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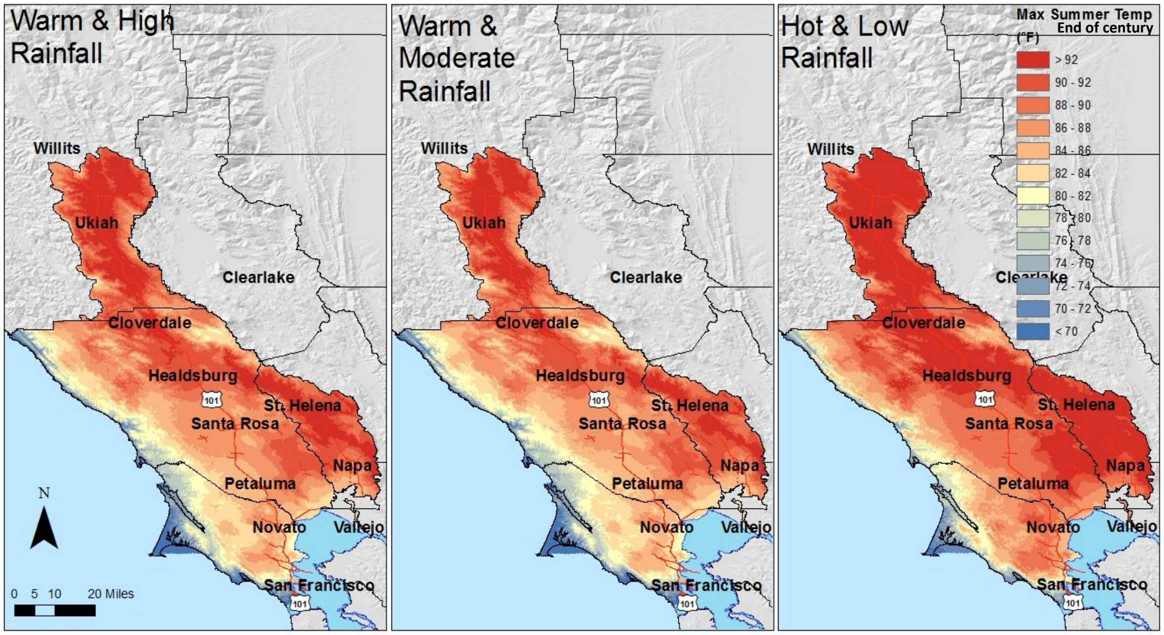
# Climate Ready North Bay
# Vulnerability Assessment Data Products

## Sonoma County Water Agency

January 2016



Elisabeth Micheli,* Lorraine Flint (USGS), Sam Veloz (Point Blue Conservation Science), Kelley (Higgason) Johnson* and Nicole Heller*
(*Dwight Center for Conservation Science at Pepperwood)

A Dwight Center for
Conservation Science

Technical Memorandum

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# Introduction

## What is Climate Ready North Bay?

To create a framework for adapting to climate change, decision-makers working in Northern California's watersheds need to define climate vulnerabilities in the context of site-specific opportunities and constraints relative to water supply, land use suitability, wildfire risks, ecosystem services, biodiversity, and quality of life (e.g. Mastreanda 2010, Ackerly et al. 2012). Working in partnership with the Sonoma County Regional Climate Protection Authority (RCPA) and the North Bay Climate Adaptation Initiative (NBCAI), Pepperwood's Terrestrial Biodiversity Climate Change Collaborative (see Chornesky et al. 2013, TBC3.org) has developed customized climate vulnerability assessments with select natural resource agencies of California's Sonoma, Marin, Napa and Mendocino counties via *Climate Ready North Bay*, a public-private partnership funded by the California Coastal Conservancy's Climate Ready program.

The goal of *Climate Ready North Bay* is to engage natural resource agencies, including water agencies, parks, open space districts, and other municipal users to collaboratively design climate vulnerability information products specific to their jurisdictions, mandates, and management priorities. With agency input guiding the development of the vulnerability assessments, spatially-explicit data products are now available to help local governments and agency staff implement informed and effective climate adaptation strategies. These products include customized maps, graphs, and summary technical reports tailored to site-specific resource management challenges, located within the watersheds illustrated in Figure 1.

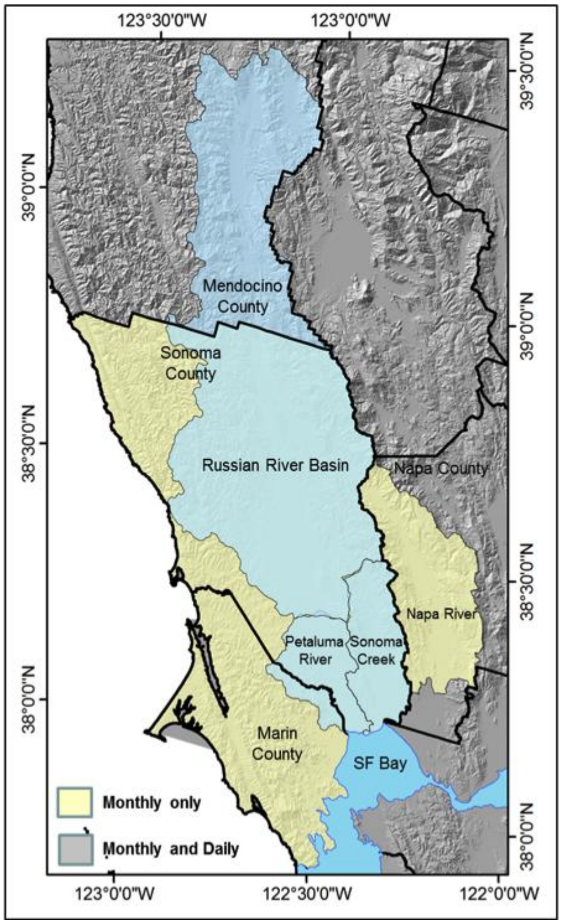


Figure 1: Map of study region, daily data domain (blue) monthly domain (blue plus yellow).

## Project Partners

*Climate Ready North Bay* is made up of a coalition of conservation leaders, land managers, decision-makers, and scientists all working together to better understand and address climate vulnerabilities to North Bay watersheds. Participating entities include: California Coastal Conservancy (funder); North Bay Climate Adaptation Initiative (partner); Sonoma County's Regional Climate Protection Authority (lead applicant): Sonoma County Water Agency (match funder and user), Regional Parks, and Agricultural Preservation and Open Space District (users); multiple Napa County departments (users); Marin Municipal Water District (user); and Mendocino Flood Protection and Water Conservation District (user). The core vulnerability assessment technical team consisted of Drs. Lisa Micheli (project manager) and Nicole Heller (Dwight Center for Conservation Science at Pepperwood), Dr. Lorraine Flint (USGS), and Dr. Sam Veloz (Point Blue Conservation Science). The project management team consisted of Lauren

Casey (Regional Climate Protection Authority), Caitlin Cornwall (NBCAI /Sonoma Ecology Center), Lisa Micheli, and Jay Jasperse and Chris Delaney (Sonoma County Water Agency).

## Technical Memorandum Overview

This technical memorandum summarizes the outcomes of engaging Sonoma County Water Agency in the *Climate Ready North Bay* collaboration to develop customized climate vulnerability assessment data products as a starting point for understanding potential climate stressors facing Sonoma County's water picture in the decades to come. A companion technical memorandum summarizes results for the North Bay region as a whole (see *Climate Ready North Bay: Regional Vulnerability Assessment Summary Technical Memorandum*). This memo summarizes Sonoma County Water Agency's jurisdictions and climate-related concerns, articulates key management questions, and provides highlights of sample data products co-created by managers and climate adaptation scientists in response to these questions. The Water Agency's management concerns with summarized data findings are grouped into three resource areas: 1) Water Resources (including rainfall, water supply, and drought); 2) Native Vegetation Response; and 3) Fire Risks. Appendices include a glossary, details on climate models, summary tables, and a list of data products generated and provided to the District and Parks. A companion PowerPoint deck is also provided that showcases sample data products and take home messages for the Sonoma County District and Parks use. (see *CRNB SCWA deck.ppt.* Appendix A summarizes data products co-created with managers and provided for adaption planning applications.

## Sonoma County Water Agency's Responsibilities and Jurisdictions

The Sonoma County Water Agency (SCWA) was created as a special district in 1949 by the California Legislature to provide flood protection and water supply services. Legislation enacted in 1995 added the treatment and disposal of wastewater to SCWA's responsibilities. SCWA is not a county department but a special district of the state, having specific limited purposes and powers, and separate sources of funding. SCWA is recognized as a national leader among water utilities in bringing cutting-edge science to bear on it's operations. It has been an active research partner of NBCAI's and the USGS for over five years within the realm of climate adaptation, and was a key advocate for this North Bay Climate Ready project as a whole.

The mission of SCWA is to effectively manage water resources for the benefit of people and the environment through resource and environmental stewardship, technical innovation, and responsible fiscal management. SCWA's key functions include: water supply to more than 600,000 residents in portions of Sonoma and Marin counties; sanitation services to over 22,000 residences and businesses; flood protection and stream maintenance for over 175 miles of creeks and waterways; environmental services related to compliance with environmental laws and regulations; production of highly treated recycled water; and ensuring transparency and communications with their community. SCWA environmental staff also works to improve the native fish resources of the Russian River and its tributaries by conducting and coordinating fishery enhancement projects. The Russian River is home to three fish that are threatened or endangered under the federal Endangered Species Act: coho salmon (endangered), Chinook salmon (threatened), and steelhead trout (threatened).

SCWA's main water sources are the Russian River, Lake Sonoma, and Lake Mendocino. The U.S. Army Corps of Engineers (Corps) owns and maintains the Coyote Valley Dam in Lake Mendocino and Warm Springs Dam in Lake Sonoma, as well as facilities for the Central Sonoma Watershed Project, which includes Spring Lake Reservoir, Matanzas Creek Reservoir, Piner Creek Reservoir, Brush Creek Middle Fork Reservoir, and Spring Creek Reservoir. SCWA controls releases to meet downstream demands and minimum instream flow requirements when reservoir levels are within the conservation pool. SCWA is also dedicated to maintaining the Laguna de Santa Rosa, a natural tributary to the Russian River that stores approximately 80,000 acre-feet of water during peak floods. In addition, SCWA manages Occidental, Russian River, Sonoma Valley, and South Park Sanitation Districts, and Airport/Larkfield/Wikiup, Geyserville, Penngrove, and Sea Ranch sanitation zones (SCWA 2015).

**Sonoma County Water Agency's Climate-related Concerns and Management Priorities**
Changes in climate impact SCWA operations on both short and long-term time scales. Short-term impacts include the immediate response necessary for acute demands of frost and heat events. The Corps is responsible for flood control, as well as resources needed for flood forecasting. Long-term impacts include a shift in priorities in planning that are now focused on building water supply reliability, largely as a result of the changes in transfer implemented via the 2004 amended Potter Valley Project (PVP) FERC license. Additionally, water supply in the Russian River basin is most sensitive to changes in springtime rainfall because the rule curve of Lake Mendocino prevents storing water needed for dry season demands until after March 1st of each year.

Currently SCWA does not have a drought definition based on climate indicators, but rather storage in Lake Mendocino is used as the indicator of available water, with drought severity evaluated relative to target reservoir levels. Due to the relatively small size and the seasonal rule curve of Lake Mendocino, it is the most sensitive component in the system to drought. SCWA has been required to seek emergency changes in operations of the Russian River System from the State Water Resources Control Board four times in the past five years due to low storage levels in Lake Mendocino. In addition, the hydrologic index determines the water supply condition of the Russian River System, but the current index is considered potentially outdated and not reflective of current available water. SCWA is actively working to update the hydrologic index, as storage and inflow thresholds defined in the Russian River System hydrologic index trigger changes in minimum in-stream flow requirements of the Russian River and Dry Creek.

Extreme events are of particular concern to SCWA, including strong atmospheric rivers, prolonged drought. Strong atmospheric rivers can cause extreme flooding to areas along the Russian River and its tributaries. Years with few or no atmospheric rivers have been linked to drought years. Due to the small size of Lake Mendocino and the amount of downstream demand, a two-year drought, such as experienced in1976 and 1977, can be very challenging to meet water needs. Frost events along the Russian River can cause sudden reductions in flow due to increased diversions from agriculture to protect crops from frost damage, but progress in recent years has been made on this issue via better coordination with upper Russian River landowners and the requirements to develop and implement Water Demand Management Plans. SCWA is also actively involved in the development of Basin Advisory Panels to create community-based plans for aquifer management in the Sonoma Valley and Santa Rosa Plain, and it is likely that SCWA will retain a meaningful groundwater management role with the advent of the recent statewide Sustainable Groundwater Management Act in concert with local water districts.

SCWA manages a number of resources and facilities that are particularly sensitive to climate during flood events or drought. Staff identified that Spring Lake and Matanzas Reservoirs, Wohler and Mirabel water diversion facilities, and the City of Santa Rosa downtown box culvert are all sensitive to flood events. In addition, flood control infrastructure is sensitive to increases in rainfall intensity.

Increased risk of fire associated with climate change is also a major concern because of potential impacts on water quality. In particular, the natural river bank filtration process that SCWA relies on to help ensure water quality could be compromised if inundated with high concentrations of ash and other post-fire erosion products.

### Potential Climate Ready Applications

SCWA is actively engaged in a number of long-term planning processes where climate ready data can be used. These are summarized below.

- SCWA Climate Adaptation Plan for Water Operations. A consultant has completed a climate adaptation work plan for the Water Agency to serve as the agency's roadmap for climate adaptation planning. Climate Ready results completed as part of this study will be used to inform the climate adaptation planning process.

- Forecast Informed Reservoir Operations (FIRO)-a collaborative effort with SCWA, Scripps, California Department of Water Resources, Bureau of Reclamation, USGS, NOAA, and the USACE.

- NIDIS-National Integrated Drought Information System-a collaborative effort with federal agencies and Scripps Institute of Oceanography.

- Fish Flow EIR. This project is being pursued as a requirement of the 2008 Biological Opinion issued by NMFS and entails modifying the Russian River hydrologic index and the minimum instream flow requirements to improve conditions for rearing salmonids and to improve water supply reliability of Lake Mendocino.

- Lake Mendocino Reliability Study. Term 17 of the May 2013 order from the State Water Resources Control Board requires the Water Agency to work with water users in the Upper Russian River to assess the long term reliability of Lake Mendocino with predicted changes in system demands.

- Groundwater aquifer planning in Sonoma Valley, Santa Rosa Plain and Petaluma Valley, including groundwater banking planning and site selection and compliance with the California Sustainable Groundwater Management Act.

- Flood Protection Planning. SCWA is in the process of creating updated flood control design criteria, which entails setting standards for mitigating stormwater runoff in cities.

- SCWA is partnering on a Climate Risk Dashboard project in concert with the Presidential Office of Science and Technology Policy that is evaluating the potential use of Climate Ready North Bay products for the Russian River as part of a “C-PREP” pilot.

## Stakeholder Engagement

Stakeholder engagement was a key component of the *Climate Ready North Bay* project. User groups included North Bay natural resource management agencies from the counties of Marin, Sonoma and Napa, and a group of staff from the cities and County of Sonoma charged with land use and infrastructure planning facilitated by Sonoma County’s Regional Climate Protection Authority’s Climate Action 2020 process. The vulnerability assessment team worked closely with these stakeholders through a series of in-person meetings, complemented by a survey prior to the first meeting, and additional correspondence and webinars between meetings.

A central goal throughout the process was to maintain an applied science focus by defining key management questions for each jurisdiction at the onset of the project, and then refining those questions throughout the project duration. Stakeholder meetings were held to jointly engage key managers and key vulnerability assessment analysts in an open dialogue that was facilitated by a project manager with training and experience in both arenas. The overall stakeholder engagement process included the steps listed below, with many allowances for feedback throughout.

- As part of the project kick-off and prior to the first meeting, administer a *Questionnaire for Managers* to start a dialogue about how current weather variability impacts agency operations and what their concerns about future change are (see Appendix C of the *Regional Vulnerability Assessment Summary Technical Memorandum*).

