Memorandum

To: Water Supply Advisory Committee

From: Robert Raucher, Karen Raucher, Russell Jones, Joel Smith, Allison Ebbets, Megan O'Grady, Stratus Consulting Inc.; Gary Fiske, Gary Fiske and Associates, and Shawn Chartrand, Balance Hydrologics, Inc.

Date: 3/13/2015

Subject: Background information on climate change effects on local hydrology

This memorandum provides technical information to support the Water Supply Advisory Committee's (WSAC's) understanding of the effect of increasing temperatures and changes in precipitation patterns due to climate change. This background information is provided to support WSAC's understanding of the hydrology and related water system yields that the Santa Cruz Water Department may need to be prepared to address in the future.

The memorandum provides a summary of climate change projections based on research conducted by Dr. Bruce Daniels, University of California Santa Cruz (UCSC); Flint and Flint (U.S. Geological Survey, USGS); and the Stratus Consulting team (Team) consisting of Stratus Consulting Inc., Gary Fiske and Associates, and Shawn Chartrand of Balance Hydrologics. The Team's summary includes results from Confluence model runs indicating a plausible demand-supply gap under both DFG-5 and the City of Santa Cruz's proposed Habitat Conservation Plan (HCP) fish flow requirements.

There is much technical information included in this background document. Bruce Daniels, Shawn Chartrand, and Joel Smith will present the information provided in this background memorandum and will be available to address questions during the April 8, 2015 Enrichment Forum.

Summary of Analysis Completed by Dr. Bruce Daniels

This section provides a brief overview and summary of climate analysis completed by Dr. Daniels (UCSC, and also Board Chair for the Soquel Creek Water District). This summary is based on his dissertation (Daniels, 2014) and personal communication. He uses observed climate data to calculate precipitation trends over time, and then projects those trends into the future to anticipate how they will impact hydrologic conditions over the next 30 years. His work was motivated by several factors:

- Climate scientists have already observed changes in precipitation features
- Even under conditions where total annual precipitation does not change, precipitation features can change, and thus affect hydrologic conditions.

Because of the large plausible range of future changes in precipitation that are found using downscaled data from global circulation models (GCMs) – i.e., GCMs do not even agree on whether a region's annual average precipitation increases or decreases in the future – Dr. Daniels decided to use an observation-based approach to evaluate future precipitation trends at a local scale.

Methodology

The Daniels study does not use climate models, but is based on historical observations from the Santa Cruz and Watsonville weather stations. Work was conducted at two study locations, Feather River and Lake Oroville, and the Soquel-Aptos Basin (which includes Live Oak). The latter location is summarized here as it is relevant to the Santa Cruz water supply.

Dr. Daniels evaluated 120 years of daily data and calculated long-term trends for three precipitation timing patterns: event intensity rate (mm/day), event duration (day), and pause between events (day). Table 1 summarizes the trend analysis results. These results show significant changes over the period of record for each parameter. Dr. Daniels found similar trends from stations throughout California.

Table 1. Rain event trend analysis

Rain event metric	Trend (per decade)	p-value	Significance (statistical)
Event intensity rate (mm/day)	-2.94%	0.17%	99.8%
Event duration (day)	2.18%	0.10%	99.9%
Pause between events (day)	1.67%	1.30%	98.7%

Next, Dr. Daniels assessed the hydrologic impacts of the observed climate changes using the Soquel-Aptos Basin USGS Precipitation Runoff Modeling System (PRMS) model that was developed by Hydrometrics under contract to the Soquel Creek Water District. The trends presented in Table 1 were extended 30 years into the future and then these precipitation trends were applied as changed climate inputs into the Soquel-Aptos model. Table 2 summarizes the key relevant hydrology changes in this future projection.

Table 2. 30-year projected changes based on past climate trends

Component	Change in intensity	Change in duration	Change in pause	Sum
Recharge	-6.7%	-0.5%	-0.3%	-7.5%
Baseflow	-5.7%	-0.3%	-0.3%	-6.3%
Streamflow	-3.0%	-0.1%	-0.1%	-3.2%

The results show a 7.5% decrease in recharge over the next 30 years; this finding is significant, especially in the context of current conditions such as active seawater intrusion in Live Oak and Seascape/LaSelva. The 6.3% decrease in baseflow could result in fish mortality or in little or no summer or fall river flow. The 3.2% decrease in streamflow is for the Soquel and Aptos Creek locations, but since they adjoin the San Lorenzo River, Dr. Daniels anticipates similar findings at that location as well.

These results are based only on observed trends for the three precipitation timing patterns and do not incorporate changes in temperature or total annual precipitation amounts. As GCM models typically predict a temperature increase of 4–10°F for this region, evaporation loss from warming of this magnitude will be very significant.

Summary of Analysis Completed by Flint and Flint: San Francisco Bay Climate Simulation

This section provides a brief summary of a climate change evaluation conducted by Flint and Flint (2012) for the Russian River Valley and Santa Cruz mountains. The study is focused on hydrologic projections derived from coupled climate and hydrologic models.

Methodology

The Flint and Flint (2012) study compiles climate and hydrologic models, enabling the authors to examine changes in climate, potential evapotranspiration, recharge, runoff, and climatic water deficit.

Climate Data

Flint and Flint (2012), in their USGS study, *Simulation of Climate Change in San Francisco Bay Basins, California: Case Studies in the Russian River Valley and Santa Cruz Mountains,* use regionally downscaled results from two GCMs selected to provide a representation of a range of relatively warm and wetter projections (PCM model) and warmer and drier results (GFDL model) for the region. The results are downscaled to a grid size of about 7.2 miles by 7.2 miles (in contrast to the GCM grid scales of about 150 miles per side).

Hydrologic Data

The climatic model results are then coupled with a regional water-balance model, called the Basin Characterization Model (BCM), developed by the authors. This is a physically based model that uses gridded data to calculate water balance components. Data inputs include topography, soil composition and depth, bedrock geology, and spatially distributed values for air temperature and precipitation. The model is calibrated with regional and local data to determine the balance of recharge and streamflow. The model has a 270-m grid size.

Findings and Conclusions

The results of this study indicate large spatial variability in climate change and the hydrologic response across the greater Bay Area region, including a specific examination of the Santa Cruz Mountains and associated watersheds.

> …although there is warming under all projections, potential change in precipitation by the end of the 21st century differed according to model. *Hydrologic models predicted reduced early and late wet season runoff for the end of the century for both wetter and drier future climate projections, which could result in an extended dry season. In fact, summers are projected to be longer and drier in the future than in the past regardless of precipitation trends. While water supply could be subject to increased variability (that is, reduced reliability) due to greater variability in precipitation, water demand is likely to steadily increase because of increased evapotranspiration rates and climatic water deficit during the extended summers* [emphasis added]. Extended dry season conditions and the potential for drought, combined with unprecedented increases in precipitation, could serve as additional stressors on water quality and habitat.
>
> By focusing on the relationship between soil moisture storage and evapotranspiration pressures, climatic water deficit integrates the effects of increasing temperature and varying precipitation on basin conditions. At the fine-scale used for these analyses, this variable is an effective indicator of the areas in the landscape that are the most resilient or vulnerable to projected changes. These analyses have shown that *regardless of the direction of precipitation change, climatic water deficit is projected to increase*, which implies greater water demand to maintain current agricultural resources or land cover [emphasis added]… This type of modeling and the associated analyses provide a useful means for greater understanding of water and land resources, which can lead to better resource management and planning. (Flint and Flint, 2012, p. 1)

Some specific findings for Santa Cruz include projected large reductions in runoff and recharge, even with the "wetter" climate projections: "There are subtle trends in the mountains of the region that could lead to dramatic changes in runoff or recharge. Declines in runoff and recharge for the GFDL model are particularly large … along the coast in the mountains near Santa Cruz, where there are decreases of nearly 250 mm/yr. Even the PCM model, which projected a general increase in precipitation, shows declines in recharge up to 200 mm/year in the Santa Cruz area" (Flint and Flint, 2012, p. 15).

