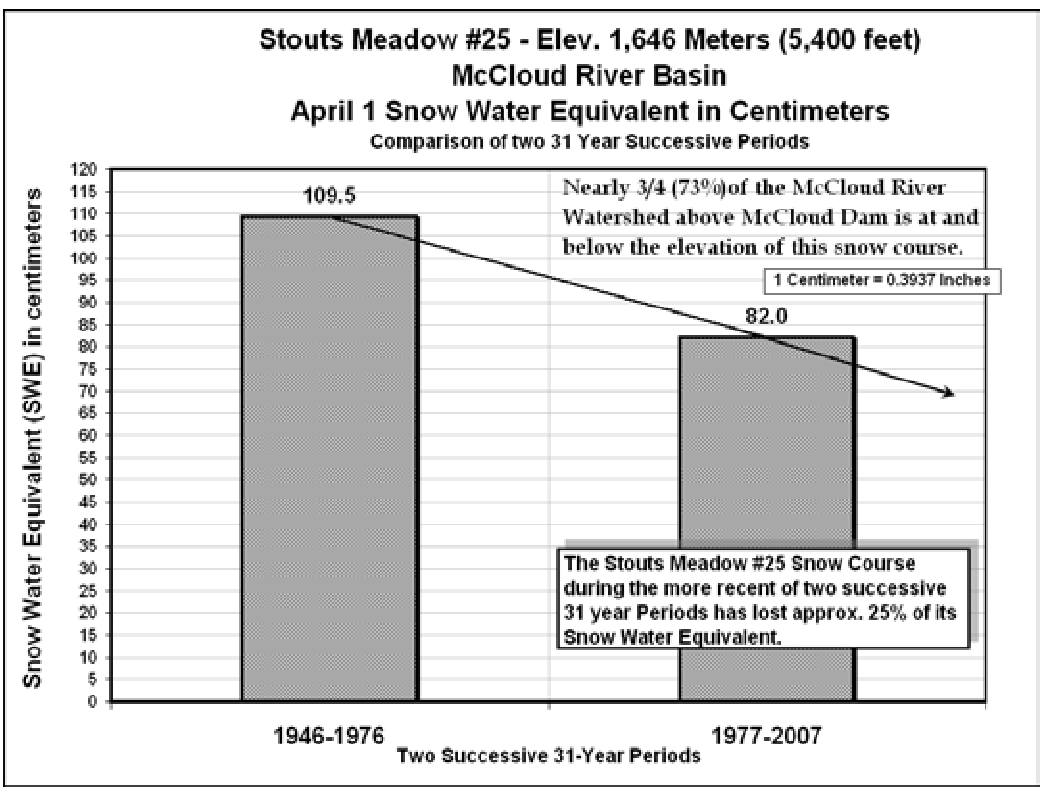

Figure 6. The April 1 snow water equivalent data as measured for the Stouts Meadow snowcourse is plotted for two successive 31-year periods. The data compilation reveals a 25 percent loss in the more recent period.

equivalent as observed at Stouts Meadow (Figure 6) has decreased an average of 25% since about 1977 with a significantly increased percentage of annual precipitation occurring as rainfall over larger portions of the watershed than pre-1977, runoff timing has not changed significantly. However, it is fortunate for project operations that this system, which was designed with pre-1970 engineering data, and relatively little surface storage capacity, has runoff timing remaining essentially unchanged in spite of the significant change in precipitation form from snowfall to rainfall. The porous volcanic basalts that characterize the slopes of Mt. Shasta, Medicine Lake Mountains, Modoc Lava Plateau, and the Hat Creek Rim areas tributary to the McCloud and Pit Rivers have many large aquifers supplied from porous surface rock and soils with a high infiltration capacity. Several large springs emerge along the lower slopes as these aquifers encounter relatively impervious older metamorphic and sedimentary strata. The active aquifer storage for the Pit and McCloud Rivers may be as large as 16 million acre feet storage (Freeman, 2007). The springs produce near constant year around outflow that for Fall River through PG&E's Pit #1 Powerhouse average long term about 42.5 to 56.6 cms (1,150 to 1,200 cfs). Figure 6 which compares two successive 31-year periods illustrates an approximate 25 percent loss of the April 1 snowpack for the Stouts Meadow snow course during the 1977-2007 period relative to the earlier 1946-1976 period. Figure 7 shows that while there was a significant decreasing trend in the April 1 snow water equivalent at the Stouts Meadow snow course, runoff just upstream of PG&E's McCloud Reservoir, which has a large aquifer outflow component has remained relatively stable long term with only a 6% downward trend, part of which may be accounted for in terms of annual precipitation change in quantity rather than precipitation form.