- At the first half-day meeting of all users, present the available range of climate futures (see *Selection of Future Climate Scenarios* below for more information on the 18 potential futures) and select one set of climate futures based on shared regional management concerns and jointly-defined criteria across user groups.

- At follow-up agency-specific scoping meetings (two hours minimum), showcase potential products in depth, answer questions in detail, and review results of the managers’ questionnaire to start collectively matching questions to data.

- As a follow up to the scoping meetings, draft an agency-specific scope of work for vulnerability data products that defines specific vulnerability metrics from the TBC3 knowledgebase of interest. Examples include: maximum and minimum temperatures, changes in water supply, degree of groundwater recharge, peak runoff and/or river discharge magnitude and frequency, drought frequency and intensity, drought stress (water deficit), changes in vegetation, and wildfire risk.

- Refine the scope based on refined management questions through iterative exchanges with users. Refinements may include time scale of data queries, revised jurisdictional boundaries, or comparisons of sites or time periods.

- Upon completion of the draft scope, the vulnerability assessment team generates products using computer models via a parallel process of in-person meetings, online coordination, and webinars.

- Present preliminary data products to user groups at a half-day meeting to review, discuss and refine through facilitated dialogue. Repeat if necessary.

- Finalize products for distribution, including production of technical memoranda and PowerPoint presentation materials.

- Scope opportunities for applications in the context of agency planning processes.

*Climate Ready North Bay's* extensive and iterative stakeholder engagement process can ideally inform technical groups in other regions working with local government and natural resource management agencies, providing a model of how to generate relevant information on climate change vulnerabilities in the context of land and water management. The North Bay approach was specifically commended in Deas (2015) as providing "…an opportunity for joint learning" as well as increasing functional access to what would have otherwise been a complicated data set by facilitating conversations between scientists and managers. A primary benefit of this project to managers was having direct access to the scientists who created the models, and therefore know the limitations of the data. In turn, the scientists learned about new dimensions of projected change that would not have been discovered without this collaborative exploration.

Slides 1-9 illustrate the project overview in the companion *CRNB SCWA deck.ppt.*

## Vulnerability Assessment Methods

### Selection of Future Climate Scenarios

The first *Climate Ready North Bay* regional stakeholder kick-off meeting was convened to select a consistent set of climate-hydrology "futures" based on regional management concerns. User groups were first introduced to a series of 18 Basin Characterization Model (BCM) downscaled future climate scenarios developed by the Terrestrial Biodiversity Climate Change Collaborative (TBC3) for the San Francisco Bay Area (Weiss et al. *in prep*). The climate futures included seasonal and annual climate and hydrology variables downscaled to 270-m grid cell resolution, derived from 18 of the approximately 100 Global Circulation Model (GCM) projections run under alternative future greenhouse gas emissions scenarios for both the 4th and 5th Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) (Meehl et al. 2007 Taylor et al. 2011). These 18 scenarios were selected via a statistical cluster analysis approach to find the minimum number of futures capable of capturing the full range of 100 peer-reviewed by the Intergovernmental Panel on Climate Change, IPCC (Weiss et al. *in prep*). See Appendix B for details on the 18 GCMs selected by TBC3 for downscaling.

Users representing all North Bay User Groups were provided a detailed introduction to the data using data visualizations (including a "climate space plot" showing each model's deviation from a common historic temperature and rainfall baseline) and explanatory tools. The users were then asked to help define a set of criteria (listed below) for selection of a final subset of climate futures.

- Is it a representative range of projected change that covers the full range of IPCC global scenarios and TBC3 Bay Area scenarios? The managers expressed a desire to focus on capturing the full range of temperature and rainfall scenarios for "business as usual" scenarios, and in particular wanted to capture the highest (Scenario 5) and lowest (Scenario 4) rainfall scenarios, in addition to the scenario that landed closest to the center (ensemble mean) of the full set of climate projections in terms of both rainfall and temperature change (Scenario 3). These three scenarios were intended to help bound the range of extreme conditions and capture "worst case scenarios." Capturing "mitigated" (significantly reduced emissions) scenarios was a lower priority than having a range of "business as usual" cases.

- Is the total number of scenarios reasonable to analyze? Since comparing and contrasting model outputs is labor intensive, a range of three to six scenarios was decided upon as reasonable for detailed comparative analyses. In combination with the other criteria, managers came to a consensus to analyze six scenarios total, with more emphasis placed on three that defined rainfall extremes plus a "central tendency" for the original set of 18 futures.

- Are scenarios realistic, do they have an equal likelihood of occurring? This discussion focused primarily on the reality of emissions scenarios, with the "super-mitigated" scenarios being judged less likely based on empirical emissions data. Managers agreed that they wanted multiple "business as usual" scenarios to compare, but also wanted to include at least one "mitigated" scenario to demonstrate the benefits of climate mitigation.

- Is it consistent with the State modeling efforts? The California Climate Change Technical Advisory Group was on a parallel track to select a set of IPCC models for statewide precipitation patterns for California's 4th Climate Assessment. To the extent feasible given that these projects were advancing in tandem, an effort to maximize the overlap between future state data products and *Climate Ready North Bay* products was made.

Through this facilitated dialogue, the user groups selected, by consensus, a subset of six future scenarios from which customized reports for the vulnerability assessments in Sonoma, Napa, Mendocino, and Marin counties would be developed (See below for a summarized list and *Appendix B: Selected Future Climate Scenarios)*.

Scenario 1: Low warming, low rainfall (mitigated emissions scenario) (GFDL-B1)
Scenario 2: Low warming, moderate rainfall (PCM A2)
Scenario 3: Warm, moderate rainfall (CCSM-4)
Scenario 4: Warm, low rainfall (GFDL-A2)

Scenario 5: Warm, high rainfall (CRNM-CM5)
Scenario 6: Hot, low rainfall (MIROC-ESM)

**Basin Characterization Model**

The climate vulnerability analyses were grounded in a watershed-based approach to assessing "landscape vulnerability," with a focus on climate-driven impacts to the hydrologic cycle. The vulnerability data products are based on the six future climate projections derived from a global set of projections peer-reviewed by the IPCC (Meehl et al. 2007; Taylor et al. 2011) described above. These global models were "downscaled" to increase their spatial resolution via a California statewide downscaling effort (Flint and Flint 2012). The USGS partners on this project analyzed the downscaled historical and projected temperature and precipitation data using the U.S. Geological Survey California Basin Characterization Model (BCM) (Flint et al. 2013; Flint and Flint 2014). The BCM models the interactions of climate (rainfall and temperature) with empirically-measured landscape attributes including topography, soils, and underlying geology. It is a deterministic grid-based model that calculates the physical water balance for each 18-acre cell (270m resolution) in a given watershed in set time steps for the entire area.

This approach enables a process-based translation of how climate interacts with physical geography to estimate local watershed response in terms of microclimate, runoff, recharge, soil moisture, and evapotranspiration. The BCM is capable of producing fine scale maps of climate trends as well as tabular time series data for a place of interest. For a detailed description of the BCM inputs, methods, and resulting datasets please see: *California Basin Characterization Model: A Dataset of Historical and Future Hydrologic Response to Climate Change: U.S. Geological Survey Data Release*. For a summary of BCM inputs, outputs and a glossary of terms, see Appendix C.

*The Climate Ready North Bay* project developed a customized BCM database for the North Bay region (Figure 1) extracted from the monthly California BCM and daily Russian River BCM (http://ca.water.usgs.gov/projects/reg_hydro/projects/russian_river.html). The California BCM uses a minimum time step of monthly results at the scale of a 270m grid, allowing the generation of scenarios at annual, seasonal, or monthly time steps. For *Climate Ready North Bay*, data was also extracted from a daily model for the Russian River to provide higher temporal resolution for evaluating potential extreme conditions within that geographic domain.

The monthly historical climate input data is downscaled from PRISM (Daly et al. 2008), and the daily data set includes historical data measured at weather stations from 1920–2010. The daily BCM model is extrapolated throughout the Russian River Basin using a method that is modified from that described in Flint and Flint (2012) in order to incorporate daily station data (Flint et al. *in prep*). Managers selected six future climate scenarios (described below) that provided a set of projections for the next 90 years (2010-2099). Data products derived include 30-year averages to delineate potential long-term trends in adherence with USGS recommendations. This allows comparison of three historic periods (1921-1950, 1951-1980—often referenced as a pre-climate change baseline, and 1981-2010—a period of assumed observed change) with three projected periods (2010-2039, 2040-2069, and 2070-2099). See Appendix D for a regional BCM output summary in 30-year time steps.

It is important to emphasize when describing BCM data products at a finer temporal resolution than the 30-y averages (such as decades, years, months or days), that unlike a weather forecast, the model does not generate *predictions* of precisely when climatic events will occur, but rather generates a physically-based time series of conditions for each scenario that is considered physically possible given the state of the science. By comparing results from a range of models, statistics can be used to describe a potential range of outcomes, but presently it cannot be determined which outcome is more likely to occur.

Navigating the necessarily *probabilistic* nature of climate data projections is perhaps one of the greatest challenges in applying these kinds of data products to real-world management issues. While managers wish we could simply provide the *most likely* outcome, for inland climate conditions, due to the uncertainty in how climate change will impact rainfall in our region, we need to facilitate consideration of multiple scenarios. Presently, in general all of the scenarios need to be considered as equally likely. In the literature this has been labeled a “scenario neutral” approach (Brown et al. 2012). This is why, moving forward, real-time climate-hydrology-ecosystem monitoring, akin to the Sentinel Site at Pepperwood’s Preserve, will be critical to understanding how climate impacts will unfold in the North Bay landscape (Micheli and DiPietro 2013, Ackerly et al. 2013).

In terms of spatial scale, the 18-acre resolution of BCM model pixels allows for aggregation of model results at spatial scales ranging from the North Bay region as a whole (the scale of this technical memorandum), to county boundaries and sub-regions (including watersheds, landscape units, service areas, and large parcels like parks). The vulnerability assessment team recommends that the model not be used to facilitate pixel-by-pixel comparisons, but rather be applied to minimum units ideally at the scale of sub-watershed planning units, or no smaller than parcels on the order of hundreds of acres.

The BCM’s direct outputs include potential changes in air temperature, precipitation (snow and rainfall, but for the North Bay only rainfall is significant), runoff, recharge, potential and actual evapotranspiration, and soil moisture storage. From these direct outputs, with additional analysis, derivative products can be generated that include climatic water deficit (the difference between potential and actual evapotranspiration—an indicator of drought stress and environmental water demand), water supply, and stream flow.

Climatic water deficit projections, including where deficits are projected to exceed the historical range of variability, estimate the combined effects of rainfall, temperature, energy loading and topography, and soil properties on water availability in the landscape. This is a useful indicator of landscape stress due to potential drought. The combination of runoff and recharge values together provide an indicator of variability in water supply (surface water and groundwater combined). Stream flow estimates require an additional step of accumulating flow and calibrating it to historical gage records. Projected stream flow time-series can be used to consider impacts on water supply, flooding risks, and aquatic and riparian resources.

As a result of the TBC3 initiative, climatic water deficit has been determined to be an excellent indicator of forest health, species composition, and fire risk. The secondary models described below for estimating trends in native vegetation composition and fire risks use this BCM output as a critical input in combination with soils, land cover, and other landscape metrics.

PowerPoint slides 16-20 in the companion *CRNB North Bay Region.ppt* illustrate the Basin Characterization Model methods.

**Climate Ready North Bay Projected Vegetation Model (PVM)**

Projected transitions in dominant vegetation types in response to future climates were modeled based on movement of the 'climate envelopes' occupied by each vegetation type. This analysis compares current vegetation cover that projected under mid- and end-century conditions for each of the six future climate scenarios. The model projects the equilibrium response of vegetation in response to future climates, assuming vegetation maintains currently observed distributions in relation to climate gradients, but is not able to predict how long it will take for these changes to unfold (i.e. decades vs. centuries) (Ackerly et al. 2015). Model results are summarized for the entire region and in selected "landscape units" (as defined by the Bay Area Open Space Council's Conservation Lands Network), and are presented in companion North Bay Climate Ready Vegetation reports.

**Fire Risk Model**

Statistical models of recent historical burning across the State, at a spatial resolution of 1080-m landscapes and a temporal resolution of 30 years (1971–2000) were combined with the BCM outputs (temperature, precipitation, potential evapo-transpiration, actual evapo-transpiration, and climatic water deficit) to determine how fire activity might change over time. North Bay Climate Ready futures used for this analysis include Scenarios 1, 2, and 4. Fire risk was modeled as the probability of burning occurring at least once within a given 30-year interval (2040-2069 and 2070-2099) or conversely, an estimated burn return interval. A metric of distance to human development is included in the model in order to estimate the additional influence of human access on fire risks (Krawchuk and Moritz 2012).

## Key Vulnerability Assessment Findings

- → *Rising temperatures across the region will generate unprecedented warm conditions for both summer and winter seasons*
- → *Rainfall is likely to be more variable in the future in term of both low and high annual extreme*
- → *The North Bay region is becoming more arid (subject to drier soil conditions) due to rising temperatures*
- → *Runoff may be increasingly flashy, with rates of groundwater recharge relatively less variable over time*
- → *Protecting available recharge areas will be critical to water supply sustainability*
- → *Water demand for agriculture may increase on the order of 10%*
- → *Fire frequencies are projected to increase on the order of 20%, requiring additional readiness planning and more aggressive fuels management*
- → *Vegetation may be in transition, meriting additional monitoring and consideration of a more drought-tolerant planting palette for restoration*

Key findings for the North Bay region include a unidirectional trend, regardless of total rainfall, towards increasing climatic water deficits across model scenarios. Therefore, managers will be facing an increasingly arid environment. Water supply indicators generally increase in variability across all scenarios, with the extreme scenarios ranging from approximately 25% greater to 25% less total rainfall, with direct implications for runoff, recharge, stream-flow and soil moisture. The climate suitability for vegetation types in the North Bay will favor drought-tolerant species, while fire risks are projected to double in especially fire prone regions. The combination of potential drought stress on water supplies and vegetation, with an approximate doubling of fire risks, should inform long-term adaptive management of natural resources. Working with agencies on potential Climate Ready North Bay product applications, strategies should build watershed resilience to drought with a focus on protecting groundwater recharge. Drought tolerance also needs to be promoted in forest, rangeland, and agricultural systems. More aggressive approaches to the reduction of forest fuel loads should be considered.

## Key Management Questions and Data Product Highlights by Resource Area

The description below is complemented by the *CRNB SCWA deck.ppt.* Relevant slide numbers are referenced at the close of each highlight section.

### **WATER SUPPLY**: NORTH BAY AND RUSSIAN RIVER PRECIPITATION

*Management Question: How may climate change impact the inter-annual variability of the North Bay region's rainfall?*

The future of rainfall quantity and variability for the North Bay region over the next century is perhaps the greatest uncertainty in efforts to project future conditions. Global models vary widely in their estimates of how climate change will impact rainfall patterns and quantity. This is because the potential effect of increased temperatures on the dynamic circulation of the oceans and atmosphere, which produces local weather, is not well understood in terms of mechanics. Therefore, some models estimate that for the North Bay region global warming will result in a major increase in available rainfall (Scenario 5), while others project little change (Scenarios 1, 2, 3), or moderate to major reductions (Scenario 4 and Scenario 6). Interestingly, for both mid-century and end-century values, projected changes in precipitation in the negative and positive directions essentially cancel each other out in the ensemble average, with no net average change in precipitation when the six models are averaged together. However, an examination of annual values underlying these long-term averages does show, in most projections, a trend of increasing variability in rainfall from year to year.

From 1951-1980 and 1981-2010, both the historic and current regional average rainfall was 43.0 inches per year. For 2040-2069, average annual rainfall is projected to span the range below.

*Scenario 3: Warm, moderate rainfall* - 42.1 in/year 2% less than the current average
*Scenario 5: Warm, high rainfall* - 53.6 in/year 25% greater than the current average
*Scenario 6: Hot, low rainfall* - 34.8 in/year 19% less than the current average

For 2070-2099, potential changes in average annual rainfall are projected to span the range below.