Their conclusions are as follows:

> Hydrologic models predict reduced early and late wet season runoff during the next century, which potentially results in an extended dry season in both climate models. Projections that estimate increased precipitation show it concentrated in

midwinter months, December and January, a trend that could increase risk of floods. In both the wetter and drier futures, potential evapotranspiration and associated climatic water deficit (CWD) are projected to steadily increase by as much as 30 percent between the 2071–2100 period in comparison to the 1971–2000 period, which means approximately 200 millimeters of additional water needed on average to maintain current soil moisture conditions in some locations to maintain the current CWD levels. Summers are projected to be longer and drier in the future than in the past regardless of precipitation trends.

While water supply could be subject to increased variability (that is, reduced reliability) resulting from higher variability in precipitation, water demand is likely to steadily increase relative to increased rates of evapotranspiration and climatic water deficit during extended summers. Extended dry-season conditions and potential for extended drought combined with unprecedented precipitation events could serve as additional stressors on water quality and habitat. Real-time monitoring of hydrological variables can be one of the most prudent planning efforts and could be central to testing hypotheses about potential climate change demonstrated in this report and equipping managers to respond. (Flint and Flint, p. 42).

Summary of Climate Change Projections for the Santa Cruz Region Conducted by the Stratus Team

This section provides a brief overview of the methods used to develop climate change projections for the Santa Cruz region by Stratus Team including: Robert Raucher, Karen Raucher, Russ Jones, Joel Smith, Allison Ebbets, Megan O'Grady: Stratus Consulting; Shawn Chartrand: Balance Hydrologics; and Gary Fiske: Gary Fiske and Associates.

Development of Streamflow Records under Climate Change

We have completed a model-scale analysis of potential impacts to streamflow and water supply using one climate change projection from one downscaled GCM for WY[1] 2015–2070. The work is intended to help inform ongoing decisions regarding HCP and water supply planning, albeit for only one possible future scenario at this point. The work was conducted through a few primary steps: (1) decompose downscaled[2] monthly climate projections into monthly projected streamflows; (2) distribute monthly projected streamflows over any given projected month to

1. WY stands for water year, defined as October 1 to September 30 of the following year.

2. GCM output was downscaled to grid cells measuring 1/8 degree by 1/8 degree (about 12 km on a side in central California). The GCM output is resolved at grid cells measuring 2 degrees by 2 degrees (about 196 km on a side in central California).

develop a projected daily record of streamflow; (3) compute hydrologic statistics for the projected months vs. the historic analysis period (WY1936–2009); (4) develop regression models of natural flows between points of diversion and reaches of anadromy for all City of Santa Cruz source streams; and (5) use the previous four steps as inputs to the HCP Hydrology Model for the (a) City July 2012 and the (b) DFG-5 HCP flow proposals. If not discussed, all other aspects and nature of the HCP Hydrology Model were left as is, and were not changed or altered.

The climate change work for the HCP has been ongoing since 2008. In 2008, we first sought to incorporate climate change into the HCP planning process. A first step to doing so involved a substantial literature review to gain an understanding of what the present state of the science was for climate change in California. This review led Balance to contact Prof. Ed Maurer at Santa Clara University to seek expert guidance on how to set-up a simplified analysis using climate change information. Our correspondence with Prof. Maurer resulted in the development of a water balance model, which serves as the basis for the climate change modeling reported here. At the time, the CalAdapt program and website (www.cal-adapt.org) were just getting up and running, driven by Gov. Schwarzenegger's November 2008 Executive Order S-13-08 that specifically asked the Natural Resources Agency to identify how state agencies can respond to climate change. We utilized the bias-corrected spatially downscaled (BCSD) GCM data[3] adopted and made available by the CalAdapt program as the basis for our modeling. Thus far we have specifically focused on the worst-case climate change dataset, which for the CalAdapt datasets is the downscaled GFDL2.1 GCM[4] for the A2[5] emissions scenario.

The original intent of our work was to use the raw climate change projection data downloaded from CalAdapt. Upon inspection and completion of a few trial model runs however, it was noted that the projected precipitation record is wet, and quite wet when compared to the historical period record (Figure 1). After much discussion amongst the technical HCP and Water Supply Planning team, it was decided that we would seek to develop a revised precipitation record. The adjusted precipitation record is termed the transient precipitation record (Figure 1), and was developed by Stratus Consulting. In short the transient record preserves the distribution of events present in the raw dataset (i.e., the variability of the raw GFDL2.1 A2 record), but scales it according to the long-term monthly rainfall depths reported for Santa Cruz. The procedure and rationale are discussed in the section: Methodology for developing the Transient precipitation record. It is important to note that *no other data* of the GFDL2.1 A2 series used for the modeling reported herein was adjusted – the raw downloaded data was used for all modeling. Each of the five steps presented in the opening paragraph is described in considerable technical detail below.

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3. The GCM data originates from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset.

4. Geophysical Fluid Dynamics Lab CM 2.1; National Oceanic and Atmospheric Administration.

5. CO_2 emissions exhibit a continual rise throughout the 21st century and by century's end achieve CO_2 concentrations that will be more than triple their pre-industrial levels

The findings and implications of the modeling efforts are presented starting on page 16 of this memorandum.

Monthly projected streamflows

Monthly records of total precipitation (mm) and average and maximum air temperature (degrees Celsius) were download from the CalAdapt website for GFDL2.1 A2 using the tabular data option. The geographic location specified for the data query was a point in the San Lorenzo River watershed just south of Ben Lomond, with approximate coordinates of 37.0595 DD by -122.0712 DD. This location and the grid cell it is in is the centroid of the San Lorenzo River watershed. Climate change data for the San Lorenzo River watershed was used because it serves as the basis of modeling for the HCP Hydrology Model, and specifically the San Lorenzo River at Big Trees USGS gage (Big Trees) is the reference gage and streamflow record (USGS #11160500).

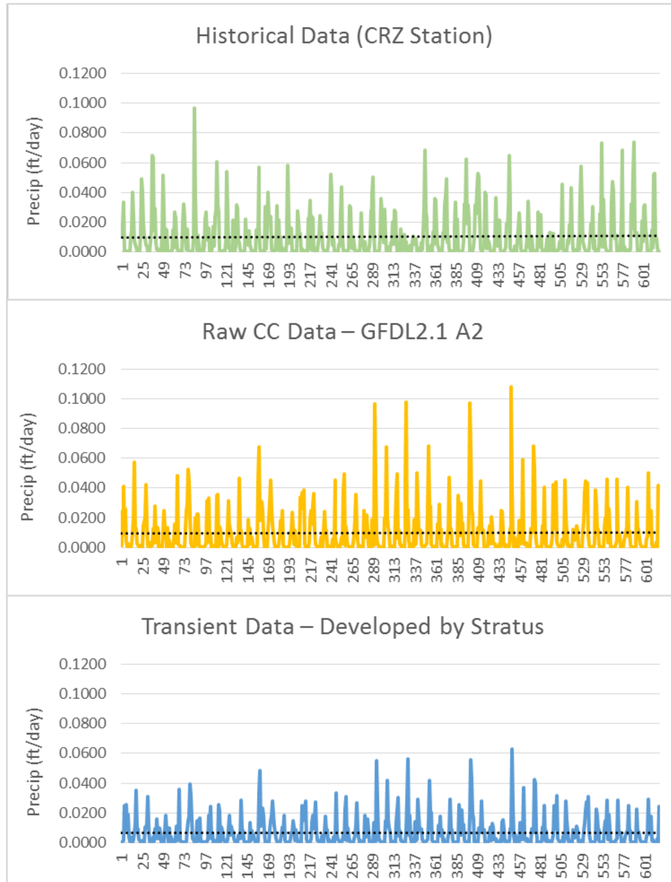

Figure 1. Comparison of the historical, raw climate change projected and transient precipitations records used in the modeling reported herein. Note that the monthly precipitation totals were divided by the number of days in the month to arrive at precipitation in feet per day. The beginning of each data series has been lined to facilitate plotting. Each data series is 50 years in length.

