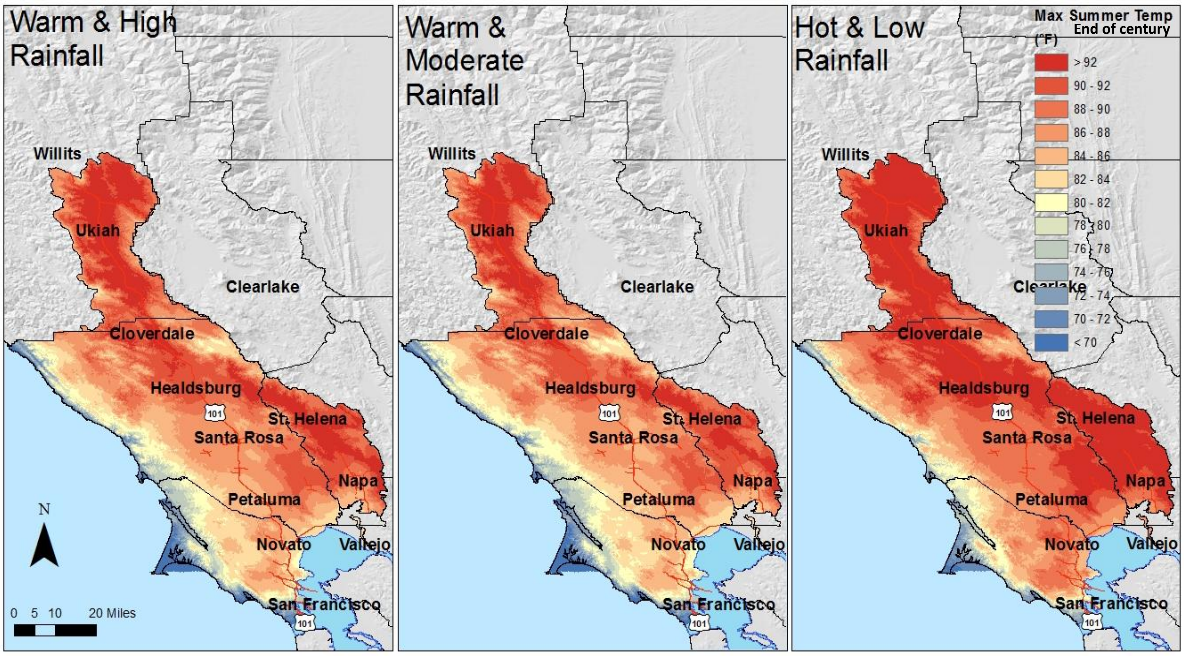
Climate Ready North Bay
Vulnerability Assessment Data Products

Napa County User Group

January 2016



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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.

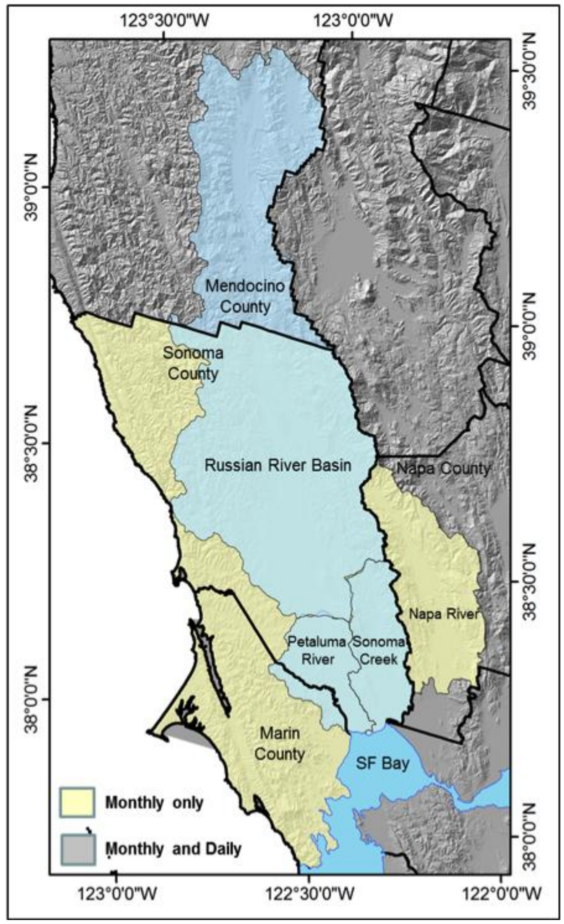


Figure 1: Map of study region shown in blue and yellow, including regions where daily data is available for analyses (blue) and those where monthly data is available (yellow). *Climate Ready North Bay 2015*.

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's Water Agency, 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 Memo Overview

This technical memo summarizes the outcomes of engaging Napa County 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 the Napa Valley (Napa River watershed) 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 engaged Napa County departments' jurisdiction 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. Napa County's management concerns with summarized data findings are grouped into three resource areas: 1) Water Resources (including surface and groundwater supply, fisheries, and flooding); 2) Agricultural Sustainability; and 3) Native Vegetation Response and Fire Risks. Appendices include a glossary, details on climate models, summary tables, and a list of data products generated and provided to the County. A companion PowerPoint deck (*CRNB Napa Valley deck.ppt*) is also provided that showcases additional sample data products and take home messages for the County's use. Appendix A summarizes data products co-created with managers and provided for adaption planning applications.

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 4-9 in *CRNB Napa Valley deck.ppt* provide a project overview.

Napa County Responsibilities and Jurisdictions

The Napa County departments engaged in *Climate Ready North Bay* included Planning (Building and Environmental Services), Public Works (Natural Resources Program) and Napa County Flood Control and Water Conservation District. These departments are engaged in long-term resource management planning, as well as permitting of new residential, commercial, and vineyard developments. The scope of the Planning department includes general plan implementation, agricultural erosion control plans, watershed planning, and development permit review. The Flood Control and Water Conservation District was also engaged based on its role in management of the watershed as a whole, with restoration and maintenance obligations on specific stream reaches and the main stem of the Napa River. The District is charged with flood protection planning and complying with state and federal requirements, including compliance with storm-water permitting requirements. While these agencies have countywide jurisdiction, this initiative is focused on the Napa Valley (which is equivalent to the Napa River watershed). However, the GIS database provided covers for the entire County, such that subsequent explorations could be conducted at the full County scale or for sub-regions.

Napa County Climate-related Concerns and Management Priorities

Napa County presented the most diverse array of management concerns and priorities of all the *Climate Ready North Bay* partners. As the County is embarking on a groundwater management plan, there are concerns about groundwater sustainability in general and relationships between granting vineyard permits and impacts on groundwater supplies. For example, there is a new requirement for vineyard permits to show that new wells can supply the project without impacting neighboring streams or properties. Because of this, it will be important to understand potential increases in demand. With multiple reservoirs located throughout the eastern hills of the valley [Napa Valley reservoirs are primarily managed by managed by the cities rather than the County, except for Rector Reservoir which is managed by the State of California], there is concern about both local water surface supplies and the sustainability of imported water, which provides 40% of the County's supply.

For watershed management purposes, Napa County had an interest in climate impacts on forest resources in terms of species of conservation concern. With a large stream and river restoration program underway, the County has questions specifically about the riparian zone, including impacts of climate change on riparian hydrology and appropriate plants for installation as part of restoration. The Flood Control and Water Conservation District's Watershed Operation staff's field experience is already showing that planting more drought-tolerant pioneer species is proving a more successful strategy than planting "classically" riparian species alone. With a strong emphasis on fisheries conservation, the County is also interested in understanding the potential hydrologic impacts on fish-bearing streams. The District's flood control responsibilities lead them to have concerns about the likelihood of increased frequency or intensity of flooding events. It was also raised that the sanitation district is doing an independent sea level rise analysis that would complement this analysis of inland climate impacts.

Napa County's management concerns are grouped into three resource areas: 1) Water Resources (including surface and groundwater supply, fisheries, and flooding); 2) Agricultural Sustainability; and 3) Native Vegetation Response and Fire Risks.

Management Concerns for Future Analysis

In the process of identifying management concerns and questions, a number of key questions amenable to analysis given the scope of this project were identified and are presented by resource areas below. Additional management questions were identified that the team determined were beyond the scope of this study, and therefore not addressed here. However we share them here as they can provide a starting point for subsequent climate adaptation work.

- What are the implications of climate change for site-specific riparian vegetation and restoration projects?
- What are the best tools to assess the localized impacts of groundwater withdrawal from a particular well?
- What will be the impact of climate change on the determination of suitable growing regions in the Napa Valley?
- What are the implications of more variable hydrology on site-specific flood infrastructure requirements?
- What are the impacts of climate change likely to be on the watersheds outside the Napa Valley from which Napa imports water?

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 summarized of the 18 TBC3 selected GCMs.

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)

Slides 10-14 in *CRNB Napa deck.ppt* address the scenario selection process.

USGS 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 *historic* 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 *historic* climate input data is downscaled from PRISM (Daly et al. 2008), and the daily data set includes historic 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 for precipitation), 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 demand), water supply, and stream flow.

Climatic water deficit projections, including where deficits are projected to exceed the historic 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 historic 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.

Slides 15-19 in *CRNB Napa deck.ppt* provide an overview of the BCM model, with slides 20-29 providing samples of outputs for the North Bay region as a whole.

Climate Ready North Bay Vegetation Model

Risk of potential future vegetation transitions were modeled using projected proportional area of landscape cover for 22 vegetation types for the historic (1951–1980) and recent (1981–2010) periods and each of the six future climate scenarios. Projected vegetation response includes the frequency and spatial extent of suitable climate space for each vegetation type throughout the region, the potential impact of climate change on vegetation for a "landscape unit" (as defined by the Bay Area Open Space Council's Conservation Lands Network) of interest, and an evaluation of which factors contribute to spatial variation in the sensitivity of the projected vegetation changes in response to climate (Ackerly et al. 2015). See Appendix A for a summary of dynamic vegetation model results for the project area.