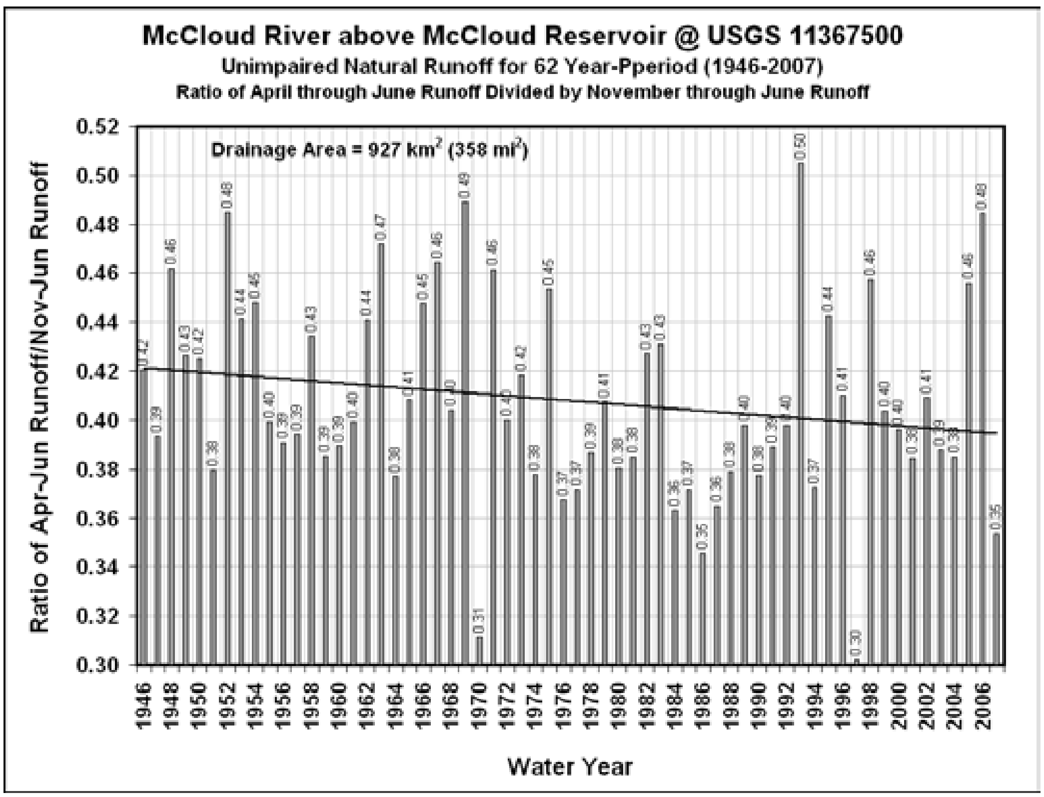

Figure 7. The shift of runoff from the April thru June spring snowmelt runoff into the November through June Period is revealed as a 6% trend shift downward. Approximately 73% of the headwater drainage to McCloud Reservoir is at or below the elevation of this snow course.

North Fork Feather River

The North Fork Feather River is located in the Sierra Nevada Mountain Range with about one third of its runoff coming from above Canyon Dam (Lake Almanor), which is located in the southern Cascades geomorphic region. The East Branch of the North Fork Feather River, which also contributes about one third of the annual runoff for the North Fork Feather at Pulga in a typical water year has a relatively low to medium elevation snow zone compared with the much higher snow zones in the southern Sierra. The nature of the soils and geology is such that once thoroughly wetted, surface runoff takes place in almost direct response to additional water availability