Prior to publication the climate change projected precipitation and air temperature datasets were bias corrected and spatially downscaled using spatial statistics reflective of observed, historical conditions. The bias correction and spatial downscaling are two different steps of post-GCM data processing. Bias correction first occurs for GCM output of the historical period 1950–1999; correction is based on adjusting GCM cumulative distributions of any one grid cell to that of the historical observed distributions of the specified grid cell. This results in a dampening or amplifying of the GCM continuous data series while preserving the mean and variability of the original GCM output. A similar step is conducted for the projected GCM dataset (i.e., the climate change projected period) using the same historical observed distributions. The gridded, historical observed datasets were developed by Maurer et al., 2002; these datasets reflect spatially averaged monthly precipitation and surface air temperature conditions computed from point measurements (stations) distributed over any one 2 degree by 2 degree grid cell. Spatial downscaling occurs by developing adjustment factors between observed historical data and the bias adjusted GCM data, where the observed data is the reference value; these adjustment factors are interpolated to the downscaled grid based on an empirical statistical method (Maurer et al., 2002). The downscaled adjustment factors are then applied to the coarse-gridded observed data to yield the bias corrected spatial downscaled climate projections.

Development of climate change projected monthly streamflow record for Big Tees followed a procedure similar to that used to develop the downscaled climate projections. The first step was to develop a calibration curve (regression model) between the historical observed climatic data for the period 1950–1999 (same data used in the bias correction and spatial downscaling steps) and the observed monthly streamflow at Big Trees for the same period. To do this the historical observed climatic data was applied to a simple water balance model to estimate monthly streamflow. The water balance model is stated as:

$$Q = P \ - \ ET \ - \ R \ + \ B(CoS) \tag{1.1}$$

The term Q is streamflow discharge (ft^3/day), P is precipitation (ft/day), ET is the evapotranspiration (ft/day), R is groundwater recharge (ft/day), and B is the baseflow addition, which is a source term dependent upon CoS (relative groundwater carry-over storage):

$$B = \sum_{i=-1month}^{-6months} P_{daily} * K * CoS \ \left[\frac{ft}{d}, -, - \right]$$

$$CoS = \frac{\left(\sum_{i=0}^{-10months} P_{daily} \right)}{\bar{P}_{daily}} \ [-] \tag{1.2}$$

The term i is an index used to specify the period of time used for a calculation, K is a simple dimensionless rate-limiting constant which characterizes the release of stored water to the source streams, and CoS is a dimensionless precipitation momentum term which scales B up or down depending on how wet or dry the present and previous nine months were relative to the long-term mean. The square brackets indicate units for the associated terms and equation. In more practical terms B serves as the primary fitting parameter for the water balance model, and improves model skill for the lowest flows. In particular, B helps to better distinguish short-term wet periods (scale of 1–3 months) from longer-term wet periods (scale of up to 10 months), when heading into the summer season. A decent example of this is WY1993 vs. WY 1997. It is important to note that Equation 1.1 lacks a change in storage term (ΔS), which would be the more typical source-related term. We are not referring to B as a change in storage term because we have no idea how storage may have or may change in the source watersheds over the time period of interest, nor do we know the initial storage conditions. The calibration curve between monthly streamflow at Big Trees computed with the water balance model vs. that measured at Big Trees is provided in Figure 2, and a comparison between the computed continuous monthly record and that reported by the USGS is provided in Figure 3. Figure 3 indicates that the water balance model does relatively decent job of reflecting historical conditions, and as usual it is most difficult to reflect the extremes within the record, although the baseflow parameter helps to accomplish this to some degree.

With the calibration between downscaled GCM climatic variables and measured streamflow at the USGS, it is possible to move forward and compute monthly streamflows for the projected climate change period. This simply involves applying the climate change climatic variables to water balance model and then using the calibration curve to compute monthly streamflow at Big Trees. This was done for the period 2015–2070.

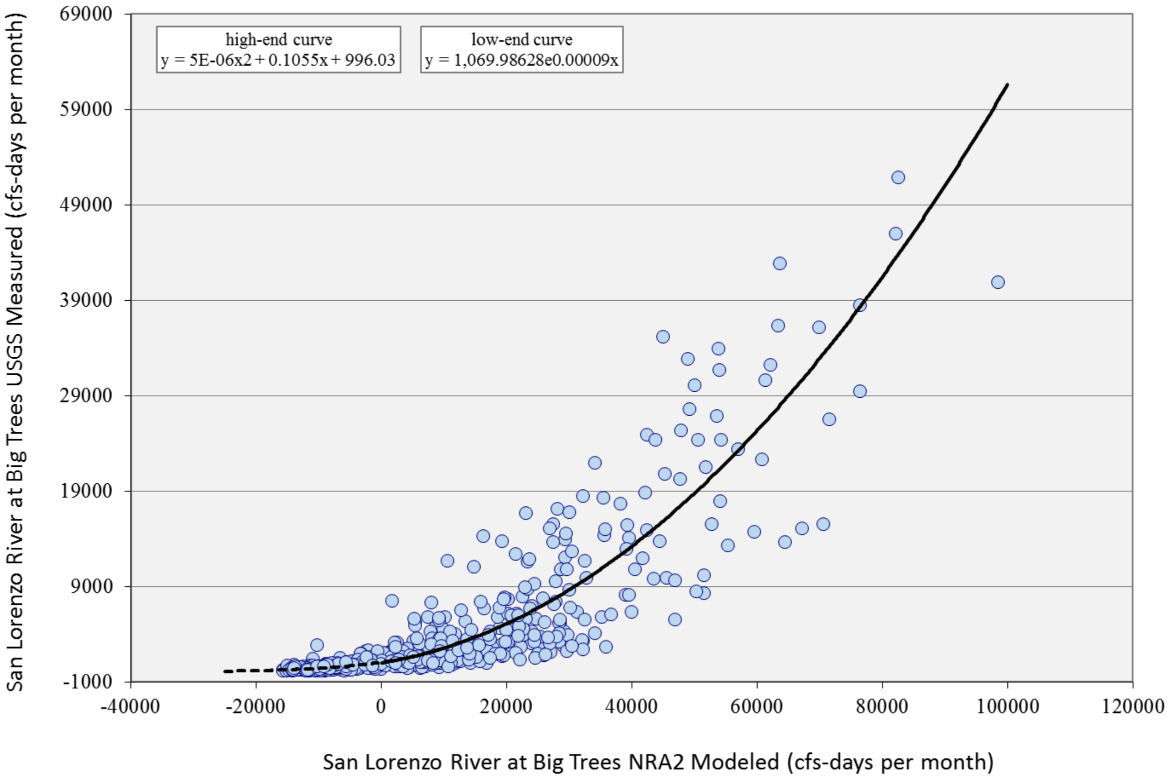

Figure 2. Calibration curve between monthly streamflow at Big Trees computed with the water balance model vs. that measured by the USGS.