Fire Risk Model

Statistical models of recent historic 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

Key findings for the Napa Valley 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 watershed supply. The climate suitability for vegetation types in the Napa Valley 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, the project team encourages exploring how to 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, and perhaps more aggressive approaches to the reduction of forest fuel loads should be considered.

- → *The Napa Valley region is becoming more arid due to rising temperatures*
- → *Rainfall is likely to be more variable in the future*
- → *Runoff may be increasingly flashy*
- → *Rates of groundwater recharge are relatively consistent over time, such that protecting recharge areas may 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 perhaps more aggressive fuels management*
- → *Vegetation may be in transition, meriting additional monitoring and consideration of a drought tolerant planting palette for forest and riparian restoration*

Key Management Questions and Summary of Data Products

Introduction

This section summarizes data products developed in response to the key management questions raised by the Napa County user group. Products include samples of vulnerability assessment data products describing projected temperatures, rainfall, runoff, groundwater recharge, climatic water deficit, vegetation transitions, and fire risk. Appendices include a list of data products, summary data tables, and a companion PowerPoint "deck" with slides highlighting these data products (illustrations including maps, tables, and talking points *CRNB Napa deck.ppt*). Corresponding slide numbers are included here for figures supporting the data summaries. Management questions are grouped by resource area with corresponding vulnerability assessment findings summarized.

Rainfall is the most variable input value to the BCM for the North Bay region as a whole and for the Napa Valley, and drives the majority of variability in primary hydrologic response outputs and secondary outputs for potential vegetation transitions and fire risks. Table 1 and Table 2 summarize BCM projected long-term trends in 30-year time steps from 2010–2099 for temperature, rainfall, runoff, groundwater recharge, and climatic water deficit in comparison to current conditions, averaged over 1981–2010, for Napa Valley (also see Appendix D, Tables 1 and 2, Napa Valley BCM output summary). Three “business as usual” emissions scenarios are included: Scenario 5: Warm, high rainfall (the highest rainfall model in TBC3’s Bay Area BCM), Scenario 6: Hot, low Rainfall (the lowest rainfall model in the TBC3’s Bay Area BCM), and Scenario 3: Warm, moderate Rainfall (the closest future to the mean of all rainfall projections for TBC3’s Bay Area BCM). These three scenarios can be considered to “bookend” high and low rainfall extremes (Scenarios 5 and 6 respectively) and a "middle of the road" future (Scenario 3).

This wide variation between model rainfall projections is the greatest source of uncertainty in projected future conditions. With values ranging from approximately 25% *less or greater* rainfall at the scale of 30-year average values, managers need to determine how to plan in the face of this magnitude of uncertainty. *Climate Ready North Bay* products allow managers to understand the range of physical and ecological impacts caused by variable rainfall, and to "unpack" the annual and seasonal variability underlying these long-term average values.

It is important to point out that, despite this broad range of projected increases or decreases in rainfall, estimated climatic water deficit (which is defined as the quantified amount of evaporative demand exceeding available soil moisture) is expected to increase across all futures. This provides managers with a key landscape condition and water demand indicator that varies only in intensity but not direction. Changes in water deficit are a critical driver of agricultural sustainability, native vegetation response, and fire risk as described in more detail below.

Additionally, all of the climate models show a consistent increase in temperatures for the Napa Valley. By century's end, total increases in maximum summer temperatures (monthly values, 30-year averages) range from 6.6 to 11.5°F, while increases in minimum winter temperatures (also monthly values, 30-year averages) range from 4.9 to 7.3°F. These significant increases in long-term temperature averages represent unprecedented extreme heat events at the scale of days and months. This increase in temperature results in increased rates of evapo-transpiration that, in turn, drive changes throughout the hydrologic cycle, which are explored in the following sections. Warmer temperatures effectively generate dryer soil conditions, which then creates more room for storing moisture subsurface in soils and aquifers, potentially reducing the total amount of available surface water.

Table 1: Basin Characterization Model, Napa Valley Watershed – Summary of outputs, three scenarios

		Historic	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	35.6	36.4	44.8	48.6	35.1	38.2	28.7	27.7
	SD	6.5	5.7	7.6	8.1	6.0	6.4	5.0	4.8
Tmn	Deg F	86.6	39.4	42.8	32.9	41.6	44.4	43.6	46.7
	SD	34.1	32.9	32.9	90.9	32.8	32.8	32.8	32.8
Tmx	Deg F	86.6	86.5	90.9	93.9	90.5	93.1	93.8	98.0
	SD	34.1	34.0	34.0	34.0	34.0	34.0	34.0	34.0
CWD	in	30.2	30.6	31.9	33.4	32.3	33.6	34.3	36.8
	SD	3.3	3.3	3.4	3.4	3.2	3.4	3.1	3.1
Rch	in	10.9	10.6	13.4	6.0	10.5	11.1	7.5	7.8
	SD	5.0	4.7	6.0	13.0	4.8	5.0	3.7	3.9
Run	in	7.1	7.8	13.0	16.1	6.9	9.5	4.3	3.8
	SD	6.8	6.8	9.3	10.7	6.5	7.5	4.5	4.4

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

Table 2: Basin Characterization Model, Napa Valley Watershed – Projected change in temperature (° F) and hydrologic indicators (% change from current), three scenarios

		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	36.4	23%	34%	-3%	5%	-21%	-24%
Tmn	Deg F	39.4	9%	-17%	5%	13%	11%	19%
Tmx	Deg F	86.5	5%	9%	5%	8%	8%	13%
CWD	in	30.6	4%	9%	6%	10%	12%	20%
Rch	in	10.6	27%	-44%	-1%	5%	-29%	-27%
Run	in	7.8	67%	107%	-11%	22%	-44%	-51%

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

Water Resources

The following section highlights results generated in response to key management questions regarding water availability and impacts on streams and aquifers of the Napa Valley.

Management Question: How is climate change projected to impact the variability of regional annual rainfall relative to the historic record?

A comparison of projected rainfall patterns in the North Bay region can be made by analyzing observed annual rainfall totals for the historic period of 1920–2009 compared to projected annual rainfall totals. This analysis can estimate the potential change in frequency of high rainfall years likely to correspond with flood risks, and low rainfall years likely to correspond with drought risks (Tables 3a and 3b).

Table 3a. Frequency of annual rainfall extremes per decade, historic/current conditions (1920-2009) and six climate ready scenarios (2010-2099)

Exceedances 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		0.22	1.00	1.00	0.11
1	GFDL_B1	2010-2099	Low warming, Low rainfall	0.56	1.44	2.00	0.00
2	PCM_A2	2010-2099	Low warming, Mod rainfall	0.67	2.56	1.89	0.33
3	CCSM4_rcp85	2010-2099	Warm, Mod rainfall	0.56	2.11	1.11	0.00
4	GFDL_A2	2010-2099	Warm, Low rainfall	0.33	1.11	2.56	0.33
5	CNRM_rcp85	2010-2099	Warm, High rainfall	2.11	4.56	0.67	0.00
6	MIROC_rcp85	2010-2099	Hot, Low rainfall	0.00	0.44	1.56	0.11

Table 3b. Percent increase or decrease (projected relative to 1920-2009) in frequency of extreme annual rainfall events per decade

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%***

Using the 90th percentile of the annual rainfall record from 1920-2009 as a threshold for "high" rainfall years, four out of five models project increases in the frequency of high rainfall years for 2010-2099. Estimated increases in frequency of high rainfall years range from approximately 40-350%, with only the extreme "hot and low rainfall" scenario 6 projecting a reduction in frequency of high rainfall years. The average frequency increase across all models is approximately 100% (equivalent to a doubling of the current frequency of high rainfall events).

Using the 10th percentile of the annual rainfall record from 1920-2009 as a threshold for "low" rainfall years, four out of five models project increases in the frequency of low rainfall years for 2010-2099. Estimated increases in frequency of low rainfall years range from approximately 10-100%, with only the extreme "high rainfall" scenario 5 projecting a reduction in frequency of low rainfall years. The average frequency increase for low rainfall years across all models is approximately 60%.

Thus, the majority of projections suggest that climate change will increase the frequency of ***both*** high and low rainfall years in the coming century. Thus it is important to remember this annual variability underlying comparisons below of 30-y rainfall averages presented in the BCM summaries (Tables 1, Appendices C and D).

Compared to the North Bay region's historic average rainfall of 43.0 in/year, the Napa Valley is in a lower rainfall region that has received an average of 7 inches (16%) less rainfall per year. However, the projected percent change for 30-year periods of precipitation discussed below is comparable to the regional projections, with a slightly lower decrease in precipitation for the hot, low rainfall scenario for Napa Valley compared to the region as a whole.

PowerPoint slides 30-33 in the companion *CRNB Napa Valley.ppt* illustrate the discussion above.

Management Question: How does rainfall variability translate to variability in Napa Valley watershed-wide water availability and potential delivery to reservoirs?

Climate Ready products developed in concert with managers focused on climate change implications for water supply in long-term (30-year) and annual time steps for the Napa Valley as a whole, for the mountains versus the valley floor, and for individual reservoir drainages.

Projected rainfall variability specific to the Napa Valley basin can be described as follows. From 1951-1980 and 1981-2010, both the historic and current Napa Valley Watershed average rainfall was 36.0 inches per year.

For 2040-2069 (mid-century), the Napa Valley watershed's average rainfall projections cover the following range.

Scenario 3: Warm, moderate rainfall – 35.0 in/year, 3% less than current
Scenario 5: Warm, high rainfall – 44.8 in/year, 34% greater than current
Scenario 6: Hot, low rainfall – 29.0 in/year, 21% less than current

For 2070-2099 (end-century), Napa Valley watershed average rainfall projections cover the range below.