*Scenario 3: Warm, moderate rainfall* - 44.8 in/year 6% greater than the current average
*Scenario 5: Warm, high rainfall* - 57.9 in/year 35% greater than the historic/current average
*Scenario 6: Hot, low rainfall* - 33.9 in/year 21% less than the historic/current average

A comparison of extreme rainfall years in the North Bay region can be made using annual rainfall totals for the period of 1920-2009, including both high rainfall years likely to correspond with flood risks, and low rainfall years likely to correspond with drought risks (Table 2). This comparison shows that if an average is taken across the six projected futures, annual peak rainfall years (defined as exceeding the 90th percentile value of the 1920-2009 period) and low rainfall years (defined as less than the 10th percentile value of the 1920-2009 period) are projected to both increase on the order of 200% and 160%, respectively. However "worst case scenarios" in terms of high and low rainfall over 30-year periods correspond to more drastic increases in extreme events. For example, under the warm and high rainfall scenario, an approximate five-fold increase in high flood risk years is projected, while under low rainfall scenarios an approximate three-fold increase in potential drought years is projected.

Table 1. Change in frequency of annual rainfall extremes per decade, historic/current conditions (1920-2009) and six climate ready scenarios (2010-2099)

| ***Percent increase or decrease per decade*** | | | | **Annual Peaks (floods)** | | **Annual Lows (droughts)** | |
|---|---|---|---|---|---|---|---|
| **Scenario #** | **Model** | **Time Period** | **Name** | **>=1940 (69.1 in/yr)** | **>90th % (56.4 in/yr)** | **<10th % (27.1 in/yr)** | **<=1976 (15.9 in/yr)** |
| | Historic & Observed Change | 1920-2009 | | | | | |
| 1 | GFDL_B1 | 2010-2099 | Low warming, Low rainfall | 150% | 44% | 100% | -100% |
| 2 | PCM_A2 | 2010-2099 | Low warming, Mod rainfall | 200% | 156% | 89% | 200% |
| 3 | CCSM4_rcp85 | 2010-2099 | Warm, Mod rainfall | 150% | 111% | 11% | -100% |
| 4 | GFDL_A2 | 2010-2099 | Warm, Low rainfall | 50% | 11% | 156% | 200% |
| 5 | CNRM_rcp85 | 2010-2099 | Warm, High rainfall | 850% | 356% | -33% | -100% |
| 6 | MIROC_rcp85 | 2010-2099 | Hot, Low rainfall | -100% | -56% | 56% | 0% |
| | | | ***Average*** | ***217%*** | ***104%*** | ***63%*** | ***17%*** |

In general, for high and moderate rainfall scenarios, variability in annual precipitation and increases in standard deviations over 30-year means, increase in the future. Low rainfall scenario results in decreased high extremes, with slightly more frequent low rainfall years.

Slides 20-25 in the companion *CRNB SCWA deck.ppt* illustrate the discussion above.

### *Management Question: How will climate change impacts regional precipitation quantities for the Russian River Basin?*

Russian River estimates for long-term rainfall (30-y average) trends can be summarized as follows and are also displayed in Table 2 below.

From 1951-1980 the historic Russian River Basin average rainfall was 45.4 inches per year and from 1981-2010, the "current" Russian River Basin average rainfall was 45.9 inches per year. For 2040-2069, Russian River Basin average annual rainfall is projected as follows.
*Scenario 3: Warm, moderate rainfall* - 44.4 in/year 3% less than current
*Scenario 5: Warm, high rainfall* - 56.8 in/year 24% greater than current
*Scenario 6: Hot, low rainfall* - 37.5 in/year 18% less than current

For 2070-2099, Russian River Basin average annual rainfall is projected as follows.

*Scenario 3: Warm, moderate rainfall* - 47.3 in/year 7% greater than current average
*Scenario 5: Warm, high rainfall* - 61.0 in/year 33% greater than current
*Scenario 6: Hot, low rainfall* - 37.0 in/year 19% less than current

Table 2. Basin Characterization Model outputs for the Russian River Basin, 1951-2099, 30-y averages

**Regional Statistics for Russian River Basin**

| | | Historical | Current | Moderate Warming, High Rainfall | | Moderate Warming, Moderate Rainfall | | Hot, Low Rainfall | |
|---|---|---|---|---|---|---|---|---|---|
| Variable | Units | 1951-1980 | 1981-2010 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 |
| Precipitation | in | 45 | 46 | 57 | 61 | 44 | 47 | 38 | 37 |
| Winter minimum temp | Deg F | 44.4 | 45.3 | 48.8 | 51.6 | 48.1 | 50.9 | 50.2 | 53.8 |
| Summer maximum temp | Deg F | 71.2 | 70.9 | 74.8 | 78.9 | 74.3 | 77.0 | 76.6 | 80.4 |
| Climatic water deficit | in | 27 | 28 | 29 | 31 | 30 | 30 | 31 | 33 |
| Recharge | in | 17 | 17 | 21 | 21 | 18 | 17 | 13 | 15 |
| Runoff | in | 19 | 20 | 33 | 37 | 20 | 23 | 13 | 14 |

| | | | Change from Current | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Current | Moderate Warming, High Rainfall | | Moderate Warming, Moderate Rainfall | | Hot, Low Rainfall | |
| Variable | Units | 1981-2010 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 |
| Precipitation | in | 46 | 24% | 33% | -3% | 3% | -18% | -19% |
| Winter minimum temp | Deg F | 45.3 | 3.5 | 6.3 | 2.8 | 5.6 | 4.9 | 8.5 |
| Summer maximum temp | Deg F | 70.9 | 3.9 | 8.1 | 3.4 | 6.1 | 5.7 | 9.5 |
| Climatic water deficit | in | 28 | 4% | 9% | 6% | 9% | 11% | 18% |
| Recharge | in | 17 | 25% | 25% | 7% | 3% | -20% | -13% |
| Runoff | in | 20 | 64% | 83% | 1% | 18% | -32% | -31% |

We conducted this analysis individually for the "upper" and "lower" basins to compare results, which were not significantly different from the whole basin average, per below.

Table 3. Comparison of projected precipitation for upper and lower basins of Russian River

| | | Lower River Precipitation | | Upper River Precipitation | |
|---|---|---|---|---|---|
| Climate | Years | in/yr | % change from current | in/yr | % change from current |
| Historic | 1951-1980 | 46 | | 46 | |
| Current | 1981-2010 | 47 | | 45 | |
| | | | | | |
| Moderate Warming, | 2040-2069 | 57 | 23 | 56 | 25 |
| High Rainfall | 2070-2099 | 62 | 33 | 60 | 33 |
| | | | | | |
| Moderate Warming, | 2040-2069 | 45 | -4 | 44 | -2 |
| Moderate Rainfall | 2070-2099 | 48 | 3 | 47 | 3 |
| | | | | | |
| Hot, Low Rainfall | 2040-2069 | 38 | -19 | 38 | -17 |
| | 2070-2099 | 37 | -21 | 37 | -18 |

Slides 26-31 illustrate the project overview in the companion *CRNB SCWA deck.ppt.*

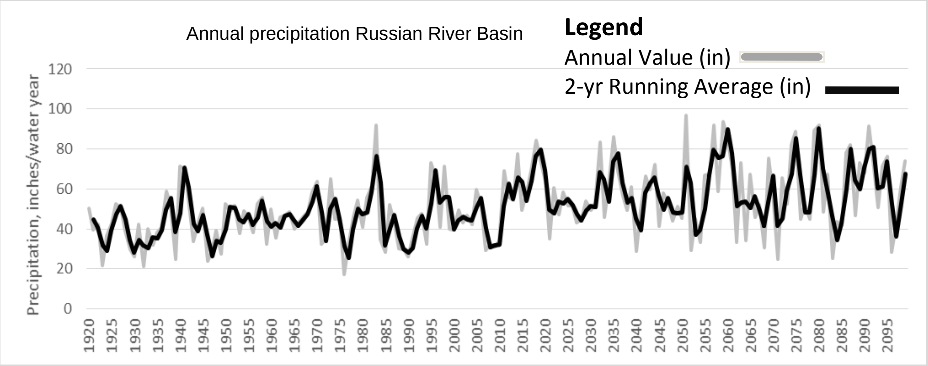
## **WATER SUPPLY**: RUSSIAN RIVER BASIN RUNOFF

*Management Question: How will climate change impact annual and spring precipitation variability in the Russian River Basin, and in turn, winter and dry season runoff?*

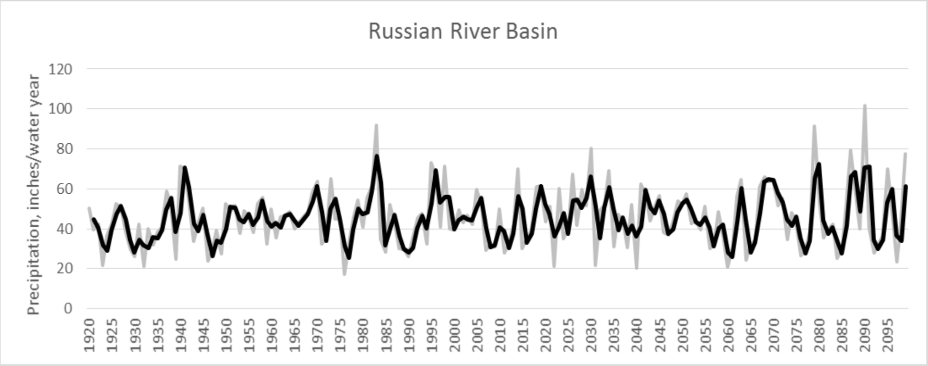
Russian River basin annual trends for precipitation and runoff were completed for annual rainfall and key runoff seasons. We used the BCM to estimate precipitation as a 2-year running average. The 2-year running average for annual precipitation ranged from a low of 37 in/y (hot, low rainfall) to 61 in/y (warm, high rainfall) compared with the 1981-2010 average of 46 in/y (see Figure 2 below). Annual runoff varied to the same degree

Figure 2. Variability in Russian River basin annual precipitation, 1920-2099, three scenarios

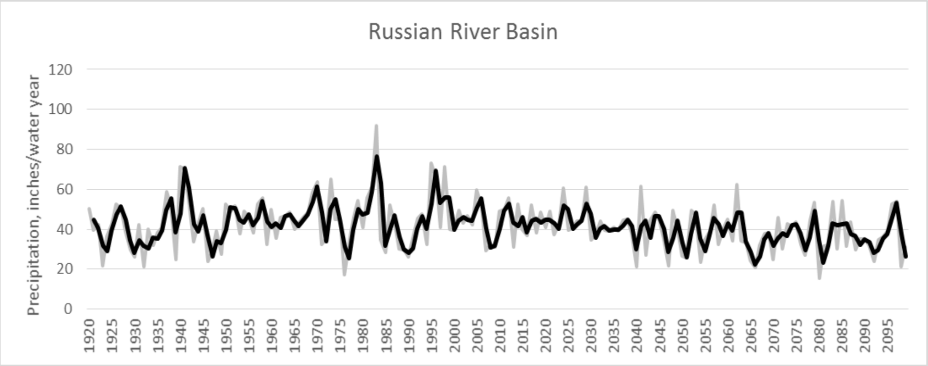
Warm &
High Rainfall



Warm &
Moderate Rainfall

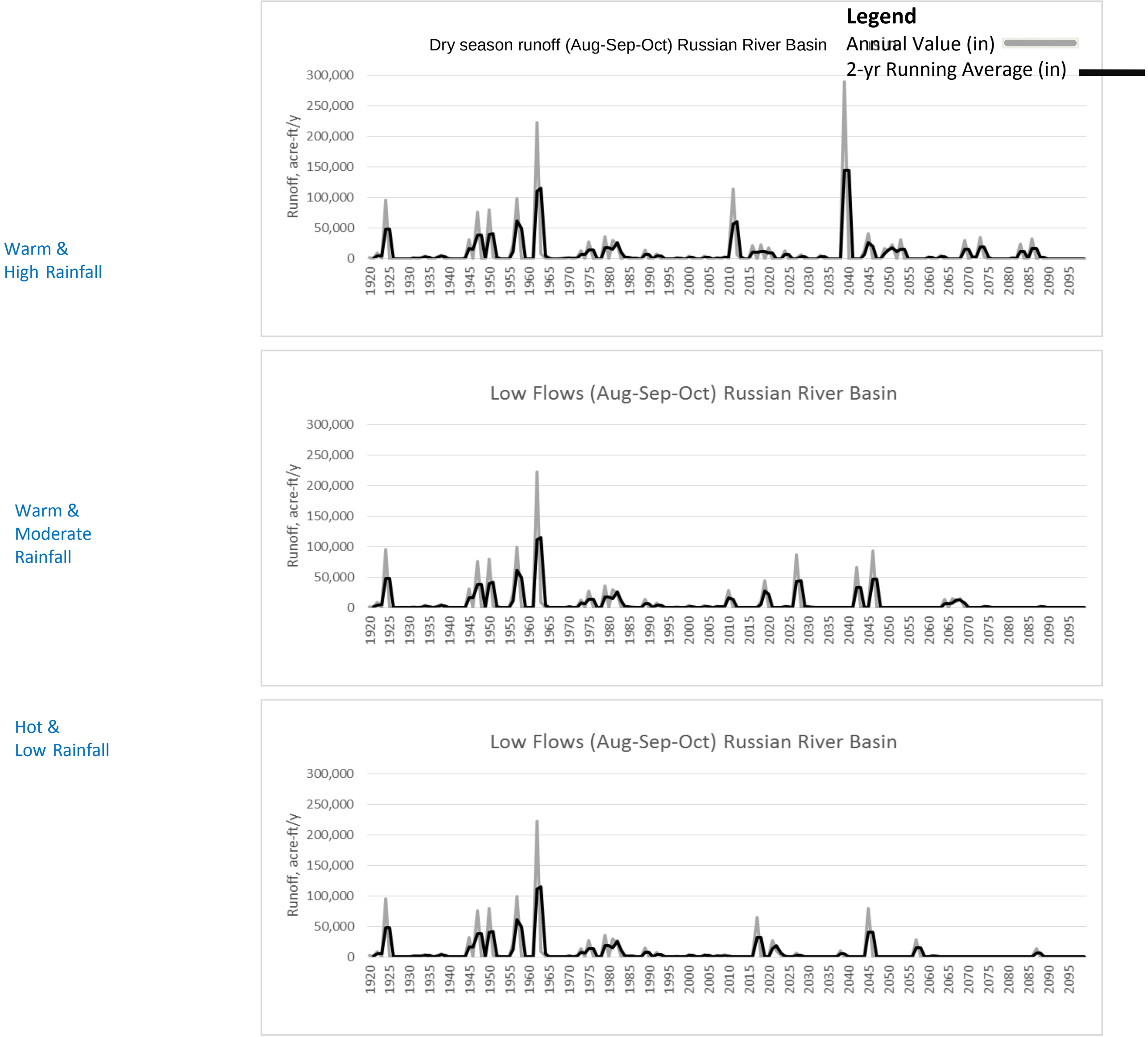


Hot &
Low Rainfall



March precipitation did not vary significantly across futures (with a range of 5.2-6.1 in/mo compared to a historic average of 5.6 in/mo) Dry season (August through October) runoff proved the most sensitive variable in this group to climate change, with reductions in all scenarios (ranging from a cumulative discharge of 1204 af/year for the low rainfall to 4253 af/year for the high rainfall scenario) compared to the 1920-2010 average value of 4423 af/year (see Figure 3 below).

Figure 3. Variability in Russian River basin annual dry season runoff, 1920-2099, three scenarios



Slides 31-36 in the companion *CRNB SCWA deck.ppt* illustrate the discussion above.