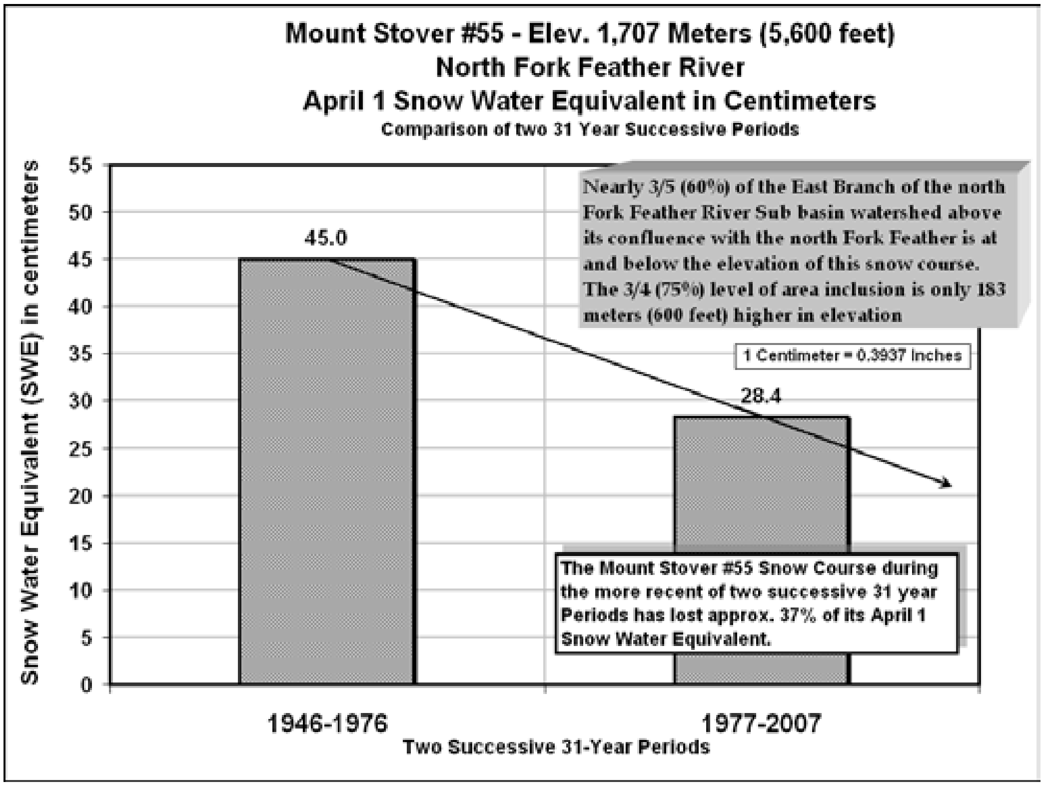

Figure 8. The April 1 snow water equivalent data as measured for the Mt. Stover snowcourse is plotted for two successive 31-year periods. The data compilation reveals a 37 percent loss in the more recent period.