Scenario 3: Warm, moderate rainfall – 38.0 in/year, 5% greater than current average
Scenario 5: Warm, high rainfall – 86.6 in/year, 27% greater than current
Scenario 6: Hot, low rainfall – 28.0 in/year, 24% less than current

Examining the two extreme high and low rainfall scenarios, plus the scenario that represents the approximate central tendency of regional climate models, establishes a broad range of potential runoff futures. From 1981-2010, the current Napa Valley average runoff was 7.8 inches per year per unit area. For 2040-2069, the range of potential Napa Valley runoff values is as follows.

Scenario 3: Warm, moderate rainfall – 6.9 in/year, 11% less than the current average
Scenario 5: Warm, high rainfall – 13.0 in/year, 67% greater than the current average
Scenario 6: Hot, low rainfall – 4.3 in/year, 44% less than the current average

For 2070-2099, the projected range for annual runoff values for the Napa Valley is as follows.

Scenario 3: Warm, moderate rainfall – 9.5 in/year, 22% greater than current
Scenario 5: Warm, high rainfall – 16.0 in/year, 107% greater than current average
Scenario 6: Hot, low rainfall – 3.8 in/year, 51% less than the current average

Model outputs show a wide range of diversity when comparing projections of annual runoff for the Napa Valley as a whole across all six future climate scenarios. Four out of five of the modeled futures show a greater magnitude and frequency of annual runoff peaks compared to the historic record (using the historic maximum value of 1983 as a reference). Only the extreme drought scenario (Scenario 6, hot low rainfall) shows a reduction in the magnitude and frequency of annual runoff peaks, with peak values approximately on the order of the historic mean.

Changes in total water supply, represented by combining recharge and runoff values in acre-feet, were projected for key zones of the Napa Valley including the mountainous regions, the valley floor, and each individual reservoir drainage area. Table 4 displays the range of potential change in water supply in the mountain regions and valley floor. The valley floor is projected to experience up to an 82% increase in water supply by the end of the century under warm-high rainfall conditions (Scenario 5), and a potential 47% decrease in water supply under hot-low rainfall conditions (Scenario 6).

Table 4: Water availability projections (recharge plus runoff in acre-ft) generated for Napa Valley comparing the mountains and valley floor, 30-year averages.

			Current	Moderate Warming, High Rainfall		Moderate Warming, Moderate Rainfall		Hot, Low Rainfall	
Rch+Run (ac-ft)		Area (acres)	1981-2010	2040-2069	2070-2099	2040-2069	2070-2099	2040-2069	2070-2099
Mountains	total	452,476	243,131	344,656	392,444	233,723	272,710	163,522	160,806
	SD		58,769	71,890	76,404	56,910	59,658	45,580	46,690
	% change			42%	61%	-4%	12%	-33%	-34%
Valley floor	total	189,418	59,142	89,894	107,424	53,860	67,413	33,201	31,061
	SD		21,889	28,335	30,616	22,300	23,755	17,066	17,567
	% change			52%	82%	-9%	14%	-44%	-47%

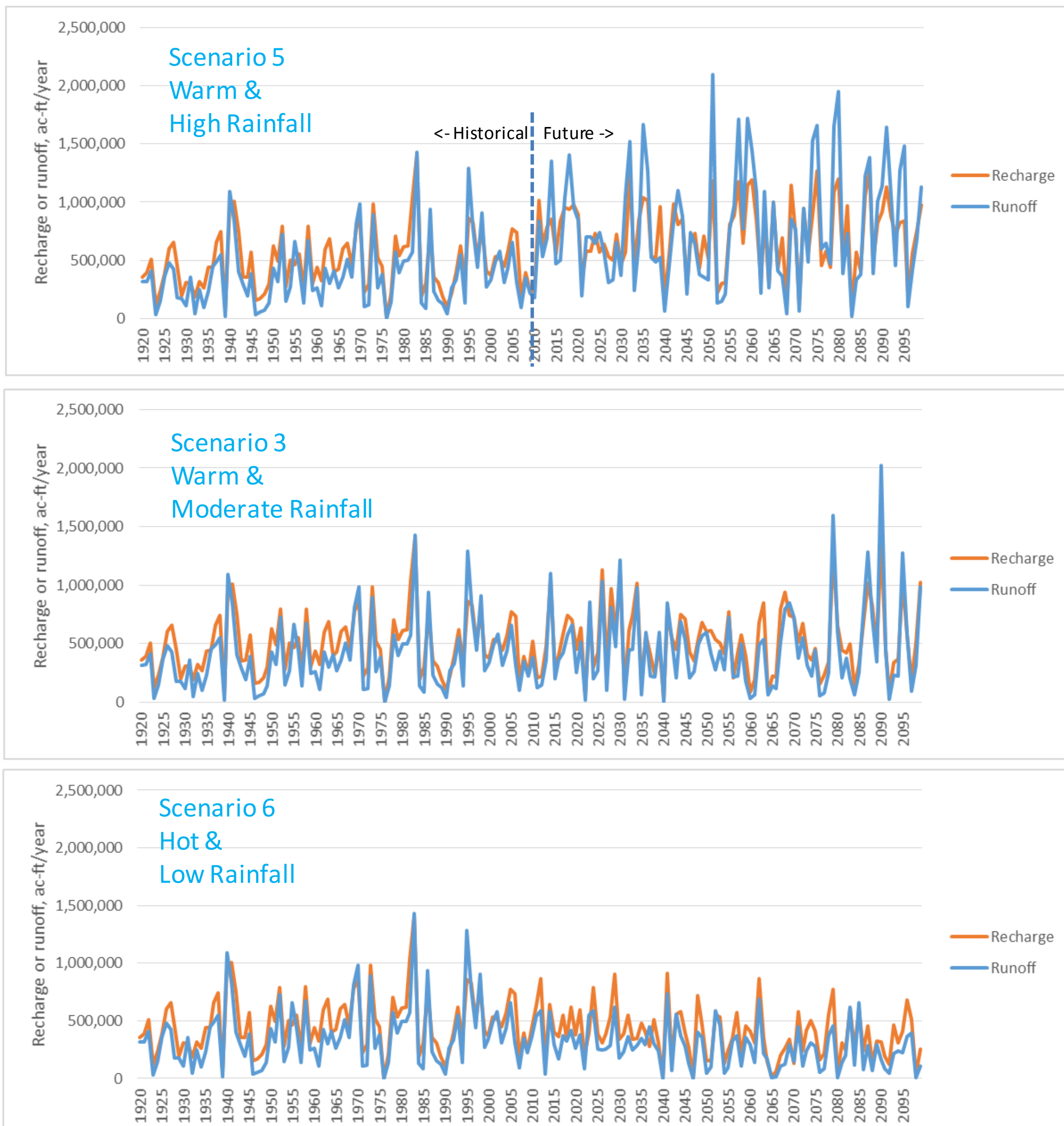
Table 5 summarizes the range of potential change in water supply in 30-year averages for each reservoir drainage area. The table shows average values across reservoirs ranging from plus 63% to minus 33% in long-term water yield by end-century (2070-2099). This analysis can facilitate a comparison of reservoir water availability that results from catchment variability in terms of topography and underlying soils and geology. For example, Lake Henessey's supply appears relatively resilient, as indicated by mid-century values (ranging from +65%, to +12%, to -22% change compared to historic, Scenarios 5, 3, 6 respectively) compared to Milliken Reservoir (which ranges from +43%, to -6%, to -36% for Scenarios 5, 3, 6 respectively). In this example the watershed characteristics of Lake Hennessey enable the reservoir to capture a higher fraction of high, medium and low rainfall years' available water compared to Milliken.

Table 5: Water supply projections (recharge plus runoff in acre-ft) by Napa Valley reservoir drainage, 30-year averages.

Reservoir Attributes		**Current**	**Scenario 5-Warm, High Rainfall**		**Scenario 3- Warm, Mod Rainfall**		**Scenario 6, Hot, Low Rainfall**	
NAME	Area (acres)	1981-2010	mid-century	end-century	mid-century	end-century	mid-century	end-century
Kimball Reservoir	2,159	5,243	7,568	8,450	5,308	5,981	3,826	3,812
Bell Canyon Reservoir	3,526	6,737	9,928	11,194	6,800	7,776	4,776	4,722
Conn Creek - Upper Reach	2,622	5,014	7,233	8,168	4,906	5,629	3,407	3,355
Moore Creek	4,571	8,347	11,819	13,377	8,034	9,287	5,607	5,537
Chiles Creek - Main Fork	4,125	7,216	10,110	11,451	6,868	7,955	4,792	4,730
Conn Creek - Main Fork	4,435	7,312	10,697	12,240	7,092	8,325	4,849	4,745
Conn Creek - East Fork	1,531	2,579	3,768	4,305	2,498	2,921	1,700	1,666
Chiles Creek - East Fork	1,720	2,941	4,047	4,581	2,746	3,186	1,914	1,891
Elder Valley Creek	1,845	2,637	3,602	4,116	2,386	2,816	1,628	1,600
Sage Creek	4,246	6,977	9,568	10,852	6,485	7,563	4,532	4,473
Lake Hennessey	5,164	7,355	12,137	13,812	8,214	9,625	5,772	5,679
Clear Creek	1,485	2,405	3,361	3,827	2,253	2,632	1,548	1,522
Fir Canyon	1,565	2,904	3,769	4,255	2,606	3,022	1,856	1,839
Rector Reservoir	6,971	12,886	18,197	20,491	12,656	14,639	9,112	9,000
Milliken Reservoir	6,141	9,829	14,053	16,089	9,285	11,017	6,322	6,122
All Reservoirs Average	*3,474*	*6,026*	*8,657*	*9,814*	*5,876*	*6,825*	*4,109*	*4,046*
% change from current			*44%*	*63%*	*-2%*	*13%*	*-32%*	*-33%*

A comparison of annual values that distinguish the relative contributions of recharge and runoff to the water supply of the Napa Valley as a whole (Figure 2) shows that, in general, runoff values are far more variable or "flashy" than recharge values. For example, while the variability in projected annual runoff values for high, mid, and low and mid rainfall futures (Scenarios 5, 3, 6 respectively) range from 4 to 15 in/year groundwater recharge values range from 8 to 11 in/year and are therefore more relatively more consistent from year to year.