**WATER SUPPLY**: RESERVOIR WATERSHED CONDITIONS

*Management Question*: *How will annual precipitation variability in the Russian River Basin in turn impact supply via surface sources for specific reservoir basins?*

For Lake Mendocino the following attributes were calculated and plotted for annual and two-year running average time steps (three scenarios, 1920-2099): total annual precipitation and runoff and spring annual precipitation and runoff. Reservoir specific watershed precipitation was also calculated and plotted for Lake Sonoma and Lake Pillsbury (three scenarios, 1920-2099). Although there are increases in the annual variability in the future for the high and moderate rainfall scenarios with a decrease in variability for the dry scenario, this isn't true for spring precipitation, where all scenarios are similar in the future. When translated into spring runoff, the low rainfall scenario is slightly higher than the other scenarios. Winter runoff is what really distinguishes the scenarios from each other as changes in seasonality tend to concentrate precipitation more in the winter; the corresponding runoff coincides with the high, moderate, and low rainfall scenarios.

Slides 37-44 in the companion *CRNB SCWA deck.ppt* illustrate the discussion above.

*Management Question*: *How will climate change impact the seasonality of annual rainfall in the Lake Mendocino basin?*

A comparison of the three "bounding" scenarios does not indicate significant changes in seasonality of average rainfall for the Lake Mendocino watershed by mid-century. We do observe that in the high rainfall scenario, the additional rainfall is concentrated in mid-winter months (Dec-Feb). In the low rainfall scenario, there are reductions in rainfall in Nov-Dec. However across scenario, there is increased variability in monthly rainfall for all scenarios, notably the moderate and high rainfall scenarios.

Slides 45-47 in the companion *CRNB SCWA deck.ppt* illustrate the discussion above.

**RUSSIAN RIVER FLOW:** FLOOD RISKS

A daily model for the Russian River was created using a subset of Climate Ready scenarios, including Scenario 1-mitigated low warming, low rainfall (GFDL B1), Scenario 2-low warming, moderate rainfall (PCM A2), Scenario 4-warm, low rainfall (GFDL A2), plus a mitigated low warming, moderate rainfall scenario (PCM A2). A more complete explanation of the daily model and calibrations can be found at: *http://ca.water.usgs.gov/projects/reg_hydro/projects/russian_river.html* (Flint et al., 2015). It should be noted this daily model does not include the extreme high and low rainfall scenarios (defined based on 30-y average values) of the complete Climate Ready set, and thus these estimates for daily average values will likely underestimate the range compared to Scenario 5-warm, high rainfall (CRNM-CM5) and Scenario 6-hot, low rainfall (MIROC-ESM).

*Management Question: How might climate change increase the risk of flooding in the Russian River Basin?*

An analysis of three day periods of high flow showed that these events are up to three times more likely to occur under the projected climate change scenarios than today. Table 3 below summarizes this analysis in units of exceedances per decade of the 99.9% exceedance threshold which is 19,298 cfs threshold for upper river (represented by the Healdsburg gage) and 38,902 cfs threshold for lower river(represented by the Guerneville gage).

Figure 4. Three-day high flow events per decade on the Russian River estimated at Healdsburg and Guerneville gages, 2001-2099

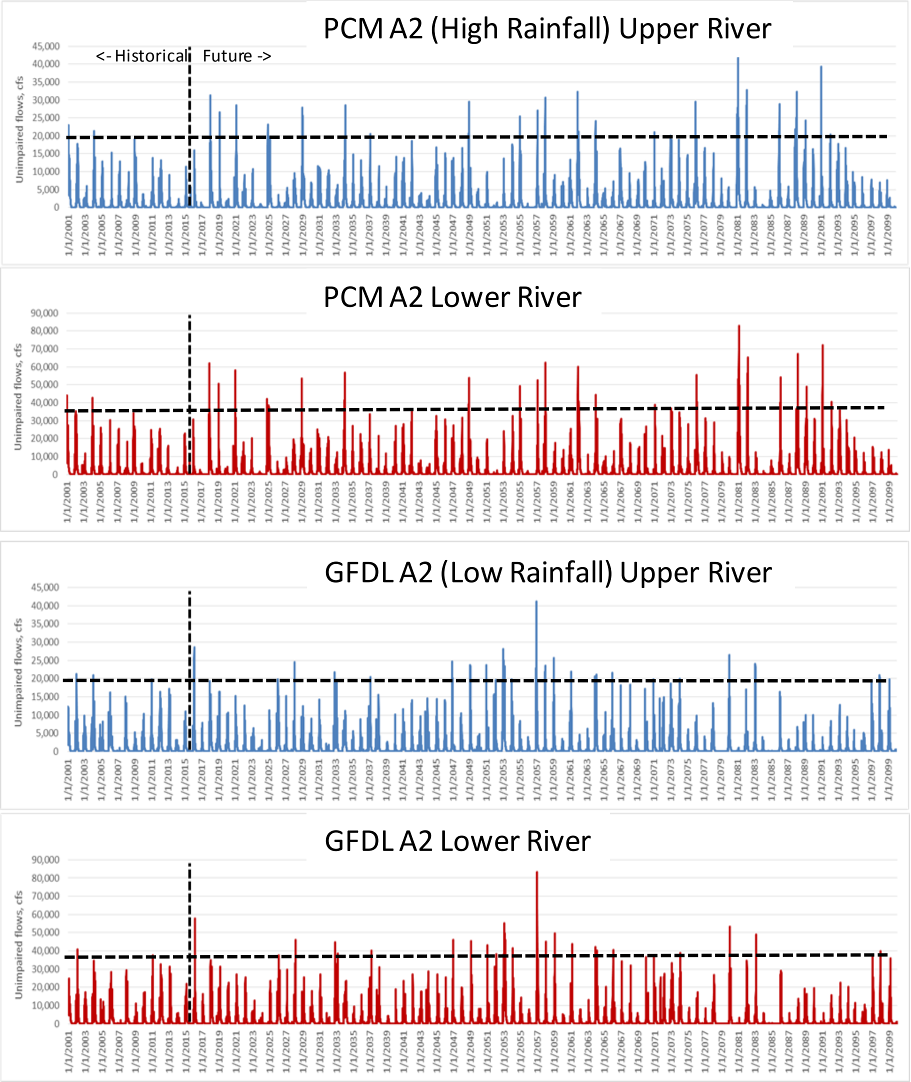


Table 3. Summary of frequency of three-day high flow events per decade on the Russian River estimated at Healdsburg and Guerneville gages .

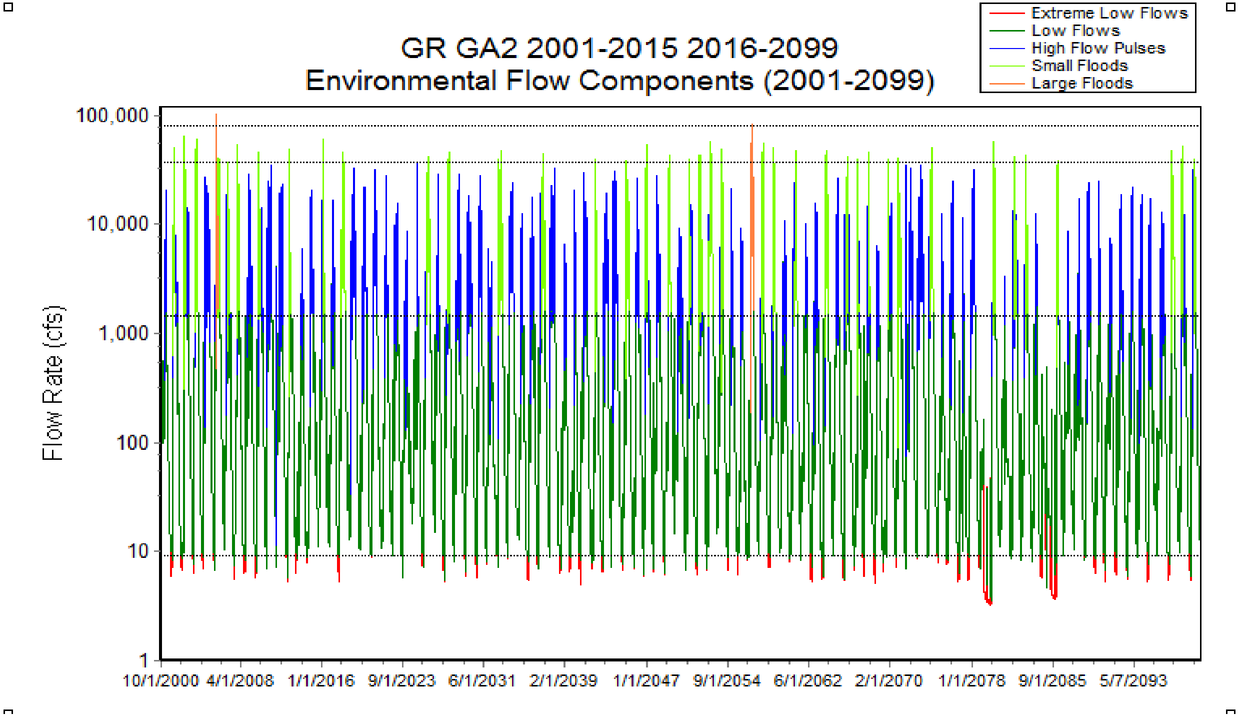
| | Upper River: Healdsburg | | Lower River: Guerneville | |
|---|---|---|---|---|
| | Current (2001-15) | Future (2016-99) | Current (2001-15) | Future (2016-99) |
| *Business-as-usual* | | | | |
| PCM A2 | 1.3 | 3.9 | 1.3 | 3.6 |
| GFDL A2 | 2.0 | 3.6 | 0.7 | 3.3 |
| *Mitigated* | | | | |
| PCM B1 | 4.0 | 4.8 | 3.3 | 4.6 |
| GFDL B1 | 2.0 | 3.7 | 1.3 | 3.6 |

### *Management Question: How might the effect of climate change on flows impact the value of the Russian River for fisheries?*

The daily flow model can use used to calculate environmental flow thresholds using an Indicators of Hydrologic Alteration software package available at the following link: (http://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/IndicatorsofHydrologicAlteration/Pages/indicators-hydrologic-alt.aspx; (Richter et al., 1996).

Key attributes for consideration include large (2-10 year return interval) and small (1-year return interval) floods, high flow pulses (5% exceedance threshold), low flows (95% exceedance threshold), and extreme low flows (the lowest 10% of low flows per definition above). The graph below color codes each of these values over the 2001-2099 period, with an increased frequency over time of both high and low flow events.

Figure 5. Environmental flow components, Russian River, 2001-2099



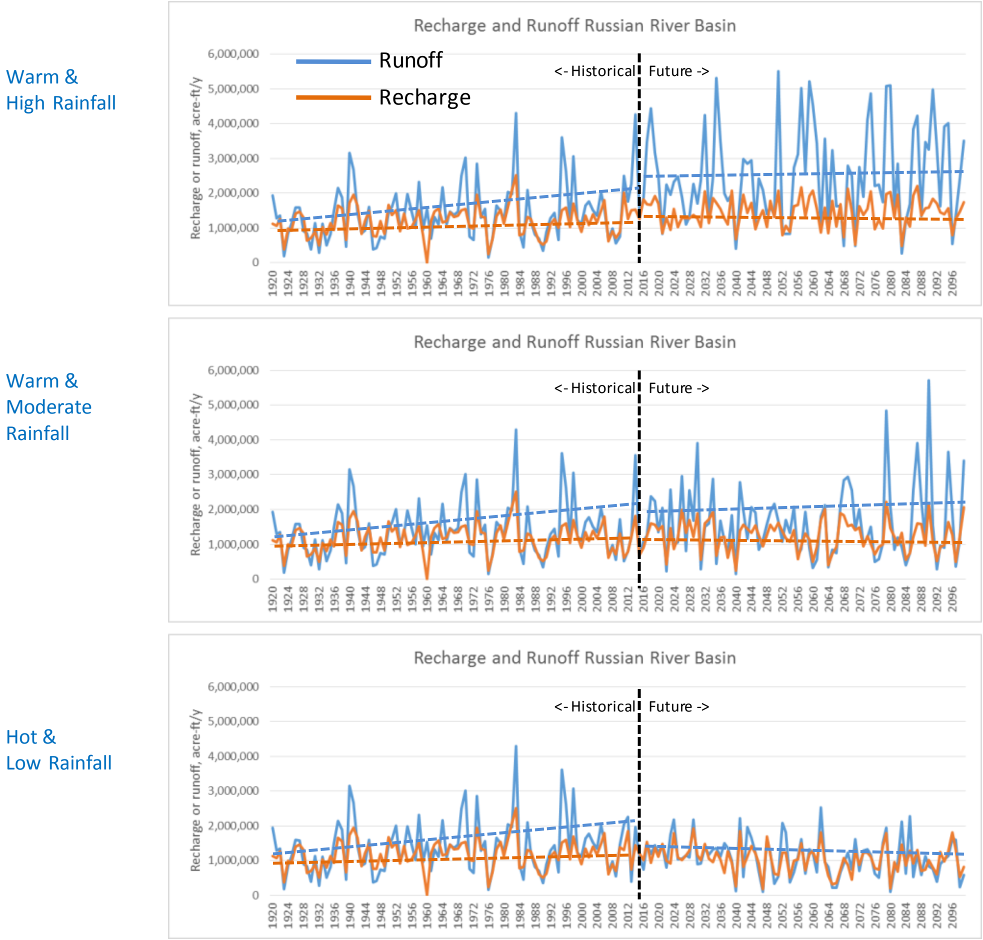
Daily flow data was also used to look at the potential shift in the date of onset of minimum low flow conditions between a reference period of 2001-2015 and a projected period of 2016-2099. This analysis showed that for Scenario 2-low warming, moderate rainfall (PCM A2) the onset of low flow occurred 5-10 days earlier than the reference period, while for Scenario 4-warm, low rainfall (GFDL A2) the onset was approximately 10+ days earlier. This suggests an extension of the low flow season, with an earlier onset of minimum flows, is projected with climate change.

Slides 40-47 in the companion *CRNB SCWA deck.ppt* illustrate the discussion above.

**WATER SUPPLY**: GROUNDWATER RECHARGE *Management Question: What is the relationship of annual recharge relative to annual runoff?*

One outcome of these Climate Ready analyses was the realization that based on an assessment of unimpaired flows, our water balance methods suggest that recharge is a less variable source of potential water supply than surface runoff. (This analysis does not address any recharge enhancement potentially resulting from sustained dry season flow releases.) Figure 4 below shows that historic average annual recharge volumes from 1920-2009 for recharge was 1.36 Maf/year while average annual runoff was 1.86 Maf/year.

Figure 6. Annual runoff and recharge (Maf/year), Russian River Basin, three scenarios



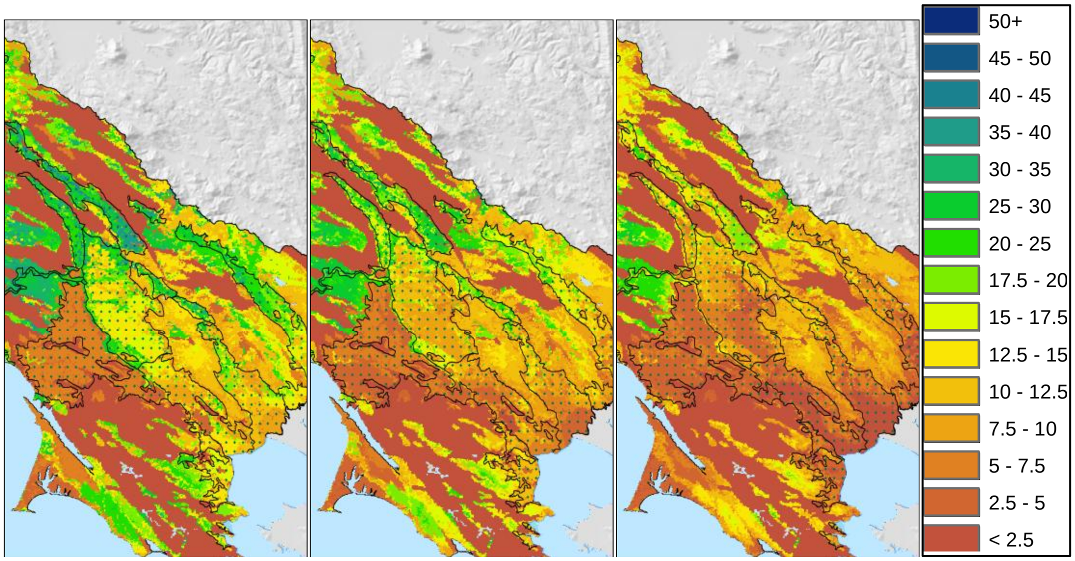
Future values (2010-2099) for runoff ranged from 1.49-3.38 Maf/year, while future values for recharge ranged from 1.19-1.79 Maf/year. Thus while the total recharge volume is generally a lower value from year to year relative to runoff, it is a much less variable source of water supply.