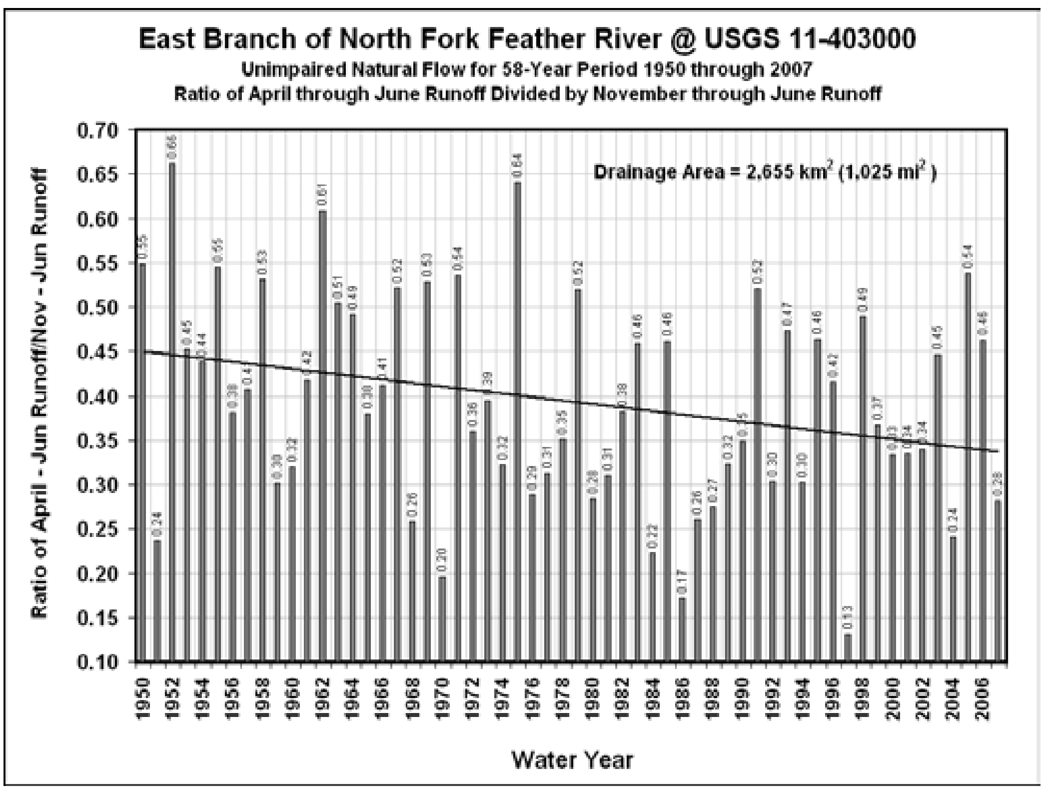

Figure 9. The shift of runoff from the April thru June spring snowmelt runoff into the November through June Period is revealed as a 27% trend shift downward.

either from snowmelt or rainfall. Similar to the McCloud and Pit River Watersheds, a large reduction in the April 1 snow water equivalent has also been observed at the low and medium elevation snow zones. Figure 8 illustrates a 37% decrease in the April 1 snowpack for Mount Stover on the North Fork Feather River; however in this case, there is a closely related timing shift in seasonal runoff response as shown in Figure 9. The East Branch of the North Fork Feather is in a rain shadow situated partly in the Basin and Range Geomorphic Province. The river crosses metamorphic, sedimentary, and some older volcanic rock. The watershed overall however is not characterized by aquifer outflow in the form of large springs such as occur for watersheds situated on the porous volcanic basalts.

South Yuba River Above Lake Spaulding

Further south, the South Yuba River headwaters above Lake Spaulding is located between about 1,525 m (5,000 ft) and 2,743 m (9,000 ft) elevations. The rock type is predominantly exposed mostly impervious granite with characteristic cracks and exfoliation. The impact of climate change on the Lake Spaulding snow course at the 1,585 m (5,200 ft) elevation is evident in a 31 percent decrease in the snow water equivalent from the 31-year 1946-1976 period to the more recent 1977-2007 period (Figure 10). Overall changes in runoff timing as a result of the shift in runoff timing is revealed in Figure 11, which indicates a 13% percent decline in slope from beginning to end of the 1946 through 2007 62-year period. This is a significant shift in runoff timing, but significantly less than for the North Fork Feather River to the north. While the low elevation snowpack as represented at the 1,585 m (5,200 ft) elevation for the Lake Spaulding snowcourse is being impacted in magnitude similar to the Feather River, runoff timing has changed less than observed for the Feather River. Figure 5 indicates that the median elevation for the Lake Spaulding Drainage is 2,134 m (7,000 ft) versus 1,737 m (5,700 ft) for the East Branch of North Fork Feather River. The South Yuba chart in Figure 11 reveals that as one moves southward along the Sierra the current impact of climate change on runoff timing generally becomes less.