Figure 2. A comparison of historic (1920-2009) and projected (three scenarios, 2010-2099) annual runoff and recharge, Napa Valley watershed



PowerPoint slides 37-47 in the companion *CRNB Napa Valley.ppt* illustrate the data findings above.

Again we see the annual variability and increasing frequency of extremes in both the positive and negative direction underlying long-term 30-y trends. The warm-high rainfall scenario (Scenario 5) shows a trend of progressively increasing runoff and recharge values towards the end of century, yet still includes approximately five very low runoff years comparable to the drought conditions of 1976-1977. Although projections for the warm-moderate rainfall scenario (Scenario 3) are comparable to historic conditions, this scenario shows more multi-year low water availability periods than the historic record (for example 2055-2075) and includes some peaks near century's end that are unprecedented in the historic record. The hot-low rainfall scenario shows a dismal trend towards steadily decreasing water availability representative of potentially unprecedented droughts relative to the historic record.

These projections suggest that recharge may be considered a more consistent component of water yield over time relative to runoff. However, this is not to discount the importance of big runoff years in supplying critical supply to reservoirs, streams, and aquifers. The relative consistency of groundwater recharge even in low rainfall years suggests that sustainable groundwater management is a good investment in water security. Companion results for just the mountain and valley floor zones show the importance of protecting long-term water supply from mountain sources under all scenarios, and the vulnerability of the valley floor to the most flashy runoff conditions of the watershed as a whole.

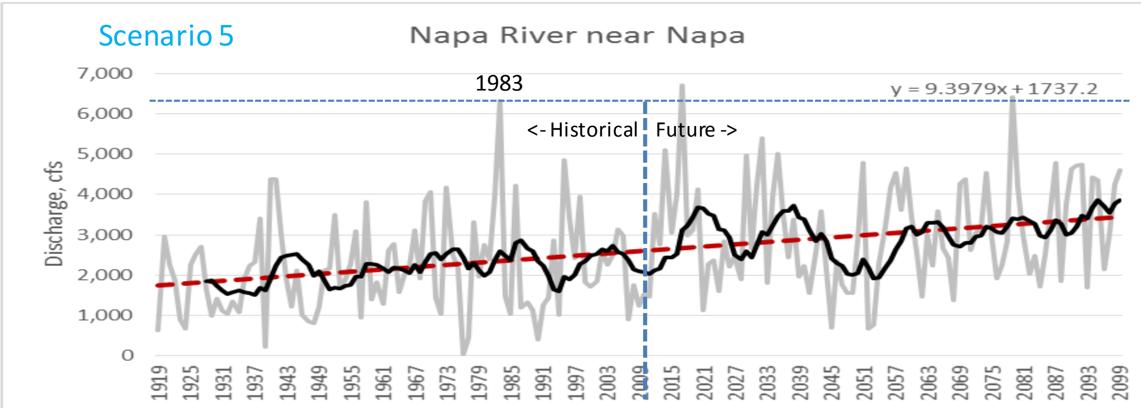
Management Question: What are the potential impacts of climate change on the flow regime of the Napa River?

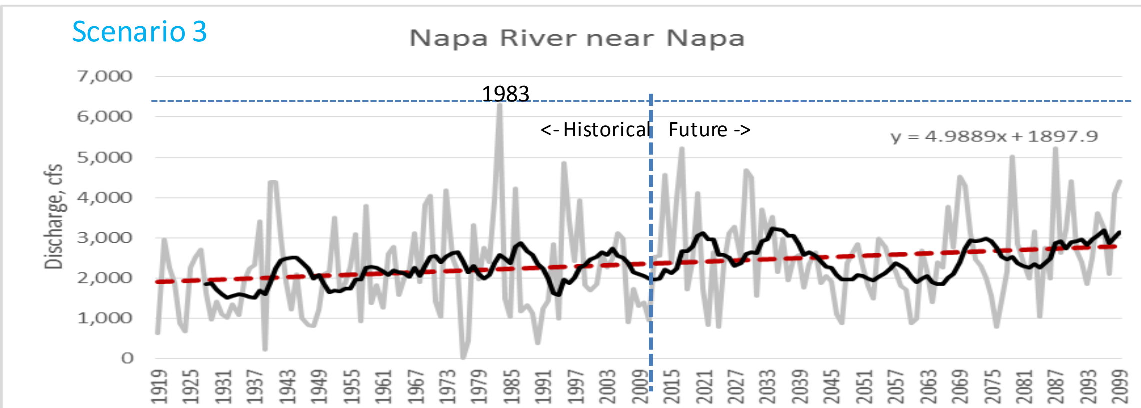
As part of the *Climate Ready North Bay* BCM analysis, a supplemental assessment was conducted using BCM outputs to estimate variability in river flows at key gages of interest identified by managers. In order to project changes in Napa River flow, historic data was analyzed from three main stem Napa River gages (Calistoga and Saint Helena gages for the "upstream" reach, and the Napa gage for the "downstream" reach) using three future climate scenarios (Scenario 3: Warm, moderate rainfall, Scenario 5: Warm, high rainfall, and Scenario 6: Hot, low rainfall). Stream flow values are projected using long term (30-year), annual, and seasonal (including winter flood season and summer base flow) time steps.

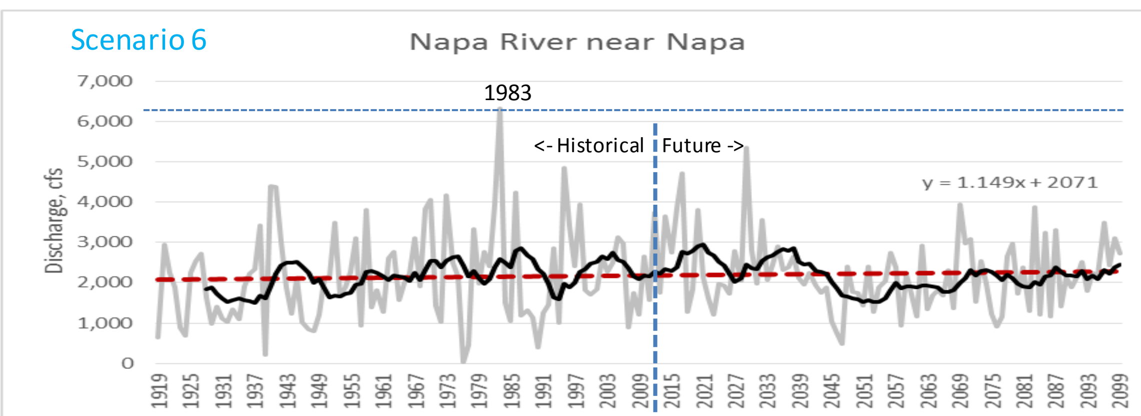
Historic (1920-2009) and modeled (2010-2099) annual river flows were compared over the last 90 years to projections for the next 90 years. For the upstream reach, the historic peak annual flow value for 1983 would be exceeded 3-5 times in the warm-high rainfall scenario, with an increasing trend in river flow overall that eliminates any low flow years as extreme as those included in the previous 90 year period. Under the warm-moderate rainfall scenario (Scenario 3) it would meet or exceed the historic peak annual flow value for 1983 1-3 times, and under the hot-low rainfall (Scenario 6), it would only meet this value one time.

For the downstream reach represented by flows at the Napa gage, Figure 3 compares annual discharge for the same three scenarios. A similar pattern is observed to the upstream gages, but with reduced inter-annual variability, and reduced differences between future scenarios.

Figure 3. A comparison of historic (1920-2009) and projected (2010-2099) Napa River discharge, Napa Gage



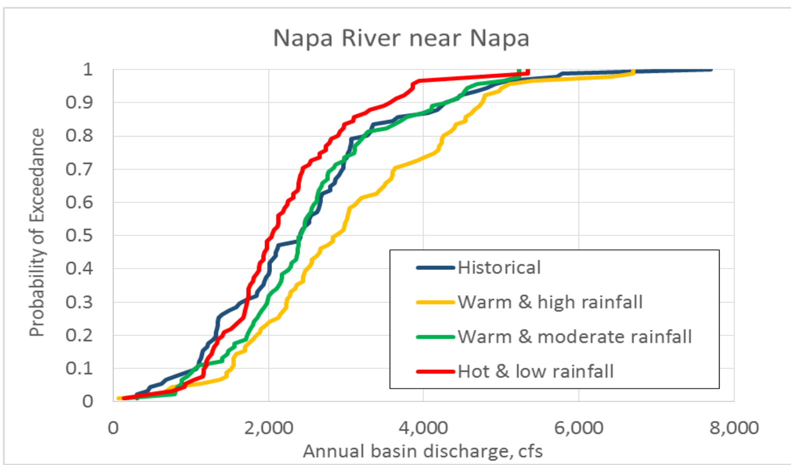




A comparison of projected and historic river flow conditions at the gage on the lower river to the upper river shows that annual peaks are less likely in the lower reach than the upper under all future scenarios. What the model is capturing is that since the alluvial valley widens and deepens in the downstream direction, the deeper soils provide for additional room to store rainfall in the soils and as groundwater recharge such that a lower fraction runs off and is available for stream flow with warming. This translates into relatively smaller peak flows downstream in comparison to upstream under all three warming scenarios.