Slides 56-58 in the companion *CRNB Sonoma County Water Agency.ppt* illustrate the discussion above.

*Management Question: What is the spatial variability of runoff and potential groundwater recharge and how might climate change impact these distributions?*

The BCM generates a variable representation of recharge rates across the study area as shown in Figure 7 below. These maps can be used to identify relatively high value recharge zones for long-term planning of recharge protection strategies. Figure 7 also shows CA Department of Water Resources designated aquifers that will be subject to the 2015 CA Sustainable Groundwater Management Act.

Figure 7. Lower Russian River basin, projected recharge 2070-2099 (inches/year), three scenarios. DWR groundwater basins are shown as stippled polygons

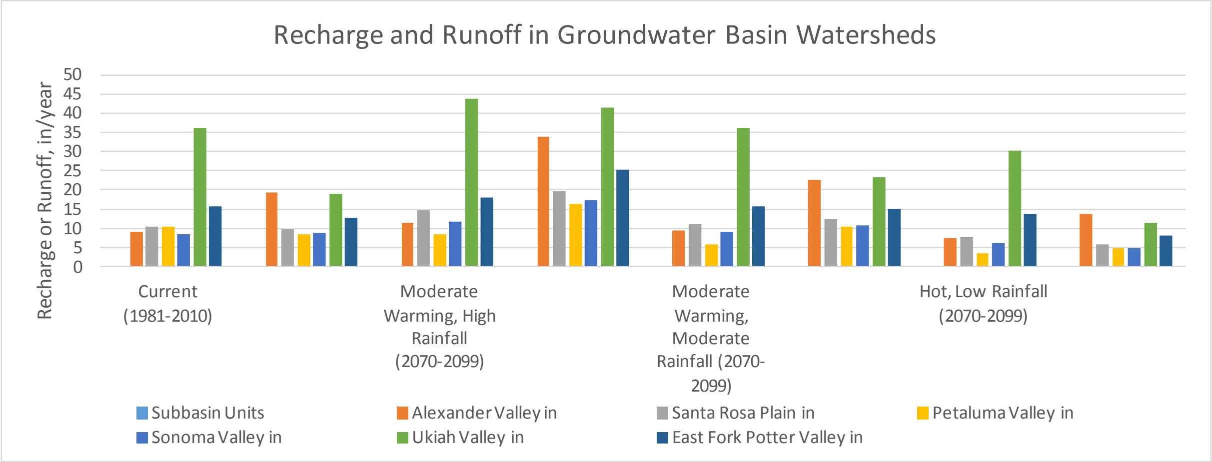


Recharge and runoff values for the SCWA service area can be summarized by individual valleys and basins per Table 4 and Figure 8 below. Recharge values for the 1981-2010 reference period range from 9.1 inches per year in the Alexander Valley to 36.1 inches per year in the Ukiah Valley (see Table 4).

Table 4. Summary of current and projected runoff and recharge values by valley unit, Sonoma County Water Agency jurisdiction, 1981-2099

| | | Current (1981-2010) | | Moderate Warming, High Rainfall (2070-2099) | | Moderate Warming, Moderate Rainfall (2070-2099) | | Hot, Low Rainfall (2070-2099) | |
|---|---|---|---|---|---|---|---|---|---|
| Subbasin | Units | Recharge | Runoff | Recharge | Runoff | Recharge | Runoff | Recharge | Runoff |
| Alexander Valley | in | 9.1 | 19.4 | 11.6 | 33.8 | 9.5 | 22.6 | 7.5 | 13.8 |
| Santa Rosa Plain | in | 10.5 | 9.8 | 14.6 | 19.8 | 11.2 | 12.3 | 7.9 | 5.9 |
| Petaluma Valley | in | 10.6 | 8.5 | 8.4 | 16.5 | 5.9 | 10.3 | 3.5 | 4.8 |
| Sonoma Valley | in | 8.6 | 8.8 | 11.9 | 17.3 | 9.0 | 10.8 | 6.2 | 4.9 |
| Ukiah Valley | in | 36.1 | 18.9 | 43.8 | 41.4 | 36.2 | 23.3 | 30.2 | 11.3 |
| East Fork Potter Valley | in | 15.7 | 12.7 | 18.1 | 25.2 | 15.6 | 14.9 | 13.6 | 8.2 |

Figure 8. Current and projected recharge and runoff by groundwater basin, SCWA geographic jurisdiction

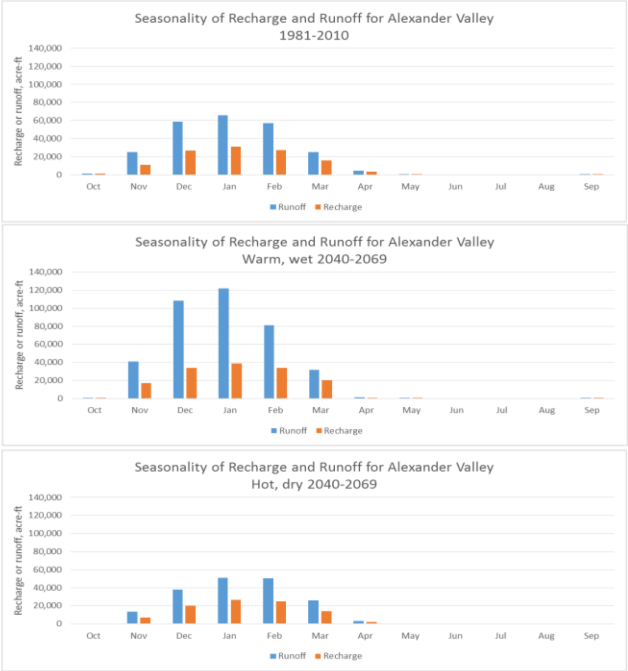


Slides 61-67 in the companion *CRNB Sonoma County Water Agency.ppt* illustrate the discussion above.

*Management Question: What is the relative seasonal variability of runoff versus recharge in key basins of interest?*

30-year averages for monthly values recharge and runoff were calculated for the Alexander Valley to see if the seasonality of available water would be significantly impacted under a range of climate change scenarios.

Figure 9. Seasonality of recharge and runoff for Alexander Valley, current vs two future scenarios



Slides 68-69 in the companion *CRNB SCWA deck.ppt* illustrate the discussion above.

## **WATER SUPPLY:** ENVIRONMENTALLY-DRIVEN DEMAND

*Management Question: How will climate change influence the frequency and intensity of heat events that trigger big upticks in demand for irrigation?*

The daily model projects a significant increase in the total number of high heat days in the Santa Rosa Plain during the summer season. SCWA requested assessment of how many 3-day windows would exceed critical heat thresholds of 95 and 100 °F. The table below shows the average number of 3 day heat events across projected daily futures. This suggests the potential for an up to 6-fold increase in the number of heat events by century's end under business as usual emissions.

Figure 10. Three-day heat waves, Santa Rosa Plain, 1981-2099, four scenarios

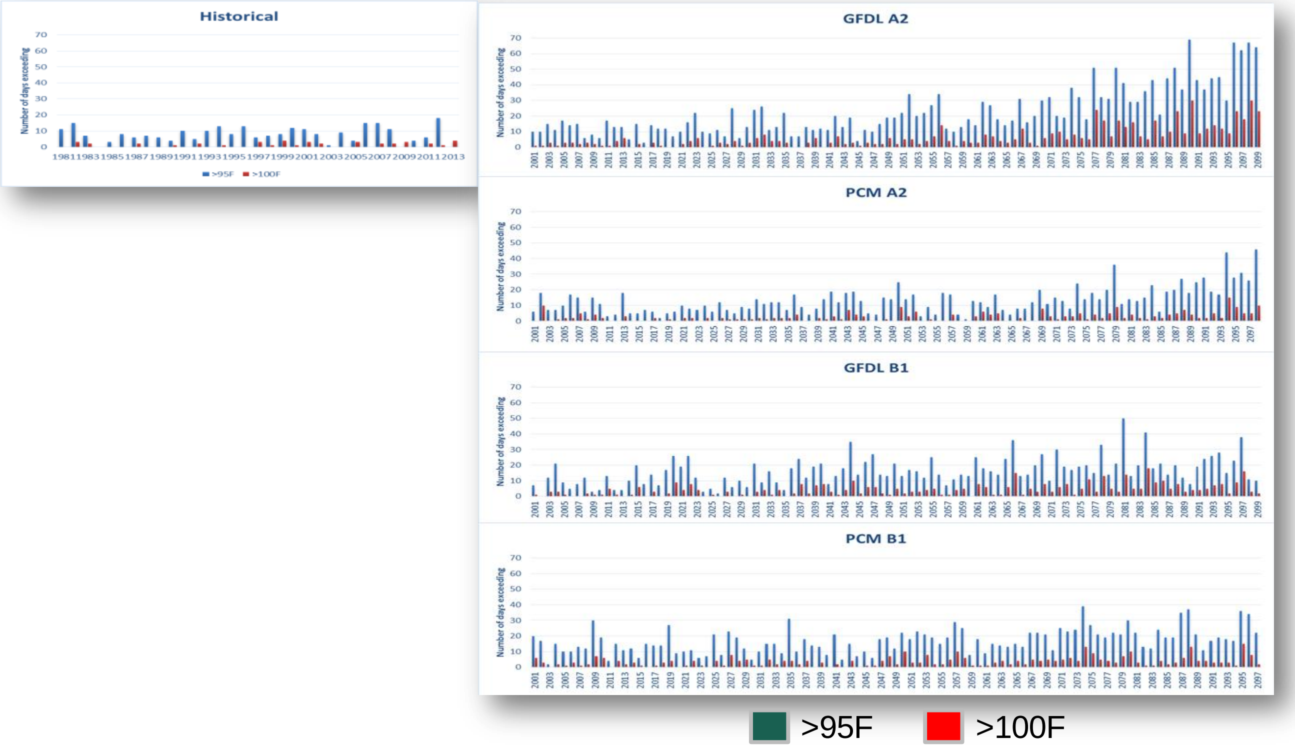


Table 5. Extreme heat days, Santa Rosa Plain, current vs 3 future time steps

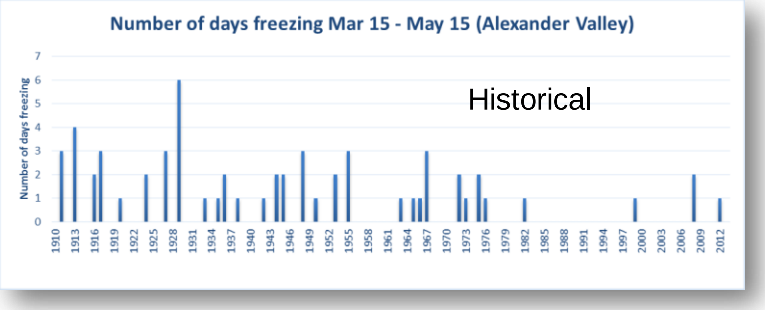
| | # of events | Tmax | Tmin |
|---|---|---|---|
| 1981-2010 | 26 | 95.7 | 93.4 |
| 2010-2039 | 39 | 96.5 | 93.3 |
| 2040-2069 | 55 | 96.4 | 93.5 |
| 2070-2099 | 148 | 97.3 | 93.5 |

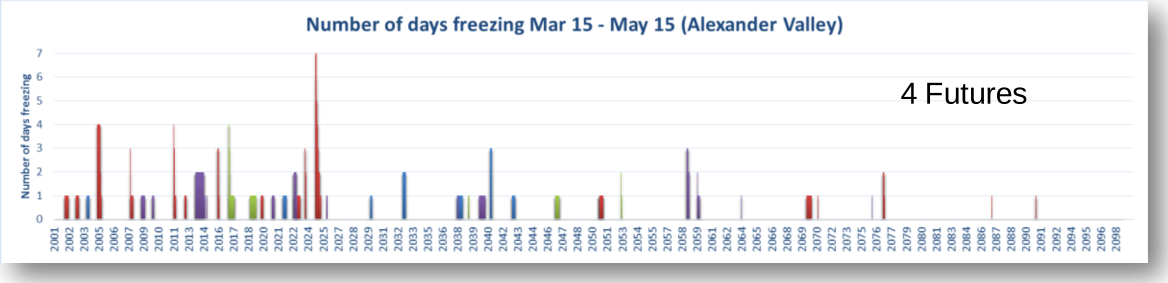
*Management Question: How will climate change influence frost frequency, and in turn, demand for frost protection in agricultural zones?*

The daily model projects a significant reduction in the total number of frost days in the Alexander Valley during the season defined by February through April-May. The table below shows a reduction on the order of 20% in the number of frost days by century's end, with an 80% reduction in total April frost days on average. We note that these results are an average for the valley, and does not account for cold air pools that may intensify cooling effects.

In terms of water supply, this may reduce demand for pumping for frost protection in vineyards in the years to come. There may also be significant impacts to agricultural crops that need chilling hours, like stone fruits, to set fruit. There may also be impacts on the life cycle of pests and vectors that would otherwise be controlled by frost conditions.

Figure 11. Number of springtime days at or below freezing, Alexander Valley, 1910-2099, four scenarios





*PCM wet model, GFDL dry model*

Slides 68-74 in the companion *CRNB SCWA deck.ppt* illustrate the discussion above.

Table 6. Frequency of springtime days at or below freezing, Alexander Valley

| | Historic 1981-2010 | | |
|---|---|---|---|
| | February | March | April |
| | 52 | 8 | 5 |
| | | | |
| | Future 2040-2069 | | |
| | February | March | April |
| PCM A2 | 38 | 5 | 1 |
| GFDL A2 | 25 | 5 | 1 |
| PCM B1 | 87 | 11 | 1 |
| GFDL B1 | 24 | 6 | 1 |
| average | 44 | 7 | 1 |
| | | | |
| | Future 2070-2099 | | |
| | February | March | April |
| PCM A2 | 24 | 3 | 0 |
| GFDL A2 | 18 | 4 | 0 |
| PCM B1 | 34 | 7 | 0 |
| GFDL B1 | 31 | 6 | 1 |
| average | 27 | 5 | 0 |

*Management Question: How might climate change influence the magnitude of landscape drought stress, estimated as climatic water deficit, across the Russian River basin? Where are the regions where this effect is mitigated by present day fog distributions?*

As an attribute of the landscape that integrates the combined effects of available rainfall, temperature, and watershed structure, climatic water deficit takes into account available water, heat exposure, and soil/geology water storage potential to estimate where and by how much potential evapotranspiration exceeds actual evapotranspiration. This term can be thought of as a measure of drought stress, or an estimate of how much more water the landscape would have used had it been available. It captures the effect of limited soil storage to meet evapotranspiration demand.

An important aspect of climatic water deficits is that, in comparison to rainfall for example, all of the future scenarios project a uni-directional trend in water deficits into the future. Climatic water deficit in the Russian River basin is projected to increase even in high rainfall scenarios. From 1981-2010, the current average climatic water deficit for the Russian River was an average of 27.9 inches per year per unit area. By the mid-century, water deficits are projected to increase from 4-11%, with an average 7 % increase across scenarios. By the end of the century, a range of 9-18% greater water deficit, with an average increase of 12% across all scenarios, is projected. Fog could potentially offset these rises, but because future fog patterns are so uncertain, its influence on future climatic water deficit is also uncertain. However we show the overlap of a USGS fog frequency map to show regions where today fog is effectively mitigating deficits.

From 2040-2069, the range of potential change in climatic water deficit is projected as follows.