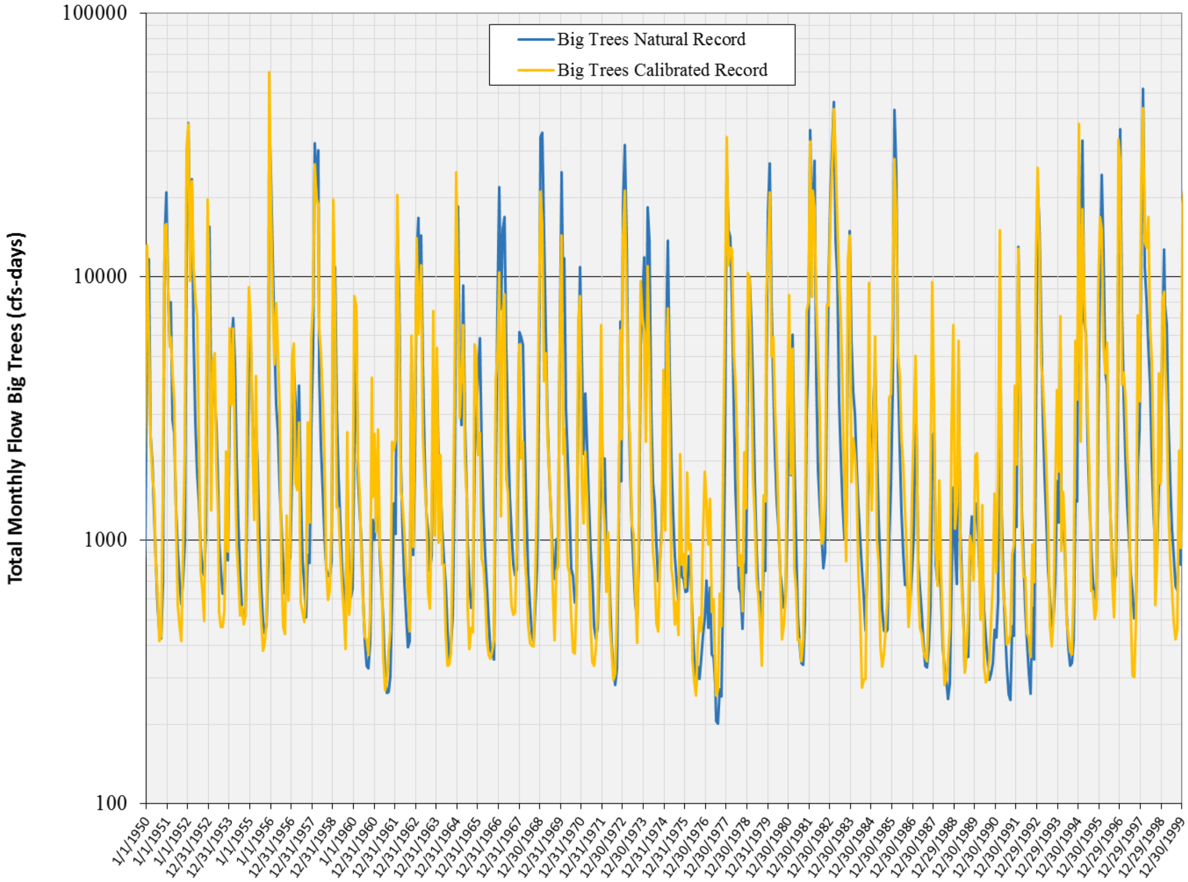

Figure 3. Continuous monthly records comparison for water balance model computed vs. USGS measured streamflow at Big Trees.

Daily projected streamflows

Arriving at a daily projected streamflow record could be accomplished many different ways; we tried several to start and ended up utilizing the most simple, which is based on long-term averages. Among other things this method is appealing because climate change projections are really about long-term trends. In detail the work involved several different steps. First, daily projected streamflows were apportioned from the projected monthly totals for the period WY2015–2070 by distributing the total monthly flow according to the long-term mean daily flow for any particular day. The Big Trees annual record of mean daily flow was computed using the USGS records for the period WY1936–2014.

The resultant preliminary daily projected climate change record contained two calculation artifacts that were removed. The removal process constitutes the second step in the daily streamflow process. The first artifact was defined by abrupt drops in flow at transitions between some winter months. This drop occurred for projections that go from very wet conditions in one month to average or dry conditions in the next, and the uncorrected drops ranged in magnitude up to roughly a factor of 10. Drops less than a factor 1.25 were not corrected. The drops were removed using exponential smoothing and re-distribution of mass to account for the changing flow conditions (i.e., this means conservation of mass was respected for any given climate change projected total monthly flow and that flow was not created or destroyed). The smoothing occurred over the first three days of any particular month, with the smoothing exponent similar to recessional constants which can be computed for the Big Trees record. The smoothing equation for the first day of the month was:

$$Q_{corrected} = Q_{uncorrected}^{previous\ day} - ((1 - e^{-0.5}) * (Q_{uncorrected}^{previous\ day} - Q_{uncorrected}^{3\ days\ ahead})) \quad (1.3)$$

The equations for days 2 and 3 are identical to Equation 1.3 except the day referenced by last Q term in the equation would decrease by 1 day, and 2 days respectively. What is important to keep in mind is that Equation 1.3 simply subtracts an exponentially decreasing flow difference from the flow computed for the last day of the previous month. In this way Equation 1.3 smooth's the transition from the end of any given previous month through the first 3 days of the next month, as long as the flow differential across the monthly transition > 1.25. The result of this step in the process is referred to as the corrected, preliminary daily projected record of flow (corrected record).

The second artifact was defined by rapid flow oscillations during many days of the winter months. This is due to the fact that the USGS record is quite long and therefore average daily flows can reflect values that are not necessarily correlated to adjoining values. As a result these oscillations simply reflect the averaging, and were smoothed out in order to avoid imprinting an overly explicit trend in the daily projected climate change record. Smoothing of the corrected record was done with a zero-order forward and reverse digital filter. This means that the location of any given peak in time is not effected, but its amplitude is adjusted based on the nature of flows forward and backward in time from any particular position, based on a specified filtering length and computed flow differences. This particular filter has the advantage of matching initial conditions well. The smoothing filter length was chosen to minimize the sum of differences between the corrected and the filtered record (< 0.1% difference in total flow). The preliminary daily projected, the corrected and the smoothed records are shown in Figure 4 for WY2068–2070.