Our stream flow analysis enables us to generate a "cumulative flow exceedence curve" for the Napa River at the Napa gage, which is a common tool for engineering river designs. For example, it is possible to compare values for the 0.50 exceedence probability event, which is often used as a first-order estimate of "bankfull" flow conditions. While the historic and projected warm and moderate rainfall future (Scenario 3) display equivalent discharge values for the 0.50 probability of exceedence (approximately 2500 cfs discharge), consideration of the low and high rainfall scenarios generate an estimated range of 2000-3000 cfs for the same exceedance probability.

Figure 4. Cumulative flow exceedence curves, historic (1920-2009) and projected (three scenarios, 2010-2099) Napa River discharge, Napa Gage



PowerPoint slides 48-51 in the companion *CRNB Napa Valley.ppt* further illustrate the discussion above.

Management Question: What is the potential increase in flood risks from drainages that exit into urban areas of the Napa Valley prone to flooding?

To analyze potential flood risks we isolated BCM runoff and discharge values for months comprising the winter flood season (December-January-February). Discharge values were used for gaged drainages, while cumulative runoff of the contributing watershed area was used for un-gaged drainages. We used the historic winter season maximum discharge or runoff value on record (1920-2010) for each gage as a conservative "flood risk" threshold (winter 1969 for upstream reaches, and winter 1986 for downstream reaches). We assumed that exceeding this winter season maximum or "peak" value from the historic record would be an indicator of likely flooding conditions in the future. We then calculated the number of winter season "peak values" projected to exceed the historic maximum threshold to compare different future scenarios.

The pattern observed in annual discharge series above was even more amplified with the isolation of winter conditions, with potentially more frequent and intense winter discharge peaks projected on the Napa River upstream relative to downstream under the moderate and high rainfall futures (Scenario 3 and 5 respectively). Out of the upstream gages, the winter flood threshold was exceeded more frequently at the Saint Helena gage than at the Calistoga gage. However, no exceedences of the winter peak threshold were associated with the hot and low rainfall future (Scenario 6), as summarized below.

Napa River upstream: Calistoga gage

Scenario 3: Warm, moderate rainfall – 2 years peak would exceed historic winter discharge peak
Scenario 5: Warm, high rainfall – 17 years would exceed historic winter discharge peak
Scenario 6: Hot, low rainfall – no years would exceed historic winter discharge peak

Napa River upstream: Saint Helena gage

Scenario 3: Warm, moderate rainfall – 7 years peak would exceed historic winter discharge peak
Scenario 5: Warm, high rainfall – 19 years would exceed historic winter discharge peak
Scenario 6: Hot, low rainfall – no years would exceed historic winter discharge peak

Napa River downstream: Napa gage

Scenario 3: Warm, moderate rainfall – no years would exceed historic winter discharge maximum
Scenario 5: Warm, high rainfall – 10 years would exceed historic winter discharge maximum
Scenario 6: Hot, low rainfall – no years would exceed historic winter discharge maximum

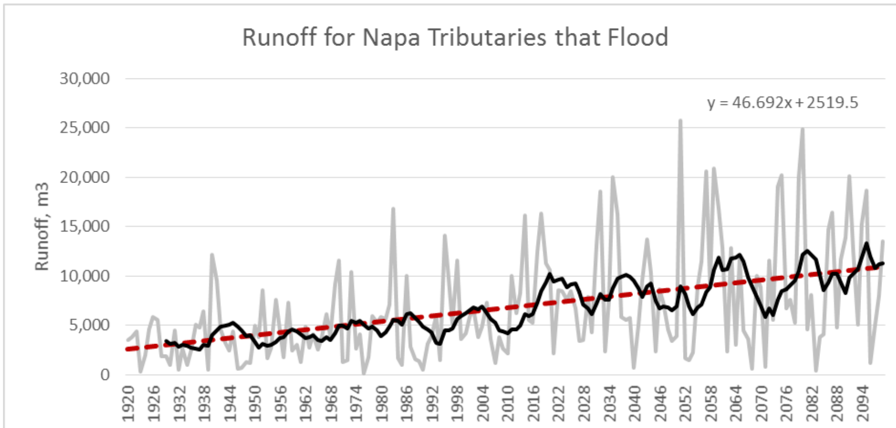
In addition to evaluating winter flood risks on the Napa River, managers wanted to evaluate the potential impact of climate change on flood risk frequency on nine tributaries to the Napa River that lack stream gages. These included Sulphur, Tulacay, and Sarco Creeks. We utilized cumulative winter season runoff for these nine drainages combined as an indicator of excess available water that could contribute to flooding. We considered exceeding the maximum winter runoff value of the historic record to indicate potential flood risks. Thus using a similar approach to defining a flood threshold based on the maximum winter discharge value of record for a gaged stream, the following range of exceedances in future projections were evaluated.

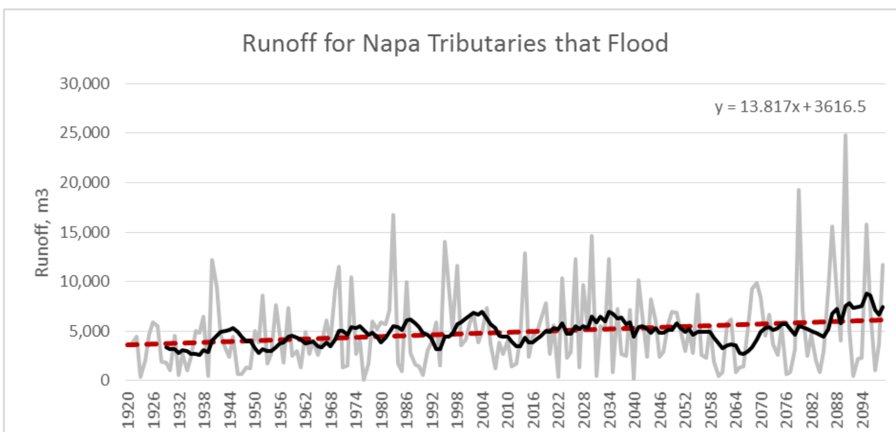
Napa River tributaries that flood:

Scenario 3: Warm, moderate rainfall – 2 years would exceed historic winter runoff maximum
Scenario 5: Warm, high rainfall – 10 years would exceed historic winter runoff maximum
Scenario 6: Hot, low rainfall – no years to exceed historic winter runoff maximum

We should be clear that a BCM data set at monthly time steps cannot help to evaluate the impact of climate change on a potential flood hydrograph (measurement of flow over time) at the time scale of actual storm events (hours or less) to evaluate the potential magnitude of the flood peak itself. However, this analysis of cumulative winter discharge or runoff can be a starting point for evaluating different levels of flood risks associated with different future scenarios. Additional work could help define a more sensitive threshold for winter conditions: our use of the maximum of record defines a very conservative flood risk indicator since on the order of ten or more floods have likely occurred in the Napa Valley over the 1920-2010 historic reference periods.

Figure 5a .Cumulative winter runoff, historic (1920-2009) and projected (three scenarios, 2010-2099)





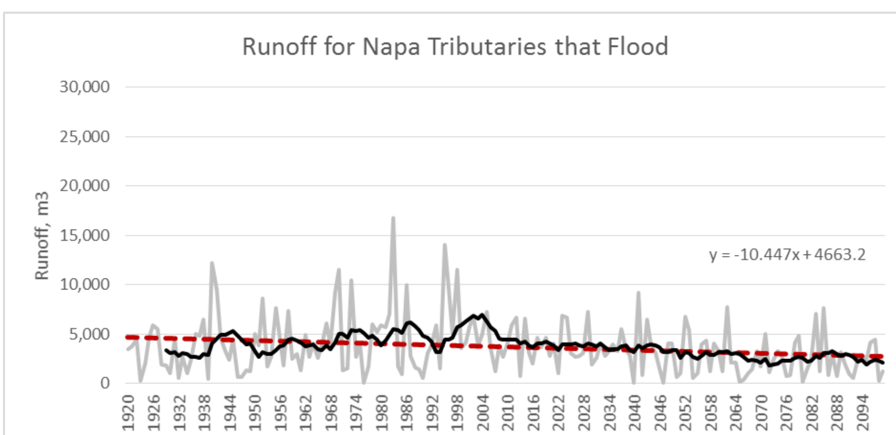
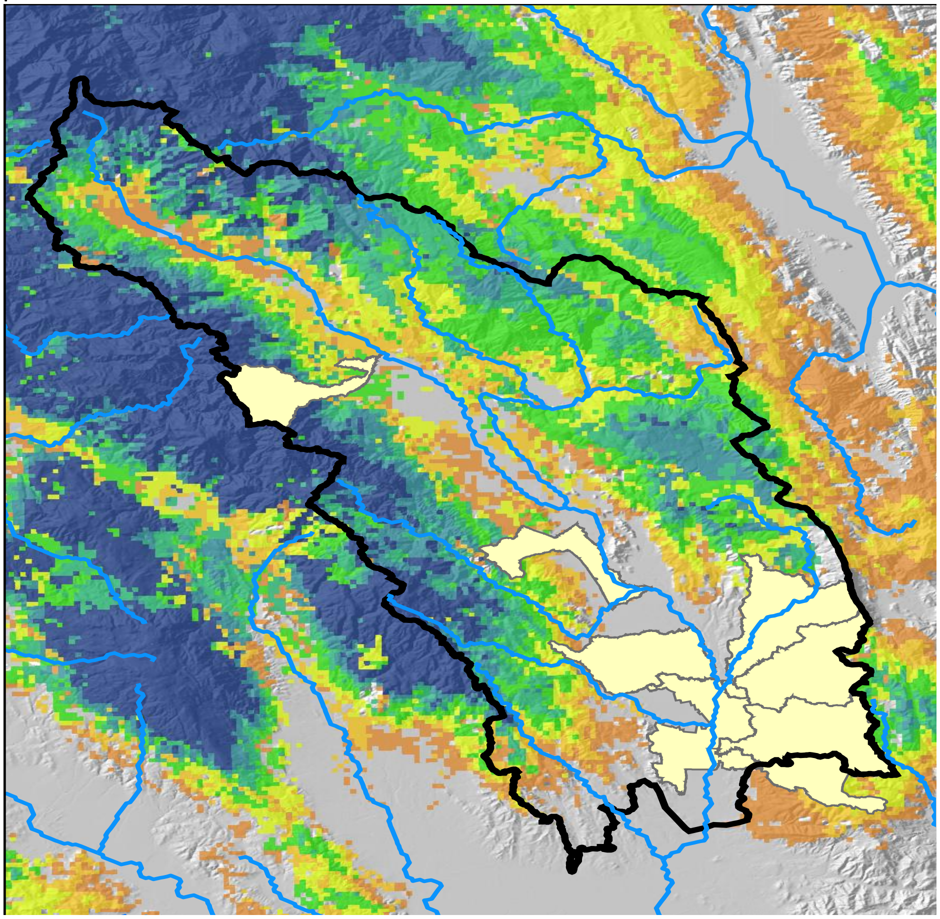