*Scenario 3: Warm, moderate rainfall* - 29.7 in/y (with 44.4 in/y rainfall), 4% greater deficit than current average

*Scenario 5: Warm, high rainfall* - 29.0 in/y (with 56.8 in/y rainfall), 4% greater deficit than current average

*Scenario 6: Hot, low rainfall* - 31.0 in/y (with 37.5 in/y rainfall), 11% greater deficit than current average

From 2070-2099, the range of potential change in climatic water deficit is projected as follows.

*Scenario 3: Warm, moderate rainfall* - 30.4 in/y (with 47.3 in/y rainfall), 9% greater deficit than current average

*Scenario 5: Warm, high rainfall* - 29.0 in/y (with 61.0 in/y rainfall), 9% greater deficit than current average

*Scenario 6: Hot, low rainfall* - 33.0in/y (with 37.0 in/y rainfall), 18% greater deficit than current average

Figure 12. Projected climatic water deficit (2070-2099), Russian River Basin, three scenarios

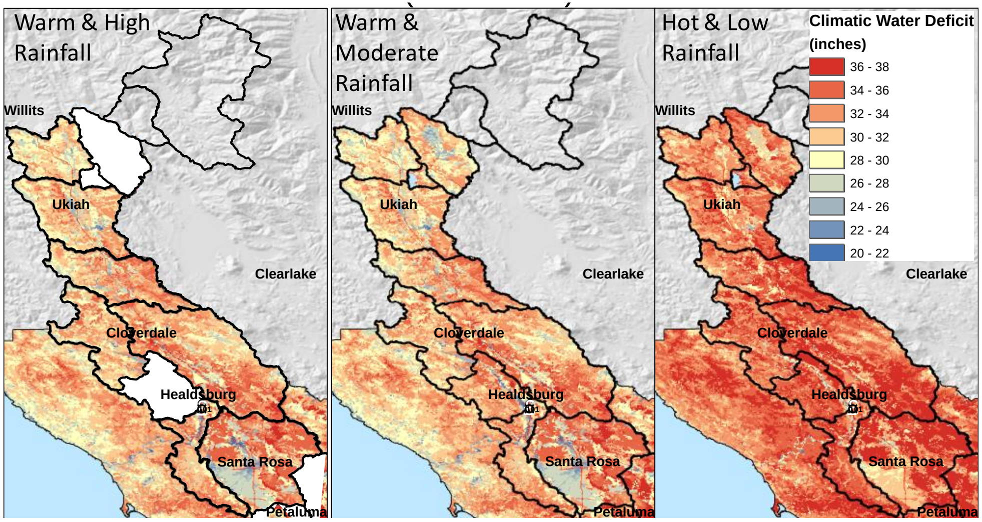
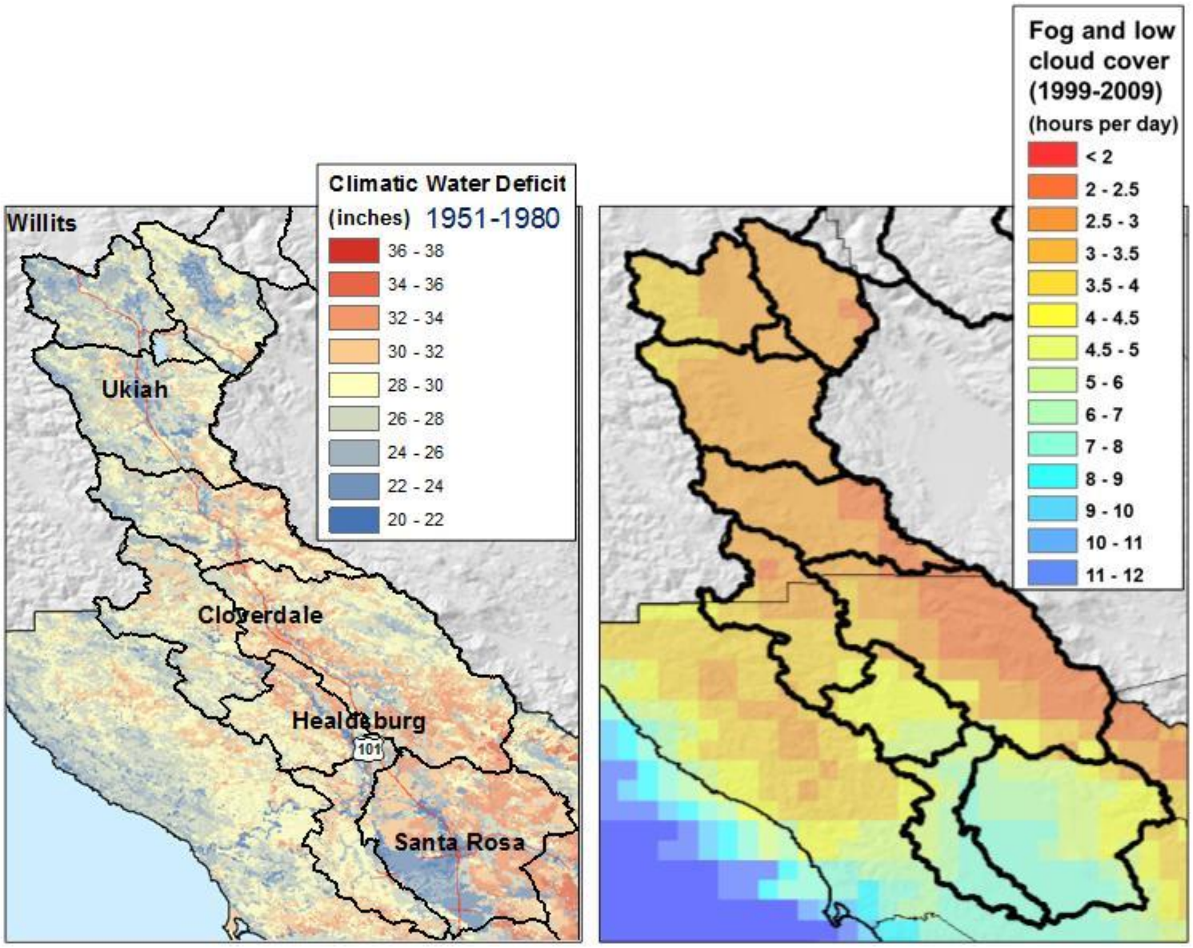


Figure 13. Historical climatic water deficit (1951-1980) distributions compared to fog frequency (average hrs/day), Russian River Basin, three scenarios



Slides 75-80 in the companion *CRNB Sonoma County Water Agency.ppt* illustrate the discussion above.

## VEGETATION TRANSITIONS

*Management Question: How might climate change affect the native vegetation distributions of Sonoma County?*

The TBC3 vegetation model developed by Dr. David Ackerly's lab at UC Berkeley was used to model potential changes in suitability for native vegetation communities in Sonoma County due to climate change. For 22 vegetation types mapped via the Conservation Lands Network, the probabilities for each vegetation type to occur in a given location within the greater San Francisco Bay Area region under the six future climate scenarios were modeled. Overall, the sensitivity of vegetation to climate change was found to be highly heterogeneous across the region, but an unexpected outcome was that sensitivity to climate change is higher closer to the coast, on north-facing slopes and in areas of higher precipitation. While cool or moist sites may be buffered from the impacts of climate change and serve as refugia for the vegetation currently in those locations, the model suggests there will still be highly dynamic and relatively sensitive to climate-driven vegetation transitions (Ackerly et al. 2015).

Changes in vegetation were modeled for 8 Sonoma County "Landscape Units" defined by the Bay Area Upland Habitat Goals Project (BAOSC 2011). Model results don't project when changes will occur in the future; rather which locations are more or less likely to be suitable for a given vegetation type. In Sonoma County, an overall reduction in suitable conditions for Redwood, Douglas-fir forests, and Montane Hardwoods is projected by across the majority of scenarios, with an increase in suitable conditions for Coast Live Oak, Semi-desert Scrub, and Chamise Chaparral is projected for all scenarios. Changes in vegetation for the Sonoma Coast Range specifically are also modeled as one of the "Landscape Units" defined by the Bay Area Upland Habitat Goals Project in 2011.

Sonoma Coast Range species level "winners and losers" can also be identified using four-square diagrams, with each color-coded quadrant in the square reflecting higher or lower temperature and rainfall, as well as the direction of change in percent cover in suitable climate for each vegetation type (Figure 2). Coast Live Oak does well in all future scenarios regardless of warming magnitude and rainfall. California Bay is sensitive to rainfall in the Coast Ranges, and therefore does well in the moderate scenarios rainfall scenarios, but declines in hot and low rainfall. Tan Oak is sensitive to rainfall and temperature; therefore it shows declines in all scenarios.

Slides 81-89 in the companion *CRNB SCWA deck.ppt* illustrate the discussion above in addition to Sonoma County landscape unit vegetation reports.

## FIRE RISKS

*Management Question: How might climate change affect fire frequency in Sonoma County and the Russian River?*

From 1971-2000, the average historic probability of burning occurring one or more times within 30 years for the Russian River basin was 18%. By the end of the century, the probability of burning on the order of 24% but doubles in some locations.

From 2040-2069, the probability of burning occurring one or more times within 30 years throughout the region is projected as follows.

*Scenario 3: Warm, moderate rainfall* - 21% probability
*Scenario 6: Hot, low rainfall* - 21% probability

From 2070-2099, the probability of burning occurring one or more times within 30 years is projected as follows.

*Scenario 3: Warm, moderate rainfall* - 23% probability
*Scenario 6: Hot, low rainfall* - 24% probability

Figure 14. Probability of burning within a 30-year window, Russian River Basin, 1971-2000 compared to 2070-2099, two scenarios

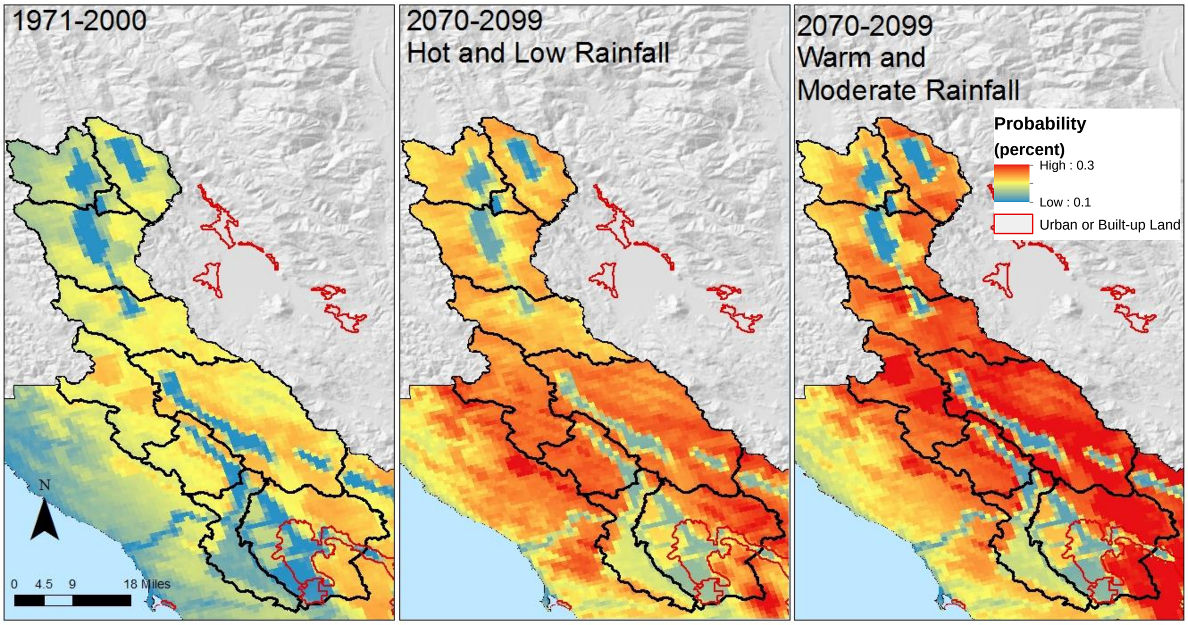


Table7. Fire Risk, Russian River Basin

| | | Current | Hot, Low Rainfall | | Warm, Moderate Rainfall | |
|---|---|---|---|---|---|---|
| Variable | Units | 1971-2000 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 |
| Probability of burning 1 or more times | Percent | 18% | 21% | 24% | 21% | 23% |
| | SD | 4% | 5% | 6% | 6% | 4% |

| | | Current | Hot, Low Rainfall | | Warm, Moderate Rainfall | |
|---|---|---|---|---|---|---|
| Variable | Units | 1971-2000 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 |
| Fire return interval | Years | 171 | 146 | 123 | 151 | 155 |
| | SD | 159 | 210 | 209 | 378 | 1287 |

It's important to note that the probability of fire occurring is actually higher in many locations located within the region in comparison to the regional averages reported here.

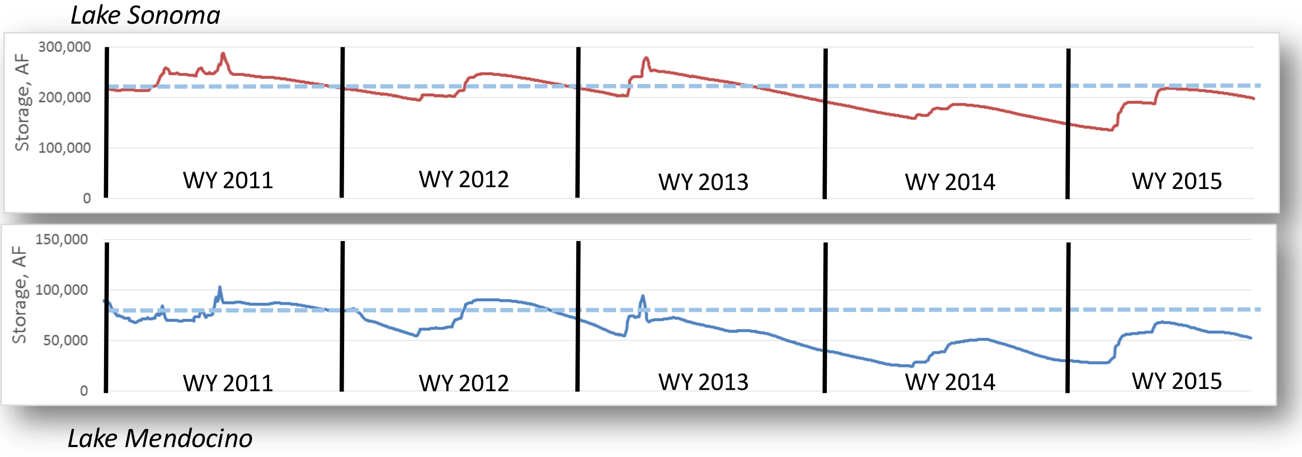
## Characterizing the 2012-2015 Drought

Developing an understanding of how drought is manifested in the Russian River basin requires characterization of changes in precipitation, air temperature, and how the water balance results in changes in soil moisture, recharge, and runoff and corresponding changes in reservoir storage and basin water supply. Included in this analysis is the representation of landscape drought that illustrates where on the landscape vegetation is the most stressed.

Time series of precipitation and soil moisture over the historic record illustrates how minimum soil moisture status is achieved during periods of low rainfall, and that the soil does not dry out every year. It also reaches very low soil moisture status for some years, notably 2001, 1994, 1987, 1973, 1970, and the lowest 2014. There are precipitation and soil moisture thresholds for the Lake Mendocino watershed above which runoff is generated, generally above 1 inch within a day.

The 2012-2015 drought was preceded by a decent water supply year in 2011, although Lake Mendocino had to be evacuated to 68,400 a-f by November 1, 2011. Ultimately both reservoirs, Lake Mendocino and Lake Sonoma, declined to below the end of WY2011 storage value in periods within both 2012 and 2013, and maintained levels below this minimum for 2014 and 2015 (see Figure 15).