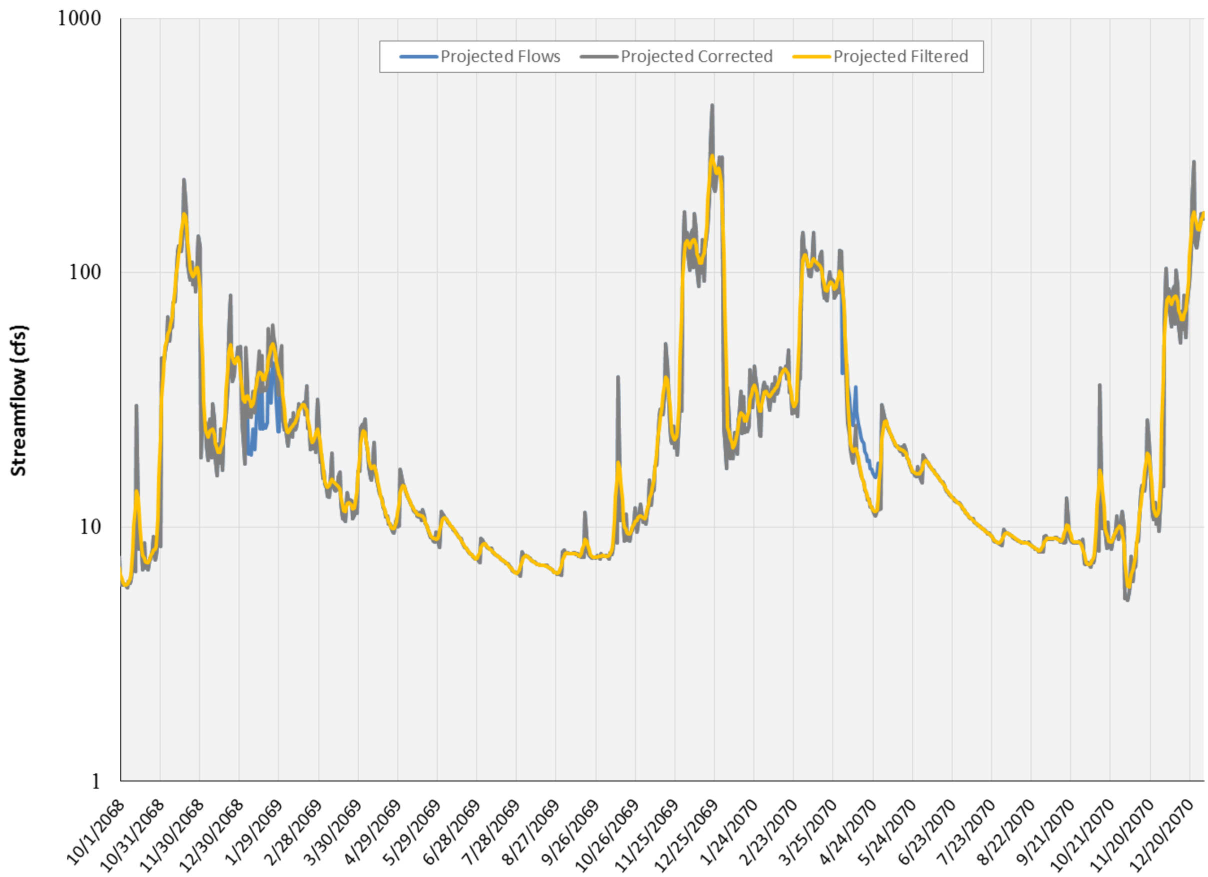

Figure 4. Comparison of climate change daily projected, corrected and smoothed streamflow at Big Trees.

Hydrologic statistics

The HCP Hydrology Model is based on use of flow statistics for the Big Trees USGS gage, which describe how dry or wet conditions are from month to month, based on the historical period as a whole. The hydrologic classification of any given month is based on 5 possible categories (percentile classes) termed critically dry (0–20%), dry (20–40%), average (40–60%), wet (60–80%) and very wet (80–100%). The HCP Hydrology Model uses the hydrologic classification to determine which HCP habitat flow rules are in effect. The flow rules are needed to first set flow aside to meet the stated needs of salmonids, and second to determine how much residual flow remains for potential water supply (results which are fed into Confluence®).

In order to facilitate comparison between the one climate change model run and those completed for the historical period, most notably with respect to analyses completed by Jeff Hagar and Gary Fiske, it was determined that monthly hydrologic conditions for the projected climate change period were to be computed relative to the historical period percentile class limits, without effecting the numerical value of those limits. This provides for the comparative scenario and implicit assumption that the general distribution of hydrologies is similar between projected and historical, but more importantly is necessary in order to make straightforward comparisons between the model datasets.

Natural flow regression models

The last step in preparing data for the HCP Hydrology Model is to specify regression models which provide a means to compute natural (i.e., un-impacted by diversion) flows within the reaches of anadromy based on associated daily flows at the points of diversion, or in the case of the San Lorenzo from Big Trees to Tait Street. These regression models were constructed from all available historical records of flow and diversion, and there application explicitly assumes that the character of the hydrologic relation from point of diversion to reach of anadromy does not change from the historical period to the projected period. The natural flow regression model for Laguna Creek is provided in Figure 5 as an example. It is worth noting that this is where some of the work completed last year to refine the low-flow regression models for the northcoast streams comes to bear, particularly for Laguna Creek, as the projected record contains many more days of very low flow, many instances of which define the lower limit of hydrologic conditions. With this perspective it is better understood that that work was partially done in preparation for the climate change model runs.

Other assumptions

A few more assumptions were made within the HCP Hydrology Model to best model the climate change projected period. These assumptions include:

- *Felton production:* Felton production was set to zero for all days in the projected period because no one knows what the Felton production may be in the future. In any event the impact of this assumption is small regardless as production at Felton represents a fraction of total water supply production.

- *Pre-existing legal bypass:* a record of annual mean daily bypass was computed for the historical bypass data and used as the model conditions for the future.

No other assumptions were made to complete the HCP modeling component to the projected climate change analysis. Model results for the City July 2012 and the DFG-5 habitat flow rules proposals were transmitted to Gary Fiske for water supply analysis with Confluence.

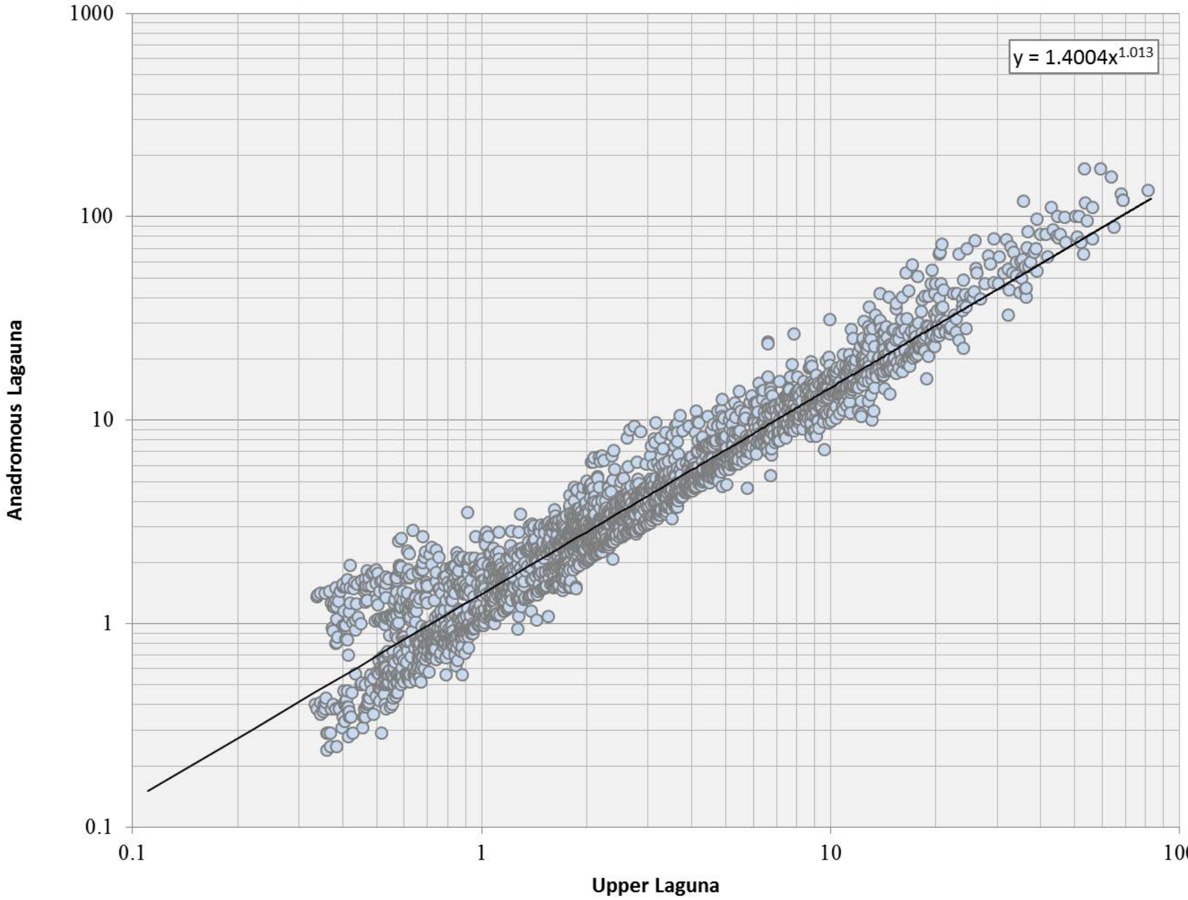

Figure 5. Natural flow regression model for Upper Laguna to Anadromous Laguna.