Figure 5b. Napa tributaries that flood

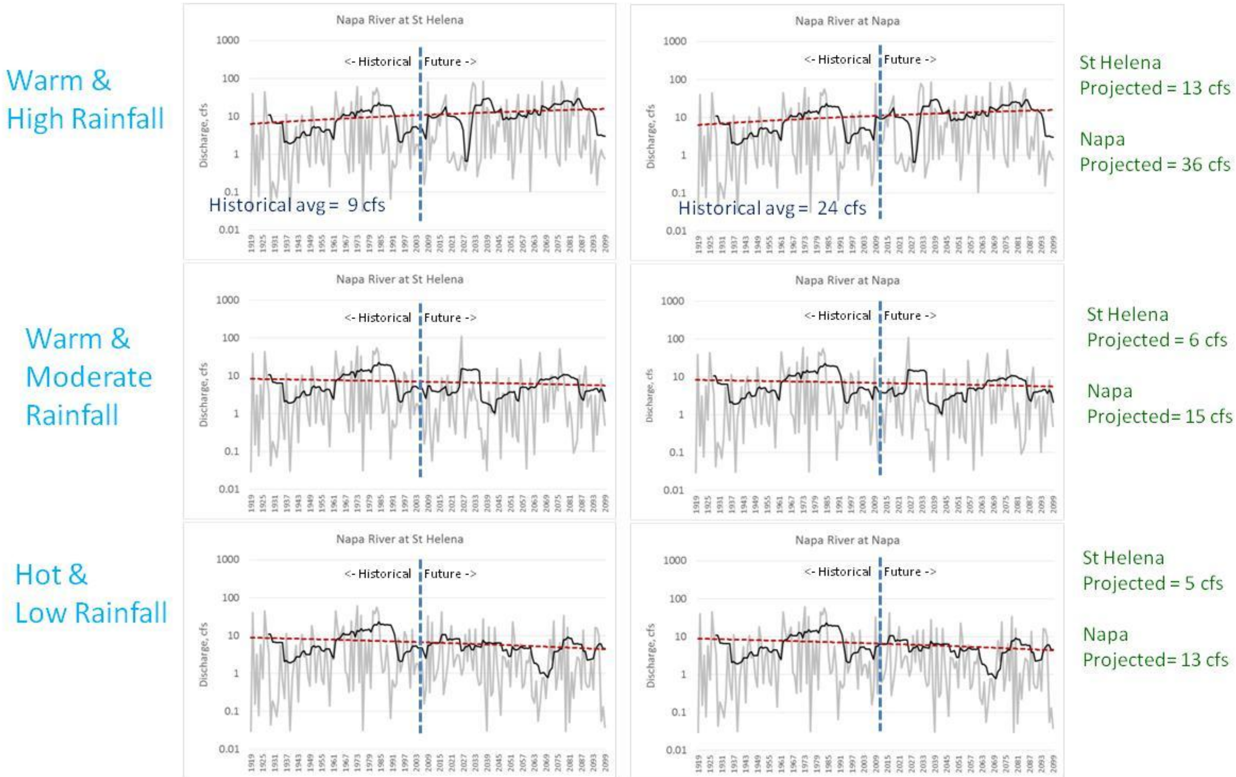


Beige areas indicate Napa River tributaries that flood

PowerPoint slides 53-56 in the companion *CRNB Napa Valley.ppt* illustrate the flood risk analysis described above.

Management Question: How will climate change potentially impact the hydrology of high value main stem reaches and tributaries for fish?

A key concern for managers is the potential impact of climate change on the hydrology of streams recognized for their value as cold water habitat for salmonid species, including Steelhead trout and Chinook salmon. To respond to this concern, periods of summer low flows (August-September-October) were assessed for the Napa River at the Saint Helena and Napa gages as an indicator of flow variability across the watershed (Figure 6). The historic 3-month average summer flow (1920-2009) for the Saint Helena gage was estimated at 9 cfs, while the equivalent value at the Napa gage was 24 cfs. Projected average values for the 2010-2100 time period are as follows.



Upstream: Saint Helena gage

Scenario 3: Warm, moderate rainfall – 6 cfs, a 33% reduction
Scenario 5: Warm, high rainfall – 13 cfs, a 44% increase
Scenario 6: Hot, low rainfall – 5 cfs, a 44% reduction

Downstream: Napa gage

Scenario 3: Warm, moderate rainfall – 15 cfs, a 38% reduction
Scenario 5: Warm, high rainfall – 36 cfs, a 50% increase
Scenario 6: Hot, low rainfall – 13 cfs, a 46% reduction

In terms of base flows, only the high rainfall scenario results in higher base flows: otherwise base flows are projected to decline on the order of greater than 40% on average. The variability of these values speaks to the need for ongoing monitoring of stream flow to confirm actual trends in real time.

Long-term trends for available water summer water on high value fisheries tributaries were also assessed to see how they may differ from the historic record. Table 6 summarizes potential long-term trends in 30-year time steps in total volumes of recharge and runoff (in acre-feet) feeding each tributary of concern. The change from historic under climate change scenarios ranges from +64% to –37%. Specific tributaries shown to be more vulnerable to climate fluctuation (Hipper, Sarco and Carneros Creeks) experience greater than 40% available water in the hot, low rainfall scenario. More resilient streams relative to recharge and runoff functions include Garnett, Simmons Canyon, Kortum Canyon, and Sode Creeks, which experience reductions on the order of 31% or less under the hot and low rainfall scenario.

Slides 57-60 in *CRNB Napa Valley deck.ppt* address this scenario

Management Question: What is the spatial variability in potential groundwater recharge and where are high value recharge zones located? How will climate change impact potential groundwater recharge in the Napa Valley?

From 1981-2010, the average amount of recharge per unit area for the Napa Valley was 10.6 inches per year. In terms of spatial variation, potential groundwater recharge ranges includes zones of high recharge ranging from 20-30 in/y in alluvial fans located in the Northern end of the valley and at the flanks of the Eastern Mayacamas. Zones of low recharge are comprised of high elevation, resistant bedrock in both the Mayacamas and Berryessa Ranges, with groundwater recharge there estimated at <2.5 inches per year. On the valley floor, groundwater recharge rates are estimated to vary from 7.5-12.5 in/y in the Northern portion of the valley, and from 2.5-12.5 in/y in the Southern portion of the valley.

BCM ranges for future valley-wide average recharge are as follows for mid- and end-century.

For 2040-2069, the range of potential Napa Valley annual recharge values is as follows.

Scenario 3: Warm, moderate rainfall – 10.5 in/year 1% less than the current average
Scenario 5: Warm, high rainfall – 13.4 in/year 27% greater than the current average
Scenario 6: Hot, low rainfall – 7.5 in/year 29% less than the current average

For 2070-2099, the range of potential Napa Valley annual recharge values is as follows.

Scenario 3: Warm, moderate rainfall – 11.1 in/year 5% greater than current
Scenario 5: Warm, high rainfall – 13.4 in/year 27% greater than current average
Scenario 6: Hot, low rainfall – 7.8 in/year 27% less than the current average

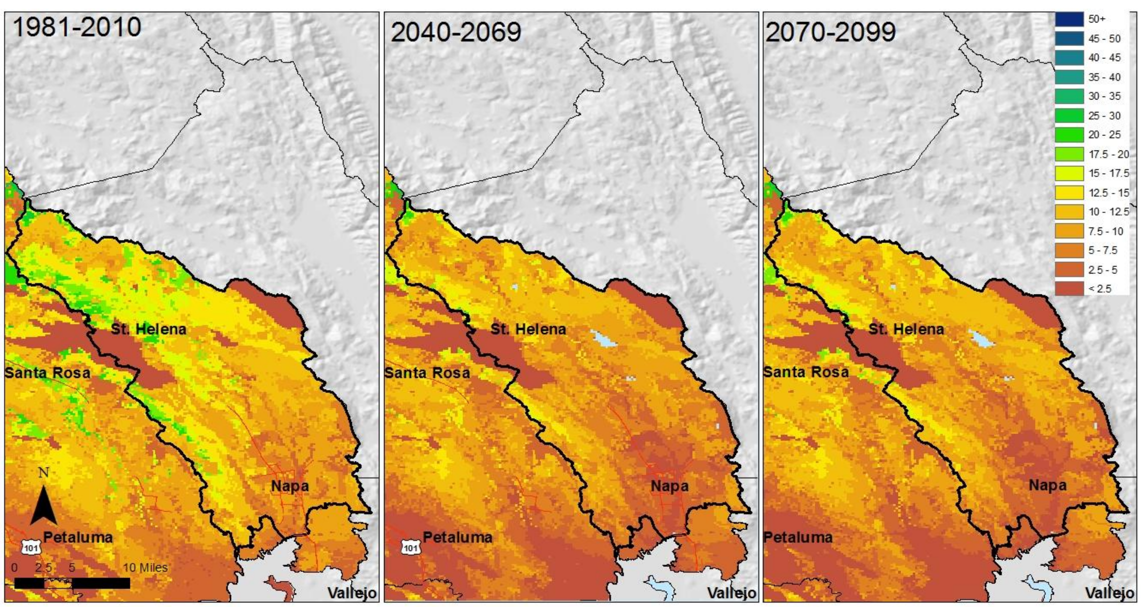
Under the hot-low rainfall future (Scenario 6), 2.5 inches of groundwater recharge per unit area is projected to be lost annually compared to 1981-2010, which amounts to a 30% reduction in groundwater recharge valley-wide. Under this low rainfall scenario, by mid-century, it is projected that much of the relatively high value recharge zones defined in 1981-2010 will be functionally providing significantly less recharge under a hot-low rainfall future, with more moderate values, on the order of 5-10 in/year, currently more characteristic of the valley floor.