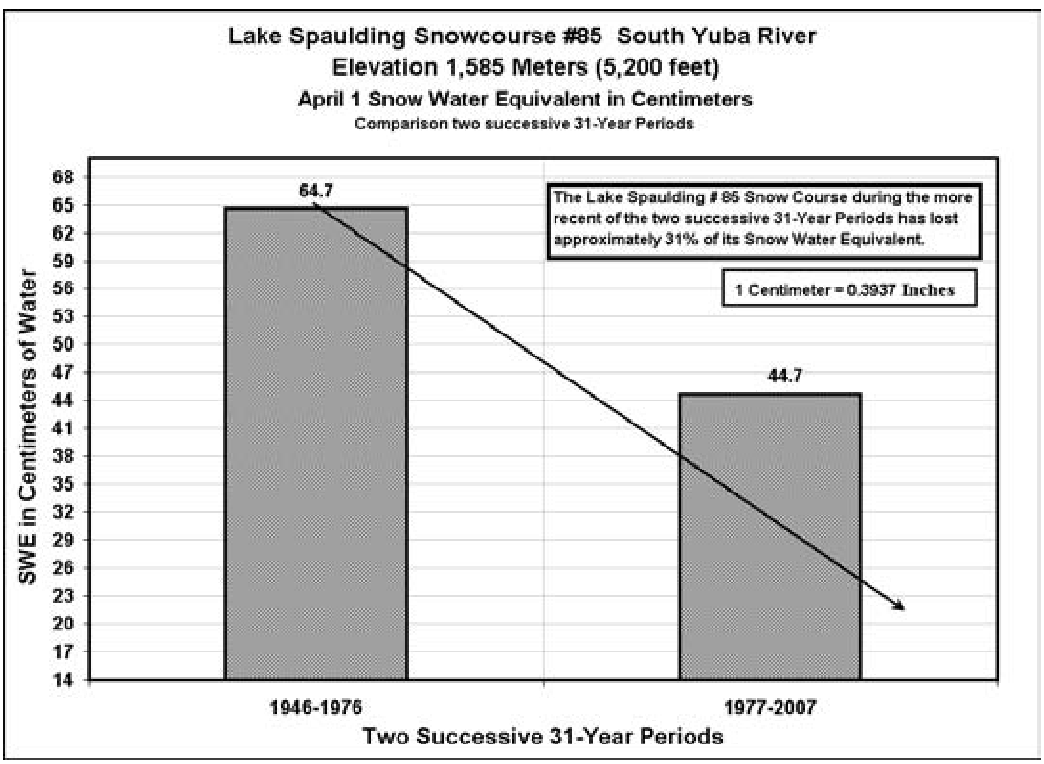

Figure 10. The April 1 snow water equivalent data as measured for the Lake Spaulding snowcourse is plotted for two successive 31-year periods. The data compilation reveals a 31 percent loss in the more recent period.

IMPACT ON PG&E'S MOUNTAIN HYDROELECTRIC SYSTEM

Overall system-wide the impact on PG&E's annual conventional hydroelectric generation production and to its generation value of a rising snowline and earlier snowmelt has not been measurable. A shift of runoff into the winter months from an increased portion of rainfall and early snowmelt has in some cases been beneficial in that water which would have historically remained frozen in the snowpack and spilled from reservoirs in the late spring