Methodology for Developing the Transient Precipitation Record

Delta Method

One weakness of the BCSD process is that it may generate model results that are wetter than observed when run for the same historic time period ("hindcast"; Lukas et. al., 2014). In order to avoid this potential "wet bias," we generated an alternative dataset by calculating the change in future monthly projections from the average monthly hindcast baseline period, and applied that change ("delta") to the average baseline observed data. We processed the data within a geographic information system (GIS) as follows. We downloaded monthly raster data (mean temperature and precipitation) from the GFDL GCM run under the A2 emissions scenario, for the hindcast baseline (1950–1999) and future (2020–2070) time periods. First, we calculated a hindcast raster layer of the average monthly (1950–1999) values on a cell-by-cell basis for the temperature and precipitation datasets. Next, we calculated the spatial average of all the cells within the Santa Cruz watershed (Figure 6) for both the average hindcast layer and each future month/year layer (i.e., monthly for years 2020–2050). We then calculated the difference between the future month/year and the hindcast average monthly data – temperatures by simply subtracting the average hindcast baseline from each future month/year, and precipitation by dividing the future month/year by the hindcast baseline (i.e., a ratio). We then applied the monthly delta output for each future month/year to the average monthly observed baseline data from the “Big Trees” dataset. Finally, we used the future monthly transient (2020–2070) as input into the flow model.

Figure 6. Santa Cruz watershed overlaid with 0.125-degree grids representative of the input climate change raster data.

Modeling System Performance with Climate Change

In our Confluence modeling of the Santa Cruz system to date, we have tested various configurations of supply, infrastructure, operating rules, and demand against an historical flow record.[6] In the IWP, that record included 59 years. More recent work has expanded that record to 73 years. The underlying assumption has been that the distribution of future streamflows will look like the flows in that record.

Thus, across hundreds of modeling runs, the essential characteristics of the flow record have remained constant. The worst drought event was 1976–1977. The 1987–1992 period represented another major drought. We knew which years in the record were very wet and which were exceptionally dry.

That no longer applies when we analyze how the system will respond to climate change. The essence of analyzing climate change is the assumption that future weather and streamflows will not be the same as the past. Rather, a new flow record has been produced. (It so happens that record includes 51 years.) There is no longer a 1976–1977 worst-case drought benchmark or a 1987–1992 sequence. As is illustrated in Figure 7 for City proposed HCP flows at Big Trees, the distribution of flows is completely different than that of the historic record.

Our approach to regulating lake drawdown has been to develop rule curves that constrain the lake so that it draws down to its minimum (1070 mg) level at the end of the driest years. While there are no longer 1976–1977 or 1987–1992 sequences *per se*, we nonetheless want to use similar principles to operate the lake in this alternative future, so we likewise developed lake rule curves designed to draw the lake down to its minimum by the end of the driest water years.

It should be noted that, while the largest impact of climate change on system reliability results from reduced flows, there is an independent impact of weather. The warmer and drier weather conditions that are expected also result in a small increase in customer demand, and also affect lake evaporation and rain-on-surface. In what follows, we have made an initial attempt to incorporate those impacts. They are small relative to the streamflow impacts.

Modeling Results

The following results all assume the mid-range 2025 interim demand forecast developed by David Mitchell (as presented at the February WSAC meeting). All of the charts and tables are denominated in percentage peak-season shortage. To convert to volumes, use Table 3.

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6. In the case of the HCP flow sets, those historic records have been modified to model various fish flow rules.

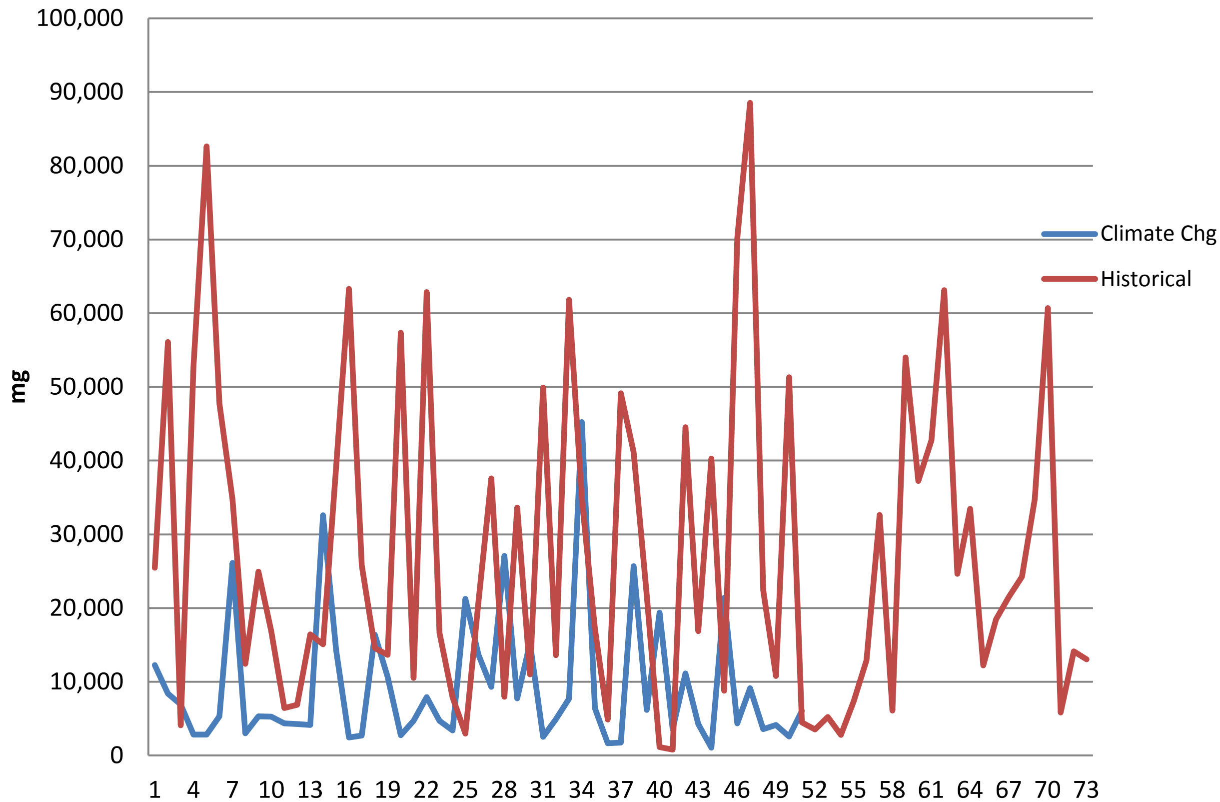

Figure 7. Comparison of annual flows at Big Trees: City proposal.

Table 3. Rough conversion between peak-season percentage and volumetric shortages: 2025 interim demands

Peak-season % shortage	Peak-season volume shortage (mg)
5%	100
10%	200
15%	300
20%	400
25%	500
40%	800
50%	1,000
60%	1,200

City Proposed Flows

Figure 8 compares the peak-season shortage duration curves for City Proposed flows with and without climate change.