Table 6: Water availability projections (recharge + runoff in acre-ft) generated for each Napa Valley fisheries tributary using 30-year averages.

		Scenario	**Warm, High Rainfall**		**Warm, Mod Rainfall**		**Hot, Low Rainfall**		
Fish Bearing Stream Name	***Area*** (acres)	*1981-2010* (acre-feet/yr)	*mid-century* (acre-feet/yr)	*end-century* (acre-feet/yr)	*mid-century* (acre-feet/yr)	*end-century* (acre-feet/yr)	*mid-century* (acre-feet/yr)	*end-century* (acre-feet/yr)	*end-century* % change
Garnett Creek	4780	120022	176393	198605	121283	137948	85508	84781	*-29%*
Napa River - Upper Calistoga Reach	1507	30282	45270	51887	30024	34739	20332	19917	*-34%*
Simmons Canyon Creek	2087	48547	70820	80026	48488	55421	34076	33726	*-31%*
Selby Creek	3755	86229	126050	142448	85918	98425	60087	59325	*-31%*
Blossom Creek	2442	49295	72873	83497	48337	55915	32749	32144	*-35%*
Cyrus Creek	1888	41404	59477	67792	39906	46013	27508	27025	*-35%*
Kortum Canyon Creek	1799	44252	62692	70676	43329	49366	30840	30521	*-31%*
Bell Creek	2673	52945	79733	91040	53214	62142	36718	36092	*-32%*
Ritchie Creek	1536	38698	54321	61449	37118	42501	25960	25596	*-34%*
Mill Creek	1410	34545	47784	54213	32464	37386	22671	22304	*-35%*
York Creek	2509	60831	82908	94223	56268	65151	39356	38785	*-36%*
Napa River - Lower St. Helena Reach	4381	69199	105269	123662	65947	80203	42718	40707	*-41%*
Sulphur Creek - Main Fork	3428	92821	122412	138120	85117	97612	61182	60582	*-35%*
Conn Creek - Lower Reach	7298	115363	170126	199131	108644	131510	72051	69166	*-40%*
Heath Creek	1782	48299	64577	72682	45048	51628	32523	32223	*-33%*
Bear Creek	6142	124454	174639	200881	116567	137505	80865	79044	*-36%*
Dry Creek	12728	287807	394976	451298	268022	314045	188026	184618	*-36%*
Soda Creek	2966	53081	78056	89041	52806	62382	37063	36399	*-31%*
Hopper Creek	3003	43527	61690	72938	38674	47568	24748	23667	*-46%*
Milliken Creek - Main Fork	5695	76765	113104	132056	71604	88155	47527	45718	*-40%*
Redwood Creek - Upper Reach	4485	107863	146929	168481	99447	116968	69157	67376	*-38%*
Pickle Canyon	1807	41423	55046	63231	37087	43854	25699	25135	*-39%*
Sarco Creek	5398	64364	97206	115271	59412	74474	37532	35239	*-45%*
Carneros Creek	5710	90805	128544	151488	81394	100362	53185	50928	*-44%*
Tulucay Creek	8058	113506	163566	190459	107216	130370	72190	69996	*-38%*
Huichica Creek	4028	57300	84348	99601	53240	66078	34723	33282	*-42%*
Average Values		*76678*	*109185*	*125546*	*72561*	*85682*	*49807*	*48627*	*-37%*
Percent Change			*42%*	*64%*	*-5%*	*12%*	*-35%*	*-37%*	

PowerPoint slides 57-60 in the companion *CRNB Napa Valley deck.ppt* illustrate the discussion above.

Figure 6. Current versus projected mid- and end-century zones of potential groundwater recharge, Scenario 6: Hot and low rainfall, Napa Valley



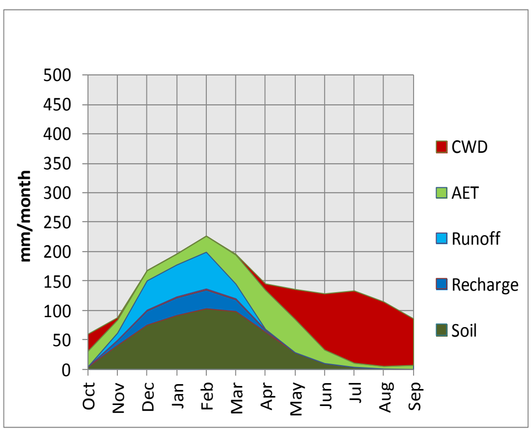
PowerPoint slides 61-65 in the companion *CRNB Napa Valley.ppt* illustrate the discussion above.

Management Question: How will climate change potentially impact the seasonality of the Napa Valley's water cycle?

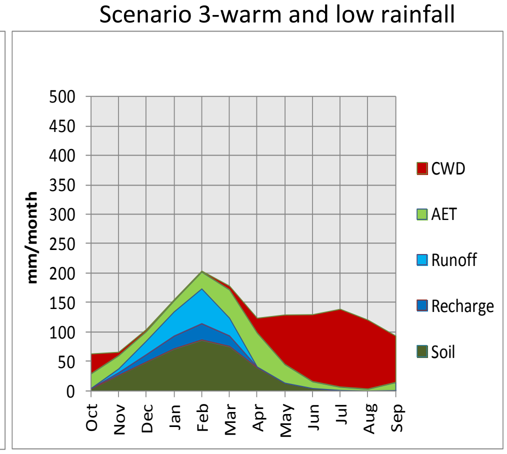
A seasonal watershed diagram provides a way to visualize how BCM variables including recharge, runoff, soil storage, actual evapotranspiration, and climatic water deficit vary over time in relationship to one another. A comparison of the watershed diagram for current conditions to projections for 2070-2099, under Scenario 3-warm, moderate rainfall, shows a projected decrease in all climate variables, except maximum and minimum air temperature and climatic water deficit, which are projected to increase. This results in a more "peaked" water cycle, with reduced water availability in the fall and spring, and water deficits beginning to accumulate earlier in the spring. An online tool for users to compare projected impacts to the annual water cycle by planning watershed for specific years of interest and with multiple projections will be available at the California Climate Commons later in 2016 capable of generation seasonal watershed diagrams for all planning g watershed in the project area.

Figure 7. Current versus end-century seasonal watershed diagram, Scenario 6-hot and low rainfall, Napa Valley.

Seasonal Water Diagram 1980-2009, Current



Seasonal Water Diagram 2070-2099
Scenario 3-warm and low rainfall



CWD= Climatic Water Deficit AET= Actual; Evaporation

PowerPoint slides 66-67 in the companion *CRNB Napa Valley.ppt* illustrate the summary above.

Agricultural Sustainability

Management Question: How will the agricultural lands of the Napa Valley be potentially impacted by climate change in terms of irrigation demand?

As an attribute of the landscape that integrates the combined effects of available rainfall, temperature, and watershed structure, climatic water deficit (CWD) is an excellent indicator of native vegetation cover or agricultural irrigation demand. It 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 on Napa Valley agricultural lands is projected to increase even in high rainfall scenarios. From 1981-2010, the current average climatic water deficit for the Napa Valley was an average of 31 inches per year per unit area. By the mid-century, water deficits are projected to increase from 6-12%, with an average 7.3% increase across scenarios. By the end of the century, a range of 9-20% greater water deficit, with an average increase of 13% across all scenarios, is projected.

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

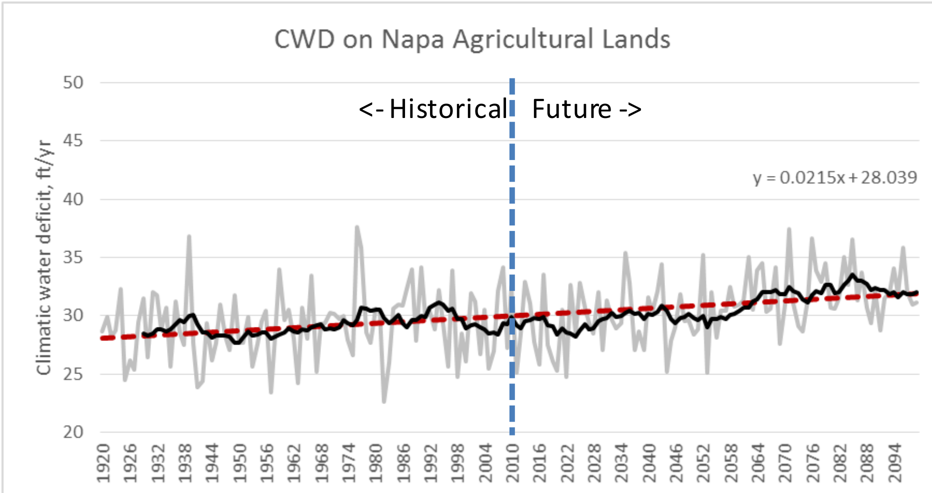
Scenario 3: Warm, moderate rainfall – 32 in/year, 6% greater annual deficit than current
Scenario 5: Warm, high rainfall – 32 in/year, 4% greater annual deficit than current
Scenario 6: Hot, low rainfall – 34 in/year, 12% greater annual deficit than current average