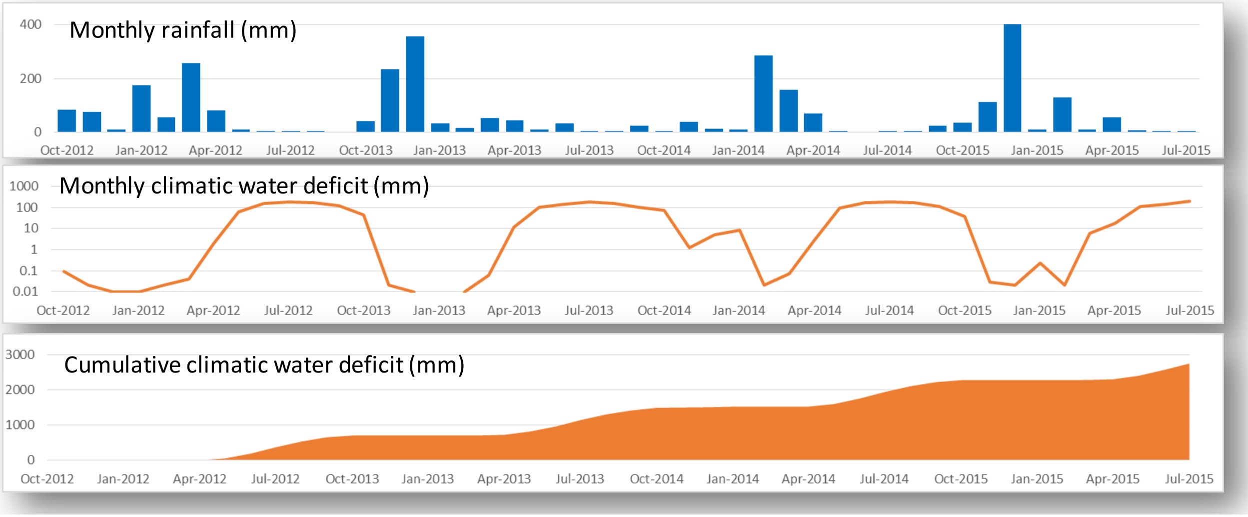
Figure 15. Water Supply (runoff plus recharge) and reservoir storage, Lake Sonoma and Lake Mendocino, WY 2011-WY 2015



We define a drought indicator for water supply as the combination of recharge and runoff. Water year 2014 was at less than 50% of 1981-2010 basin-wide average over most of the basin. The drought indicator for landscape stress is climatic water deficit, which during a drought seldom reaches a seasonal low, so continues to accumulate in many locations from year to year. Average annual CWD for the basin is 690 mm, yet reaches as high as 819 for WY2014.

In order to visualize how the drought develops spatially month by month from Oct2013 to July2015, a series of slides indicating a time series of monthly precipitation and CWD accumulated monthly over the entire time period. In order to discriminate the spatial variation, the legend for WY2013 extends from 0 to 800 mm, for WY2014 from 800-1600 mm, and for 2015 from 1600-2400 mm. By July of 2015 the CWD had accumulated to unprecedented levels in many of the eastern mountains, but WY2014 was by far the most critical year with CWD at up to 120% of normal.

Figure 16. Monthly rainfall, climatic water deficit monthly increments, cumulative climatic water deficit, Russian River Basin, WY 2011-WY 2015



The implications of drought and the influence of CWD on vegetation are illustrated in an evaluation of future climates on redwood forest and blue oak woodland, dominant species in the basin. These species currently occupy locations within the basin that reflect a certain range of CWD. Future projections of CWD for the hot dry GFDL A2 scenario are shown to rise for each 30 year time period for those same locations. Notably, the average annual CWD for the 2012-2015 and the rise of 20% CWD over the basin is above the mean CWD for the end of century for this business as usual scenario, suggesting that under prolonged conditions the redwood forest will fare poorly in comparison to the blue oak woodlands.

In summary, impacts to the water supply differ year to year from impacts to the landscape. Whereas water supply took the worst hit in 2012 and 2014, CWD was the highest in 2013 and 2014. Given the cumulative impacts of CWD, it may take longer for the landscape to overcome the long term effects of the drought that it will take for the water supply to be replenished.

- Impacts to water supply (reservoirs) differs year to year from impacts to the landscape
- Water supply was impacted the most in 2012 and 2014
- The landscape was impacted the most in 2013 and 2014
    - By July 2015 the cumulative impacts of CWD were summed up to 3 normal years for most of the watershed
- Given the cumulative impacts of CWD, it may take longer for the landscape to overcome the long term effects of the drought than the water supply

The companion *CRNB SCWA 2012-2015 drought.ppt* illustrates the discussion above.

**Management Questions: Beyond Scope of this Study**

*What will the impact of climate change be on stream temperatures that in turn will impact fisheries habitat value?*

While the BCM can provide downscaled temperature data relevant to this topic, responding to this management question requires a complementary stream temperature model be developed for the Russian River Basin. The Water Agency has been collaborating with NOAA to improve temperature modeling in the Russian River Basin. Currently an adaptation strategy has been to develop a notification system that alerts users of temperature forecasts that exceed 100 deg F.

*How do reservoir operations potentially influence groundwater recharge, in particular during periods of sustained high flows during the dry season that exceed unimpaired flow estimates used in this study?*

This study generated recharge estimates based on estimates of unimpaired flow conditions. If This might be a conservative estimate of actual recharge values for aquifers adjacent to the river due to sustained dry season flows provided by the reservoirs. A next step could be an analysis of recharge enhancement due to flow increases during the summer season due to reservoir releases.

*How can we estimate impact of potentially variable groundwater recharge rates on actual aquifer levels?*

To thoroughly assess the impacts to aquifer recharge requires the development of a coupled surface water groundwater model, as has been completed for the Santa Rosa Basin in an earlier study. This is an option to pursue for the other groundwater basins, once they have a groundwater model in place.

**Summary**

SCWA is a leader in developing science-based water management solutions. They are proceeding with a team to evaluate the climate vulnerability of their collection, storage and distribution system. Climate Ready North Bay products will be used to estimate a range of environmental driver that may impact both demand and supply. SCWA has already moved forward with advancing real-time field data collection to increase the accuracy of its water supply knowledgebase, including soil moisture monitoring in concert with the USGS. It will also be integrating Climate Ready findings into a number of additional adaptive planning efforts for groundwater, stormwater, and potentially its sanitation facilities. The data provided here can help inform what has been *a climate response function* for each of these operations to define a range of potential future conditions and how to respond effectively to them.

In general, the following take home messages can be made based on this analysis.

- Sonoma County and the Russian River basin are getting more arid due to rising temperatures

- Rainfall is likely to be more variable in the future.

- Runoff may be increasingly flashy, while rates of groundwater recharge are likely to be more consistent.

- Protecting recharge areas will be critical to groundwater sustainability.
- Water demand for agriculture is likely to increase on the order of 10% or more.
- Fire risks projected to increase on the order of 20% or more: managers may need to consider fire readiness and more aggressive fuels management strategies.
- Vegetation may be in transition-merits monitoring and consideration of drought tolerant planting palettes for restoration.
- The 2011-2014 drought showed that water deficits can accumulate across years when there is insufficient rainfall to recharge soil moisture storage.

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# APPENDICES

## Appendix A: List of Climate Ready data products for Sonoma County Water Agency

**Data Product: North Bay Regional Rainfall**-Annual Magnitude and Frequency
**Data Product: BCM Outputs** table of 30-year means for annual precipitation, recharge, runoff, minimum winter air temperature, maximum summer temperature, climatic water deficit, for three (mapped) futures, and fire risk for two (mapped) futures.
*Filename: 16-01-22 CRNB SCWA BCM and Fire summary tables.xls*
*Filename: 16-10-22 CRNB annual regional rainfall.xls*
*Slides: 21-24*

**Data Products: Drought Frequency-Russian River basin**, basic drought indicators and evaluation of 2012-2015 drought severity.

- Time Series: Running 2-yr average Annual and March precipitation compared with 76/77 threshold line: three (mapped) futures
- Time Series: Running 2-yr average Winter and Summer runoff: three (mapped) futures

*Filenames: rrbasins_ppt.xlsx, rrbasins_rchrun.xlsx*
*Deck Slides: 32-36*
*Characterization of 2012-2015 Drought: Deck Slides: 96-122*

**Data Product: Reservoir Inflows**- Precipitation (PPT) and Runoff

- Time Series: Lake Mendocino running 2-yr average Annual and Spring (MAM) precipitation and runoff, Winter (DJF) runoff: three (mapped) futures
- Time Series: Lake Sonoma and Lake Pillsbury running 2-yr average Annual precipitation
- Bar charts: Lake Mendocino average monthly precipitation for historical and 6 futures

*Filename: Reservoir precipitation table.xlsx, Reservoir runoff table. xlsx*
*Deck Slides: 39-47*

GROUNDWATER RECHARGE
**Map Data Products:** Groundwater basins within the **Russian River Basin, groundwater recharge** maps-30 y time steps, 3 scenarios
*Deck Slides: 62-67*
**Data Products: Recharge and runoff statistics for groundwater basins watersheds**
*Filename: Regional Statistics RR.xlsx*
**Data Products: Time series of Russian River basin runoff and recharge** (annual)-3 scenarios
*Filename: rrbasins_rchrun.xlsx, Regional Statistics RR.xlsx*
*Deck Slides: 60*

ENVIRONMENTALLY-DRIVEN DEMAND
**Data Product: Daily Analysis Maximum Temperatures** using 95F and 100F as thresholds

- Daily data queries use 4 daily futures to quantify potential increase in, frequency (# of events), duration (# of days events last), and, intensity (average minimum, maximum and average temperature) of heat events 3-days or longer

*Filename: RR basins_daily air temperature.xlsx*

*Deck Slides: 72*

**Map Data Product:** show zones impacted by fog uncertainty-overlay study area with TBC3 fog frequency to identify areas where fog is a key factor.
**Data Product: Daily Analysis Minimum Temperatures**

- Total # of frost days and table of February-March-April-May frost days

*Filename: RR basins_daily air temperature.xlsx*
*Deck Slides: 74*

FLOODING

**Data Product: Historic and Projected daily streamflow,** Upper Russian at Healdsburg and Lower Russian at Guerneville.

- Time Series: Daily unimpaired flows for historical (2001-2016) and future (2017-2099) for GFDL and PCM A2 and B1. Calculated changes in frequency of upper highest 3-day flows.

Filename: *Russian_unimpaired flows_futures.xlsx* (SCWA already has these)
Deck Slides: 51

FISHERIES

**Management Question:** *How might climate change affect the fisheries value of Sonoma County and the Russian River?*
**Data Product: Historic and Projected daily streamflow,** Upper Russian at Healdsburg and Lower Russian at Guerneville.

- Time Series: Daily unimpaired flows for historical (2001-2016) and future (2017-2099) for GFDL and PCM A2 and B1. Calculated changes in frequency of lowest 3-day flows.

Filename: *Russian_unimpaired flows_futures.xlsx* (SCWA already has these)
Deck Slides: 53

FIRE RISKS

- Geographic area RR basin and reservoir catchments-Provide maps of increased frequency/reduced return interval for GFDL A2 and PCM A2.

*Filename: 16-01-22 CRNB SCWA BCM and Fire summary tables.xls*
*Slides: 90-94*

**Map Data products: Drought Intensity 2012-2015**, spatial distribution of landscape stress and water availability

- Maps of monthly drought accumulation for climatic water deficit with histogram of precipitation 2012-2015
- Maps of annual 2012-2015-to date climatic water deficit and recharge plus runoff

# Appendix B: Selected Future Climate Scenarios for Detailed Analysis

## Table 1. Six Selected Futures for North Bay Regional Vulnerability Assessment (in yellow) in context of original 18 TBC3 scenarios

| Graph Label | Model | Emissions Scenario | Assessment Report Vintage | Time Period | Summer Tmax °C | Summer Tmax Increase | Winter Tmin °C | Winter Tmin Increase °C | Annual Precipitation (mm) | % Change Precipitation | % Change Water Deficit |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | historic (hst) | N/A | N/A | 1951-1980 | 27.9 | | 3.9 | | 1087 | | |
| | current | N/A | N/A | 1981-2010 | 27.9 | | 4.3 | 0.4 | 1095 | 1% | 1% |
| | *Assumption: Business as Usual* | | | | | | | | | | |
| 6 | miroc-esm | rcp85 | AR5 | 2070-2099 | 34.0 | 6.1 | 8.4 | 4.6 | 865 | -20% | 24% |
| | miroc3_2_mr | A2 | AR4 | 2070-2099 | 33.0 | 5.1 | 7.1 | 3.2 | 887 | -18% | 20% |
| | ipsl-cm5a-lr | rcp85 | AR5 | 2070-2099 | 33.0 | 5.0 | 9.6 | 5.7 | 1325 | 22% | 16% |
| | fgoals-g2 | rcp85 | AR5 | 2070-2099 | 32.3 | 4.3 | 7.1 | 3.2 | 1099 | 1% | 22% |
| 5 | cnrm-cm5 | rcp85 | AR5 | 2070-2099 | 31.9 | 4.0 | 7.7 | 3.9 | 1477 | 36% | 12% |
| 4 | GFDL | A2 | AR4 | 2070-2099 | 31.7 | 3.8 | 7.7 | 3.9 | 861 | -21% | 21% |
| 3 | ccsm4 | rcp85 | AR5 | 2070-2099 | 31.4 | 3.5 | 7.1 | 3.2 | 1163 | 7% | 12% |
| 2 | PCM | A2 | AR4 | 2070-2099 | 30.6 | 2.6 | 6.3 | 2.4 | 1159 | 7% | 11% |
| | | | ***Business as Usual Average*** | | **32.2** | **4.3** | **7.6** | **3.7** | **1104** | **2%** | **17%** |
| | *Assumption: Mitigated* | | | | | | | | | | |
| | miroc-esm | rcp60 | AR5 | 2070-2099 | 32.6 | 4.7 | 7.1 | 3.2 | 922 | -15% | 14% |
| | giss_aom | A1B | AR4 | 2070-2099 | 30.9 | 3.0 | 6.4 | 2.5 | 1104 | 2% | 11% |
| | csiro_mk3_5 | A1B | AR4 | 2070-2099 | 30.8 | 2.8 | 6.5 | 2.6 | 1506 | 38% | 4% |
| | | | ***Mitigated Average*** | | **31.4** | **3.5** | **6.6** | **2.8** | **1177** | **8%** | **10%** |
| | *Assumption: Highly Mitigated* | | | | | | | | | | |
| | mpi-esm-lr | rcp45 | AR5 | 2070-2099 | 30.1 | 2.2 | 5.8 | 1.9 | 1148 | 6% | 5% |
| | miroc-esm | rcp45 | AR5 | 2070-2099 | 30.1 | 2.2 | 6.9 | 3.0 | 949 | -13% | 14% |
| 1 | GFDL | B1 | AR4 | 2070-2099 | 30.1 | 2.2 | 6.1 | 2.2 | 923 | -15% | 10% |
| | PCM | B1 | AR4 | 2070-2099 | 29.5 | 1.6 | 5.5 | 1.7 | 1197 | 10% | 5% |
| | | | ***Highly Mitigated Average*** | | **30.0** | **2.1** | **6.1** | **2.2** | **1055** | **-3%** | **8%** |
| | *Assumption: Super Mitigated* | | | | | | | | | | |
| | miroc5 | rcp26 | AR5 | 2070-2099 | 29.8 | 1.9 | 5.2 | 1.3 | 953 | -12% | 9% |
| | mri-cgcm3 | rcp26 | AR5 | 2070-2099 | 29.2 | 1.3 | 4.8 | 0.9 | 1315 | 21% | 2% |
| | giss-e2-r | rcp26 | AR5 | 2070-2099 | 28.4 | 0.4 | 4.6 | 0.7 | 1344 | 24% | -4% |
| | | | ***Super Mitigated Average*** | | **29.1** | **1.2** | **4.8** | **1.0** | **1204** | **11%** | **2%** |
| | | | ***ALL Scenarios Average*** | | **31.1** | **3.2** | **6.7** | **2.8** | **1122** | **3%** | **11%** |