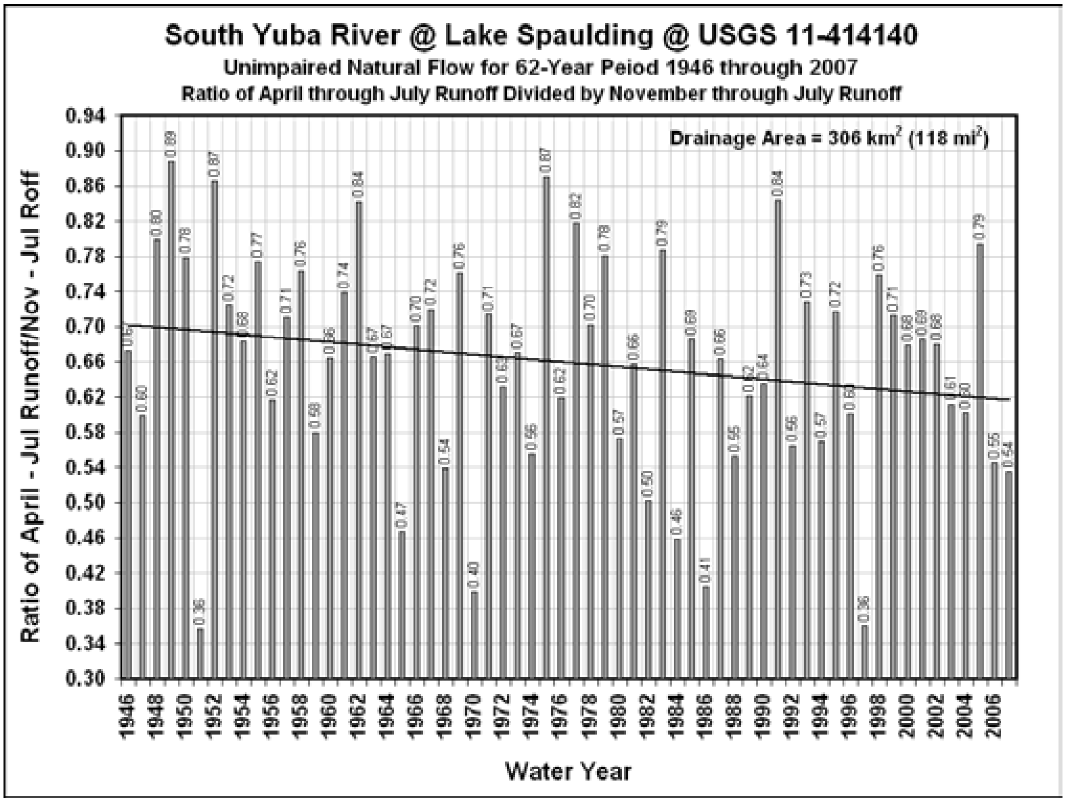

Figure 11. The shift of runoff from the April through July spring snowmelt runoff into the November through July Period is revealed as a 13% trend shift downward.

and/or early summer months now becomes available for generation in the January through March period. This late winter runoff from the snowpack provides an extended period for reservoir operators to generate from the relatively small mountain reservoirs (Freeman, 2003). However, if the rising snowline trend continues, a point in time will likely take place specific to each subbasin reach in terms of elevation and geology when generation value loss is likely to occur with increasing frequency, therefore overshadowing the benefits of having runoff shift to earlier in the winter period. At some time in the future a point is reached, when additional water will need to remain in the reservoirs and be carried through the winter storm months to increase assurance for filling the reservoir in the late spring period. Carrying over a higher winter minimum in the mountain reservoirs will increase the risk of spilling. The opportunity cost of storing the water to assure summer filling rather than generating with it increases the risk of loss from spill if rain generated runoff rapidly fills the reservoir and the reservoir spills past the powerhouses. With increased reliance on the remaining precipitation uncertainty for filling reservoirs rather than the historical certainty of a measurable snowpack, the management risk in terms of potential for lost value from storing water in late winter and early spring significantly increases. Assuming that the trend continues toward a reduced snowpack that eventually reaches into the higher headwater exposed granite portions of the Sierra, the relatively impervious, steep terrain may lead to significantly larger and more rapid winter runoff for the mountain reservoirs with increased frequency of winter spills. It becomes somewhat of a paradox that to assure filling under increased remaining runoff uncertainty, mountain reservoir storage levels in winter may need to be deliberately held higher with increased risk of spill. As the snowpack continues to disappear, in effect the ability to fully and efficiently utilize reservoir storage also diminishes due to the increasing uncertainty of filling the reservoir. Currently in terms of winter operations for maintaining flood space, the California Division Safety of Dams only requires that spill gates remain open during the November 1 through March 31 winter period. PG&E reservoirs essentially have no flood control requirements outside of providing a safe reservoir operation.

Some of the first negative impacts to conventional hydro generation production from continued climate change will likely take place on the relatively low elevation North Fork Feather River followed by negative generation impacts taking place on the South Yuba River-Bear system with increasing frequency. It is currently believed by the author that negative impacts that will begin to occur with sufficient frequency to cause overall generation losses for PG&E's hydroelectric system will likely become significant by about 2025 for the Feather and

Yuba Rivers. While the American River also appears to have a large potential for impacts on hydroelectric generation, PG&E has only the Chili Bar Powerhouse, a relatively small, low head 7 MW powerhouse on the South Fork American River. Climate change impacts for watersheds on the higher elevation Stanislaus River drainage and south of the Stanislaus are not anticipated to adversely impact PG&E's hydroelectric production or generation value for possibly 20-35 years at the current rate of snowpack reduction. The elevation of the southern Sierra headwaters are such that effects of sufficient warming, which has potential to impact runoff and adversely affect our hydroelectric operations in the higher elevations are likely to be delayed compared with the lower elevations to the north. Impacts of continued climate change will have a significant impact on reducing the snowpack in the relatively low elevation McCloud and Pit River Basins, but because of the porous nature of these volcanic watersheds with their large springs, any adverse impact on hydroelectric operations is likely to remain minimal.