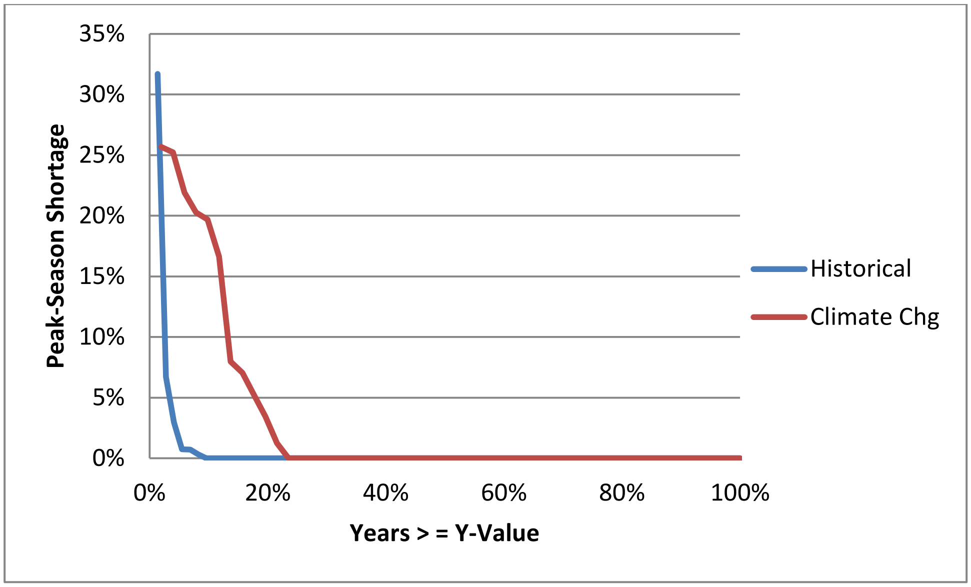

Figure 8. Peak-season shortage duration curves with and without climate change: City proposed flows.

Two differences between the two curves are immediately noticeable:

- Climate change shifts the curve upward and to the right, meaning there is an increased likelihood of larger shortages. Whereas with historic flows, there is a small chance (< 10%) of any shortage at all, this rises to more than 20% with climate change. The probability of a shortage greater than 20% increases from about 1% with historic flows to about 8% with climate change. This shift is shown in a different form in Figures 9 and 10.

- Despite the overall degradation of system reliability under climate change, we see in 9 that the worst-year shortage is actually somewhat less under climate change. The reason for this is illustrated in Figure 11, which magnifies the lower end of the 7 Big Trees flow distributions. The worst drought events in each case are highlighted and we see that despite the substantial overall reduction in flows under climate change, the worst drought event is not quite as severe as the historical 1976–1977 event.

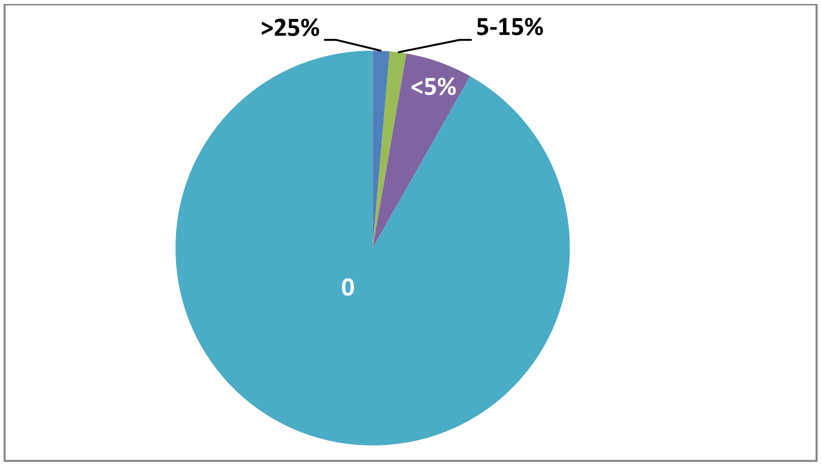

Figure 9. Peak-season shortage distribution: City proposed flows (historical).

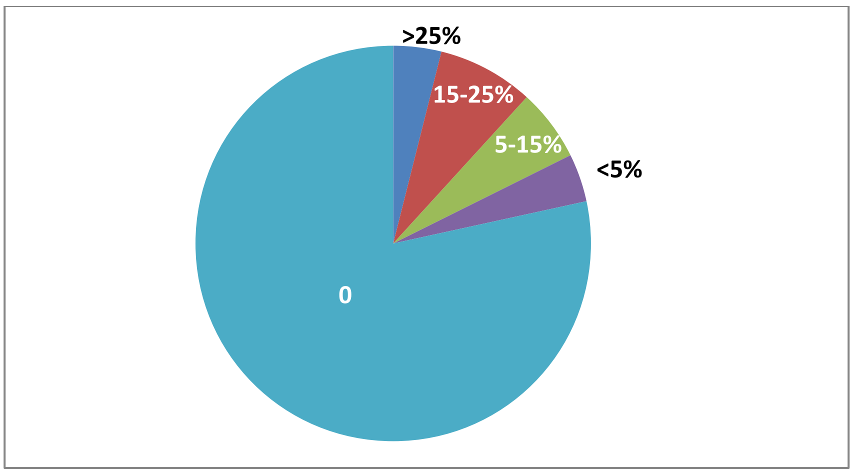

Figure 10. Peak-season shortage distribution: City proposed flows (climate change).

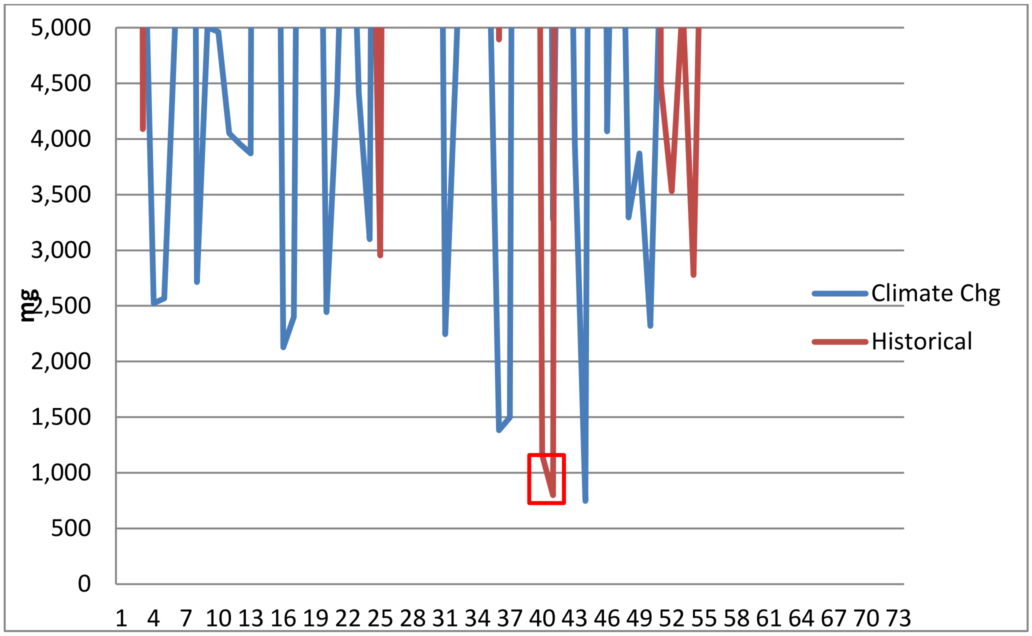

Figure 11. Magnified Big Trees dry-year flows: City proposal.

DFG-5 Flows

Figures 12–14 show the same system reliability comparisons for DFG-5 flows.