# Climate-Hydrology Futures: North Bay Region and Russian River Basin

## Table 2. Six Selected Futures for North Bay Regional Analysis: Mid-Century Values.

| | Model | Emissions Scenario | IPCC Assessment | Short-hand name | Time Period | Summer Tmax °F | Summer Tmax Increase °F | Winter Tmin °F | Winter Tmin Increase °F | Annual Precipitation (in) | % Change Precipitation | % Change Water Deficit |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Observed** | historical baseline | N/A | N/A | | 1951-1980 | 82.2 | | 39.0 | | 42.8 | | |
| | current | N/A | N/A | | 1981-2010 | 82.2 | | 39.7 | 0.7 | 43.1 | 1% | 1% |
| **Projections** | | | | | | | | | | | | |
| **1** | GFDL | B1 | AR4 | low warming-low rainfall | 2040-2069 | 85.2 | 2.9 | 42.7 | 3.7 | 42.6 | -1% | 6% |
| **2** | PCM | A2 | AR4 | low warming-mod rainfal | 2040-2069 | 85.0 | 2.7 | 41.1 | 2.1 | 43.8 | 2% | 7% |
| **3** | CCSM-4 | rcp85 | AR5 | warm-mod rainfall | 2040-2069 | 86.0 | 3.7 | 42.0 | 3.0 | 42.2 | -1% | 8% |
| **4** | GFDL | A2 | AR4 | warm-low rainfall | 2040-2069 | 86.3 | 4.0 | 43.2 | 4.2 | 39.8 | -7% | 12% |
| **5** | CNRM-CM5 | rcp85 | AR5 | warm-high rainfall | 2040-2069 | 86.5 | 4.2 | 43.0 | 4.0 | 53.8 | 26% | 6% |
| **6** | MIROC-ESM | rcp85 | AR5 | hot-low rainfall | 2040-2069 | 89.2 | 6.9 | 41.4 | 2.4 | 35.0 | -18% | 14% |
| ***Average*** | | | | | | **86.3** | **4.1** | **42.2** | **3.2** | **42.9** | **0%** | **9%** |

## Table 3. Six Selected Futures for North Bay Regional Analysis: End-Century Values.

| | Model | Emissions Scenario | IPCC Assessment | Short-hand name | Time Period | Summer Tmax °F | Summer Tmax Increase °F | Winter Tmin °F | Winter Tmin Increase °F | Annual Precipitation (in) | % Change Precipitation | % Change Water Deficit |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Observed** | historical baseline | N/A | N/A | | 1951-1980 | 82.2 | | 3.9 | | 42.8 | | |
| | current | N/A | N/A | | 1981-2010 | 82.2 | | 4.3 | 0.4 | 43.1 | 1% | 1% |
| **Projections** | | | | | | | | | | | | |
| **1** | GFDL | B1 | AR4 | low warming-low rainfall | 2070-2099 | 86.2 | 4.0 | 6.1 | 2.2 | 36.3 | -15% | 10% |
| **2** | PCM | A2 | AR4 | low warming-mod rainfal | 2070-2099 | 87.0 | 4.7 | 6.3 | 2.4 | 45.6 | 7% | 11% |
| **3** | CCSM-4 | rcp85 | AR5 | warm-mod rainfall | 2070-2099 | 88.5 | 6.2 | 7.1 | 3.2 | 45.8 | 7% | 12% |
| **4** | GFDL | A2 | AR4 | warm-low rainfall | 2070-2099 | 89.1 | 6.9 | 7.7 | 3.9 | 33.9 | -21% | 21% |
| **5** | CNRM-CM5 | rcp85 | AR5 | warm-high rainfall | 2070-2099 | 89.5 | 7.2 | 7.7 | 3.9 | 58.1 | 36% | 12% |
| **6** | MIROC-ESM | rcp85 | AR5 | hot-low rainfall | 2070-2099 | 93.3 | 11.0 | 8.4 | 4.6 | 34.0 | -20% | 24% |
| ***Average*** | | | | | | 88.9 | **6.7** | **7.2** | **3.3** | **42** | **0.0** | **15%** |

**Table 4. North Bay Region Basin Characterization Model Outputs, 1920-1999.**

| | | Historical | Current | Moderate Warming, High Rainfall | | Moderate Warming, Moderate Rainfall | | Hot, Low Rainfall | |
|---|---|---|---|---|---|---|---|---|---|
| Variable | Units | 1951-1980 | 1981-2010 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 |
| Ppt | in | 42.6 | 43.0 | 53.6 | 57.9 | 42.1 | 45.6 | 34.8 | 33.9 |
| Tmn | Deg F | 38.8 | 39.7 | 43.0 | 45.9 | 41.9 | 44.8 | 44.1 | 47.3 |
| Tmx | Deg F | 82.2 | 82.2 | 86.4 | 89.4 | 86.0 | 88.5 | 89.2 | 93.4 |
| CWD | in | 28.0 | 28.4 | 29.8 | 31.3 | 30.3 | 31.4 | 32.0 | 34.6 |
| Rch | in | 11.0 | 10.2 | 12.8 | 13.2 | 10.7 | 10.8 | 8.2 | 8.5 |
| Run | in | 14.0 | 14.2 | 22.8 | 26.9 | 14.0 | 17.3 | 9.7 | 9.3 |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | Percent Change from Current or Change in Temperature | | | | | |
| | | | Current | Moderate Warming, High Rainfall | | Moderate Warming, Moderate Rainfall | | Hot, Low Rainfall | |
| Variable | Units | | 1981-2010 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 |
| Ppt | in | | 43.0 | 25% | 35% | -2% | 6% | -19% | -21% |
| Tmn | Deg F | | 39.7 | 3.2 | 6.1 | 2.2 | 5.0 | 4.3 | 7.6 |
| Tmx | Deg F | | 82.2 | 4.1 | 7.2 | 3.8 | 6.3 | 7.0 | 11.2 |
| CWD | in | | 28.4 | 5% | 10% | 7% | 11% | 12% | 22% |
| Rch | in | | 10.2 | 25% | 29% | 4% | 6% | -20% | -17% |
| Run | in | | 14.2 | 61% | 90% | -1% | 22% | -32% | -34% |

# Appendix C: Climate Models Used in the Basin Characterization Model and Glossary of Terms

### Table 1. Global Circulation Models used in the California Basin Characterization Model calculation of hydrologic response to future climate projections.

| Originating Group(s) | Country | Model Abbreviation | IPCC Assessment Report | Emissions scenario or representative concentration pathway | Downscaling method |
|---|---|---|---|---|---|
| National Center for Atmospheric Research | USA | CCSM_4 | 5 | RCP 8.5 | BCSD* |
| Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique | France | CNRM-CM5 | 5 | RCP 8.5 | BCSD |
| LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS,Tsinghua University | China | FGOALS-G2 | 5 | RCP 8.5 | BCSD |
| NASA / Goddard Institute for Space Studies | USA | GISS-E2 | 5 | RCP 2.6 | BCSD |
| Institut Pierre Simon Laplace | France | IPLS-CM5A-LR | 5 | RCP 8.5 | BCSD |
| Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC) | Japan | MIROC-ESM | 5 | RCP 4.5 | BCSD |
| Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies | Japan | MIROC-ESM | 5 | RCP 6.0 | BCSD |
| Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies | Japan | MIROC-ESM | 5 | RCP 8.5 | BCSD |
| Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology | Japan | MIROC5 | 5 | RCP 2.6 | BCSD |
| Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology) |  | MPI-ESM-LR | 5 | RCP 4.5 | BCSD |
| Meteorological Research | Japan | MRI-CGCM3 | 5 | RCP 2.6 | BCSD |

| Originating Group(s) | Country | Model Abbreviation | IPCC Assessment Report | Emissions scenario or representative concentration pathway | Downscaling method |
|---|---|---|---|---|---|
| Institute | | | | | |
| CSIRO Atmospheric Research | Australia | CSIRO_MK3_5 | 4 | A1B | BCSD |
| NASA / Goddard Institute for Space Studies | USA | GISS_AOM | 4 | A1B | BCSD |
| Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC) | Japan | MIROC3_2_MEDRES | 4 | A2 | BCSD |
| US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory | USA | GFDL | 4 | A2 | CA** |
| US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory | USA | GFDL | 4 | B1 | CA |
| National Center for Atmospheric Research | USA | PCM | 4 | A2 | CA |
| National Center for Atmospheric Research | USA | PCM | 4 | B1 | CA |

**Table 2. Downscaled climate model input and hydrologic model output variables used in the California Basin Characterization Model.**

| Variable | Code | Creation Method | Units | Equation/model | Description |
|---|---|---|---|---|---|
| Maximum air temperature | tmx | downscaled | degree C | Model input | The maximum monthly temperature averaged annually |
| Minimum air temperature | tmn | downscaled | degree C | Model input | The minimum monthly temperature averaged annually |
| Precipitation | ppt | downscaled | mm | Model input | Total monthly precipitation (rain or snow) summed annually |
| Potential evapotranspiration | pet | Modeled/ pre-processing input for BCM | mm | Modeled* on an hourly basis from solar radiation that is modeled using topographic shading, corrected for cloudiness, and partitioned on the basis of vegetation cover to represent bare-soil evaporation and evapotranspiration due to vegetation | Total amount of water that can evaporate from the ground surface or be transpired by plants summed annually |
| Runoff | run | BCM | mm | Amount of water that exceeds total soil storage + rejected recharge | Amount of water that becomes stream flow, summed annually |
| Recharge | rch | BCM | mm | Amount of water exceeding field capacity that enters bedrock, occurs at a rate determined by the hydraulic conductivity of the underlying materials, excess water (rejected recharge) is added to runoff | Amount of water that penetrates below the root zone, summed annually |
| Climatic water deficit | cwd | BCM | mm | pet-aet | Annual evaporative demand that exceeds available water, summed annually |
| Actual evapotranspiration | aet | BCM | mm | pet calculated* when soil water content is above wilting point | Amount of water that evaporates from the surface and is transpired by plants if the total amount of water is not limited, summed annually |
| Sublimation | subl | BCM | mm | Calculated*, applied to pck | Amount of snow lost to sublimation (snow to water vapor) summed annually |
| Soil water storage | stor | BCM | mm | ppt + melt - aet - rch - run | Average amount of water stored in the soil annually |
| Snowfall | snow | BCM | mm | precipitation if air temperature below 1.5 degrees C (calibrated) | Amount of snow that fell summed annually |
| Snowpack | pck | BCM | mm | Prior month pck + snow - subl -melt | Amount of snow as a water equivalent that is accumulated per month summed annually (if divided by 12 would be average monthly snowpack) |
| Snowmelt | melt | BCM | mm | Calculated*, applied to pck | Amount of snow that melted |

| Variable | Code | Creation Method | Units | Equation/model | Description |
|---|---|---|---|---|---|
| | | | | | summed annually (snow to liquid water) |
| Excess water | exc | BCM | mm | ppt - pet | Amount of water that remains in the system, assuming evapotranspiration consumes the maximum possible amount of water, summed annually for positive months only |

Source: Flint, L.E., A.L. Flint, and J.H. Thorne. 2013. *California Basin Characterization Model: A Dataset of Historical and Future Hydrologic Response to Climate Change: U.S. Geological Survey Data Se*t, http://calcommons.org; http://cida.usgs.gov/climate/gdp.

## Table 3: Glossary of Basin Characterization Model Terms

| |
|---|
| **AET: Actual Evapotranspiration (mm or in H2O per month or per year)** |
| AET is the amount of water transferred from the soil to the atmosphere through vegetation transpiration and direct surface evaporation. Decreased AET means less vegetation productivity. Increased AET means more vegetation productivity. |
| **CWD: Climatic Water Deficit (mm or in H2O per year)** |
| CWD is an integrated measure of seasonal water stress and aridity. It is the additional amount of water that could have been evaporated had it been freely available. It is calculated as a cumulative sum over the dry season. Increased CWD means higher water stress for vegetation, and greater risk of fire. Greatly increased CWD (50-100+ mm/year over 30 years) can lead to death of existing vegetation through drought stress. Decreased CWD means less water stress and potentially lower fire risk. |
| **PET: Potential Evapotranspiration (mm or in H2O per month or per year)** |
| PET is the amount of water that could be evaporated if it were freely available (or, provided an unlimited supply of water). Increased PET means higher evaporative demand. Decreased PET means less evaporative demand. |
| **DJF Tmin**: **Average Winter (December-February) daily minimum temperature °C** or **°F** |
| The average minimum temperature over the coldest months of the year (December- February). DJF Tmin is a prime determinant of frost and freeze frequency, and chilling hours for winter dormant plants. |
| **JJA Tmax: Average Summer (June-August) daily maximum temperature °C** or **°F** |
| The average summer maximum temperature in the three warmest months of the year (June-August). JJA Tmax is a prime determinant of heat wave extremes, and is an important contributor to PET and aridity. |
| **PPT: Precipitation (mm or in H2O per month or per year)** |
| PPT is the total annual precipitation in mm (25.4 mm = 1”). Increased PPT directly increases runoff, may increase recharge if distributed through the rainy season, and can ameliorate aridity if it falls in March-May (higher AET and lower CWD). Decreased PPT directly decreases runoff and recharge, and increases aridity (lower AET and higher CWD). |
| **Recharge: Recharge (mm or in H2O per month or per year)** |
| Recharge is water that percolates below the rooting zone and becomes groundwater for more than a month. Recharge is affected greatly by bedrock permeability and soil depth. Recharge is a precious resource. Recharge provides natural subsurface storage that is the source of stream baseflow in the dry season, and many Bay Area communities depend on well water. Conservation of high recharge areas is a high priority. Increases in recharge results in greater groundwater aquifer storage and maintenance of baseflow (stream flows during periods absent precipitation), especially during multi-year droughts. Decreases in recharge results in less groundwater storage and loss of baseflow, especially during multi-year droughts. |
| **Runoff: Runoff (mm or in H2O per month or per year)** |
| Runoff is the water that feeds surface water stream flow, and generally occurs during storms when the soil is fully saturated with water. Runoff occurs on shallower soils more rapidly than on deeper soils. |

# Appendix D: Sonoma County Basin Characterization Model Summary Data Tables

### Table 1: Basin Characterization Model, Sonoma County: Three "business as usual" models used for map products, 1951-2099.

| | | Historical | Current | Moderate Warming, High Rainfall | | Moderate Warming, Moderate Rainfall | | Hot, Low Rainfall | |
|---|---|---|---|---|---|---|---|---|---|
| Variable | Units | 1951-1980 | 1981-2010 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 |
| Ppt | mm | 1083 | 1091 | 1361 | 1471 | 1069 | 1158 | 885 | 861 |
| Tmn | Deg C | 7.10 | 7.67 | 9.58 | 11.10 | 9.16 | 10.72 | 10.33 | 12.36 |
| Tmx | Deg C | 21.80 | 21.78 | 23.87 | 25.39 | 23.58 | 25.08 | 24.89 | 27.04 |
| CWD | mm | 712 | 722 | 758 | 796 | 770 | 798 | 812 | 880 |
| Rch | mm | 279 | 260 | 325 | 336 | 271 | 275 | 208 | 216 |
| Run | mm | 356 | 360 | 578 | 684 | 356 | 439 | 246 | 237 |
| | | | | Percent Change from Current | | | | | |
| | | | Current | Moderate Warming, High Rainfall | | Moderate Warming, Moderate Rainfall | | Hot, Low Rainfall | |
| Variable | Units | | 1981-2010 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 | 2040-2069 | 2070-2099 |
| Ppt | in | | 43 | 25% | 35% | -2% | 6% | -19% | -21% |
| Tmn | Deg F | | 39.7 | 8% | 15% | 5% | 13% | 11% | 19% |
| Tmx | Deg F | | 82.2 | 5% | 9% | 5% | 8% | 9% | 14% |
| CWD | in | | 28 | 5% | 10% | 7% | 11% | 12% | 22% |
| Rch | in | | 10 | 25% | 29% | 4% | 6% | -20% | -17% |
| Run | in | | 14 | 61% | 90% | -1% | 22% | -32% | -34% |

*Variables: Ppt=precipitation, Tmn=minimum winter temperature (monthly), Tmx=maximum summer temperature (monthly), CWD=climatic water deficit, Rch=recharge, Run=runoff*