ADAPTING PG&E's MOUNTAIN HYDROELECTRIC OPERATION TO EFFECTS OF CLIMATE CHANGE

Reservoir releases for the mountain reservoirs in PG&E's hydroelectric system are currently optimized in near real-time to capture highest value in terms of forecasted energy prices and to minimize its net open position. In other words the combination of price for electrical energy replacement and the value assigned to ancillary services is a primary objective function for currently determining the reservoir release strategy. This is a probabilistic process that hedges water release guidance toward minimizing probabilistic opportunity cost. Since many of the operating constraints are directed toward filling seasonal reservoirs at the end of snowmelt runoff, this filling objective will become increasingly important in successfully meeting the optimization objectives. As runoff timing continues to shift from the historical spring and summer snowmelt period into the winter period, it is likely that in order to increase the likelihood for filling, the current hedging algorithm will increase reservoir minimum storage levels and shift the risk focus of not filling to the risk of spilling water in the spring if precipitation is above normal for the remaining period of uncertainty. If in the past PG&E held a reservoir past Dec 31 at 18.5 hm^3 (15 TAF), the model might now recommend 38.0 hm^3 (25 TAF) to increase the likelihood for filling with the reduced probability for historical snow accumulation beyond Dec 31. This would be accommodated in the model by reducing the numerical hardness for minimum winter carryover, while increasing hardness for having a full reservoir on some date following snowmelt. Also as an increase in winter runoff from rainfall and an earlier melt becomes increasingly common; it is likely that the water managers will become increasingly conservative in setting winter conveyance maximums and increase their focus on managing hydroelectric facilities for accommodating increased rates of sedimentation.

CONCLUSIONS

The PG&E mountain hydroelectric system is unique for California in that nearly 40 percent of its annual conventional hydroelectric generation historically has come from aquifer outflow or springs. That ratio is not anticipated to change significantly with continued climate change. While the northern California watersheds for the Pit, McCloud and North Fork Feather River above Canyon Dam are relatively low elevation, the current runoff timing for these volcanic basalt watersheds is expected to remain mostly unchanged and therefore not adversely impact water used in producing hydroelectric generation. The infiltration rate is high on the porous volcanic basalts regardless of the precipitation form. PG&E is planning an aquifer recharge project utilizing ground based cloud seeding to further enhance the aquifer recharge process. PG&E's North Fork Feather River and to a lesser extent the Yuba River are also relatively low elevation watersheds, but because the geology is different, increased losses in hydroelectric production for these northern Sierra watersheds are anticipated to become increasingly likely and significant starting 15-20 years from now. Currently getting some increased runoff in these rivers, if not in the form of floods is actually conducive to increasing generation production. Winter energy pricing has been relatively high in recent years, and the prospect for getting some runoff into the reservoirs earlier reduces the likelihood for spill in the late spring/early summer period. For the central Sierra from about the Mokelumne River south, most of the mountain reservoir are located above 1,070 m (3,500 ft) and the headwaters range in elevation up to about 2,440-2,745 m (8,500 ft -9,000 ft) in elevation. PG&E is currently estimating that significant impacts of climate change that adversely impact PG&E's hydroelectric generation in the southern Sierra are unlikely for the next 20-35 years. The higher elevation, mostly exposed granite headwaters area, is characterized by relatively impervious granites with some occasional patches of shallow volcanics. Once the effects of the rising snowline impacts these higher, relatively steep portions of the Sierra, runoff and consequent erosion and flood concerns may become significant in terms of the winter operation. Not much is known with any certainty at this time regarding how the economics will net out for hydroelectric facilities that receive inflows from this high elevation, relatively steep and impervious headwaters area.

Applying coupled reservoir simulation and climate models to better understand the impacts of climate change on some of PG&E's watersheds will likely lead to an improved understanding of what to expect. PG&E is currently assisting the Lawrence Livermore National Laboratory to model some of PG&E's hydroelectric systems on these rivers in hope that we can eventually understand what to expect with more certainty and develop an effective 'adaptive strategy' to work with the coming climate change.

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