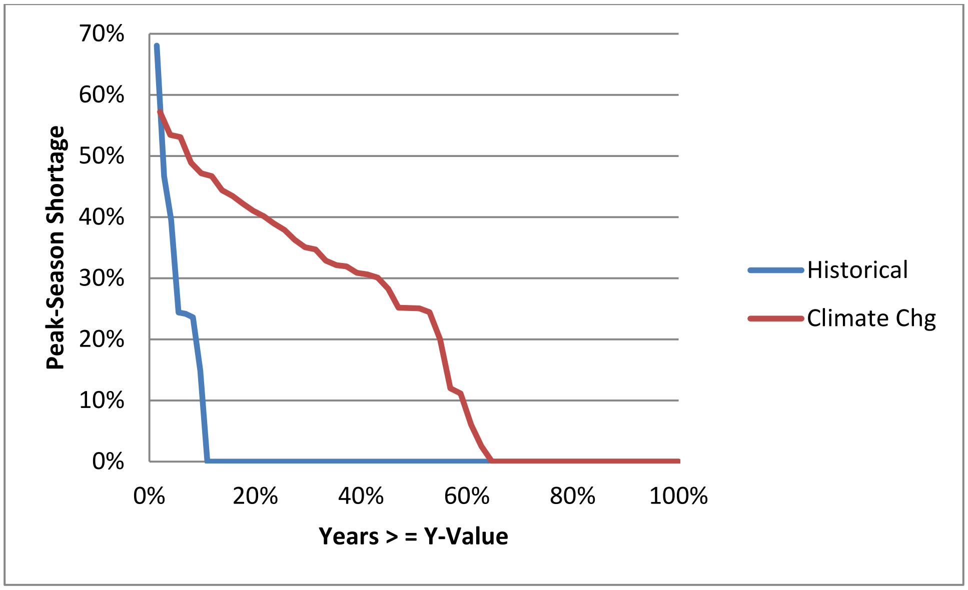

Figure 12. Peak-season shortage duration curves with and without climate change: DFG-5 flows.

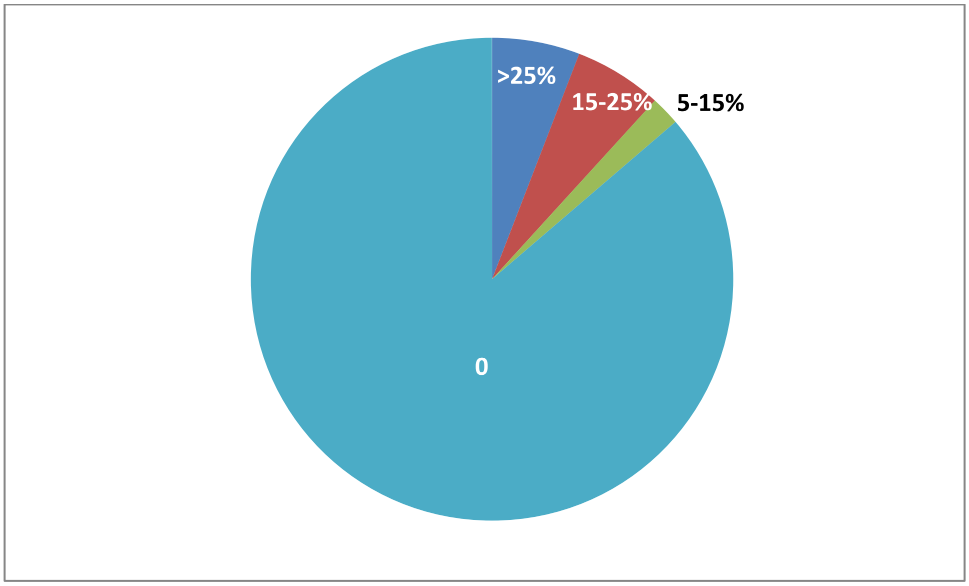

Figure 13. Peak-season shortage distribution: DFG-5 flows (historical).

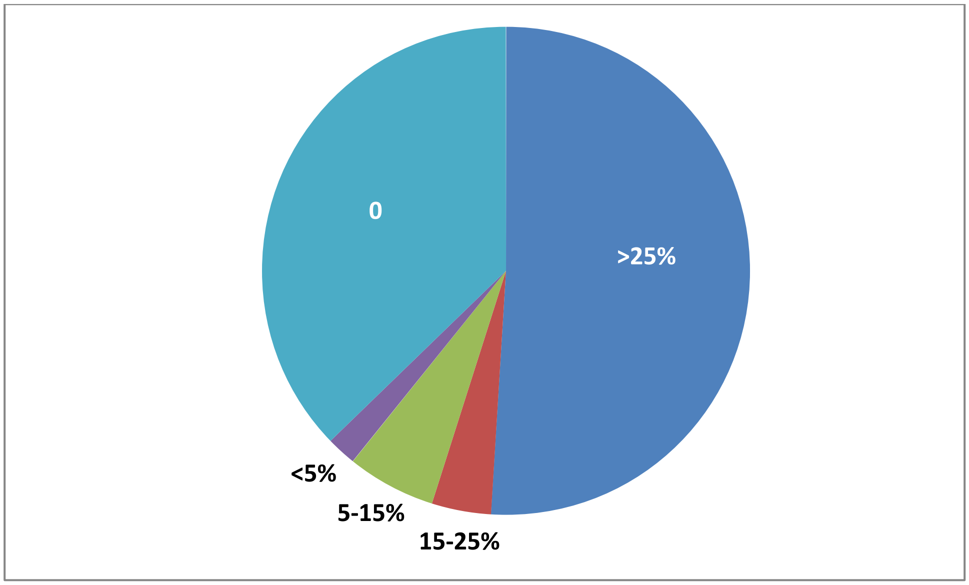

Figure 14. Peak-season shortage distribution: DFG-5 flows (climate change).

While the types of impacts are similar, their magnitudes with DFG-5 are much increased. For example, under more than 60% of hydrologic conditions, there will be a peak-season shortage. In fact, a shortage exceeding 25% can be expected in just over half the years.

Implications

The foregoing results highlight the importance of considering climate change as Santa Cruz plans for its water supply future. Even under the City's proposed HCP flows, which represent an upper bound on the streamflows that will likely be available for diversion and storage, water customers would have to contend with frequent shortages under this climate change scenario. If the outcome of the HCP negotiations are closer to the California Department of Fish and Wildlife's (CDFW's) DFG-5 proposal, the frequency and magnitude of shortages becomes much more onerous.

Thus with climate change, the City's water future will look qualitatively different. With historical flows, while there is a real possibility of large peak-season shortages, these are generally confined to the driest years with the large majority of conditions having no shortages. This is clearly not the case with climate change. Instead, significant shortages can be expected in many years. With DFG-5 flows, large shortages can be expected in the majority of years. The pattern of water availability to customers will be markedly altered.

References

Cayan, D., M. Tyree, M. Dettinger, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, N. Graham, and R. Flick. 2009. *Climate Change Scenarios and Sea Level Rise Estimates for the California 2009 Climate Change Scenarios Assessment.* California Climate Change Center publication CEC-500-2009-014-F. August. Available: http://tenaya.ucsd.edu/~cayan/New_Pubs/D20_Cayan_etal_2009.PDF. Accessed 1/5/2015.

Daniels, B.K. 2014. Hydrologic Response to Climate Change in California: Observational and Modeling Studies. Dissertation. Available: http://yourwaterfuture.org/BruceDaniels/Dissertation.pdf. Accessed 3/6/2015.

Hydrometrics. 2011. Estimation of Deep Groundwater Recharge Using a Precipitation-Runoff Watershed Model Soquel-Aptos, California. Available: http://www.soquelcreekwater.org/documents/reports/estimation-deep-groundwater-recharge-using-precipitation-runoff-watershed-model.

Flint, L.E. and A.L. Flint. 2012. Simulation of Climate Change in San Francisco Bay Basins, California: Case Studies in the Russian River Valley and Santa Cruz Mountains. U.S. Geological Survey Scientific Investigations Report 2012–5132. Available: http://pubs.usgs.gov/sir/2012/5132/. Accessed 7/22/2014.

Lukas, J., J. Barsugli, N. Dlesken, I Rangwala, and K. Wolter. 2014. *Climate Change in Colorado: A Synthesis to Support Water Resource Management and Adaptation.* Fourth edition. A Report for the Colorado Water Conservation Board. Western Water Assessment, Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado Boulder.

Available:
http://wwa.colorado.edu/climate/co2014report/Climate_Change_CO_Report_2014_FINAL.pdf. Accessed 3/12/2015.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen, 2002, A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States. *J. Climate* 15(22):3237–3251.