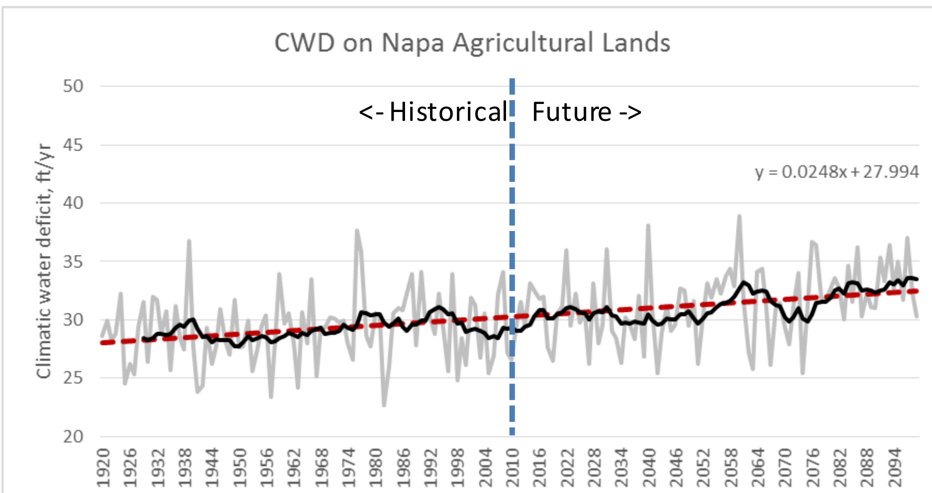
For 2070-2099, the range of potential change in climatic water deficit is projected as follows.

Scenario 3: Warm, moderate rainfall – 34 in/year (with 38.2 in/y rainfall), 10% greater deficit than current average
Scenario 5: Warm, high rainfall – 33.4 in/year (with 48.6 in/y rainfall), 9% greater deficit than current average
Scenario 6: Hot, low rainfall – 37 in/year (with 27.7 in/y rainfall), 20% greater deficit than current average

With a 10% increase in water deficit equivalent to approximately 3 in/year of water per unit area over agricultural areas, this analysis provides a first order indicator of potentially increased irrigation demand for current crop cover. This analysis could be refined by construction of a correlation between historic estimates of water used for agricultural irrigation with the historic BCM geodatabase provider. Adaptation strategies could evaluate new sources of water, or alternatively, agricultural adaptation strategies could look at crop management approaches to mitigate the effects of increased temperature on water demand, including, for vineyards, crop selection and planting layouts.

Figure 9a. Historic (1920-2009) and projected (2010-2099) climatic water deficit on agricultural lands, Napa Valley, three future scenarios (5, 3, 6 respectively).





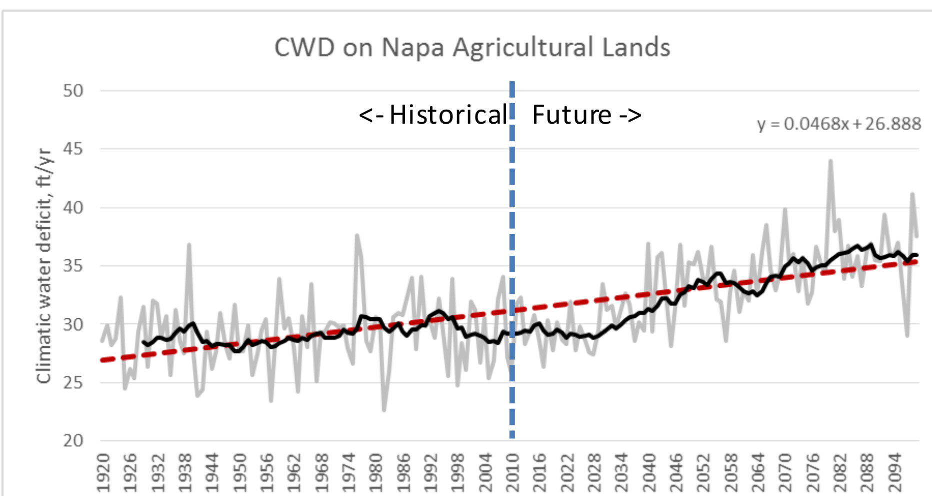
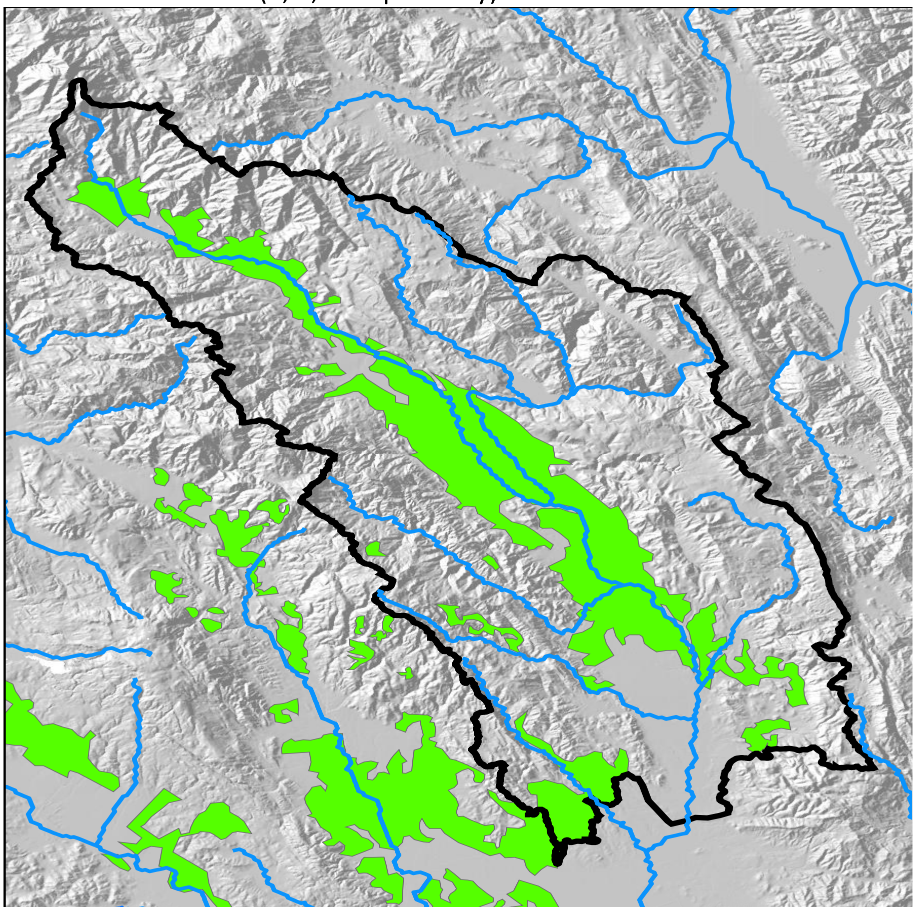


Figure 9b. Historic (1920-2009) and projected (2010-2099) climatic water deficit on agricultural lands, Napa Valley, three future scenarios (5, 3, 6 respectively).



Green areas represent agricultural lands analyzed

PowerPoint slides 65-67 in the companion *CRNB Napa County.ppt* illustrate the discussion above.

Native Vegetation Response and Fire Risks

Management Question: What will be the impact of climate change on important upland vegetation types, and can you identify potentially stable vegetation communities for conservation planning?

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 the Napa Valley 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 they will still be highly dynamic and relatively sensitive to climate-driven vegetation transitions (Ackerly et al. 2015).

Changes in vegetation were modeled for five Napa Valley “Landscape Units” defined by the Bay Area Upland Habitat Goals Project (BAOSC 2011). In Napa Valley, for warm scenarios with either high or low rainfall (Scenarios 4 and 5), there is an increase in suitable conditions for Chamise Chaparral, Coast Live Oak, and Interior Live Oak from approximately 5% of the total landscape today to 5-25% by late century, depending on the amount of rainfall. Under the warm, moderate rainfall scenario (Scenario 3) suitable climate for Semi-desert Scrub emerges and becomes common by late century. With the hot, low rainfall scenario (Scenario 6), suitable climate for grassland declines from 20% today to less than 10% in the late century. With low warming and low rainfall (Scenario 1), mixed Montane Chaparral declines from ~10% of the total landscape today to less than 5% by mid-century. When comparing different Landscape Units, there can be significant differences between projected vegetation responses under the same future climate scenario, as illustrated by Blue Ridge Berryessa compared to the Southern Mayacamas Mountains. See file *CRNB Napa Valley Vegetation Reports.pdf* from Appendix A.

Using the Northern Mayacamas Mountains as an example, 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 (See Appendix A). For example, in this Landscape Unit, California Bay Forest is not sensitive to temperature or rainfall, and therefore does well in all future scenarios regardless of warming magnitude and precipitation. Oregon Oak is sensitive to rainfall in the Northern Mayacamas, and does well in high rainfall scenarios (Scenario 3 or 5), but declines in low rainfall (Scenario 6). It also fairs worse in hotter scenarios, but the impacts are not substantial. Canyon Live Oak is sensitive to rainfall and temperature; therefore it shows declines in all scenarios. For a comparison of differential vulnerability of vegetation across Napa Valley Landscape Units see Appendix A.

PowerPoint slides 73-80 in the companion *CRNB Napa Valley.ppt* illustrate the discussion above.

Management Question: What will be the impact of climate change on the potential fire frequencies in the Napa Valley?

From 1971-2000, the average historic fire return interval for the naturally vegetated portions of the Napa Valley was every 129 years. From 2070-2099, fire return intervals for the entire valley are projected as follows.

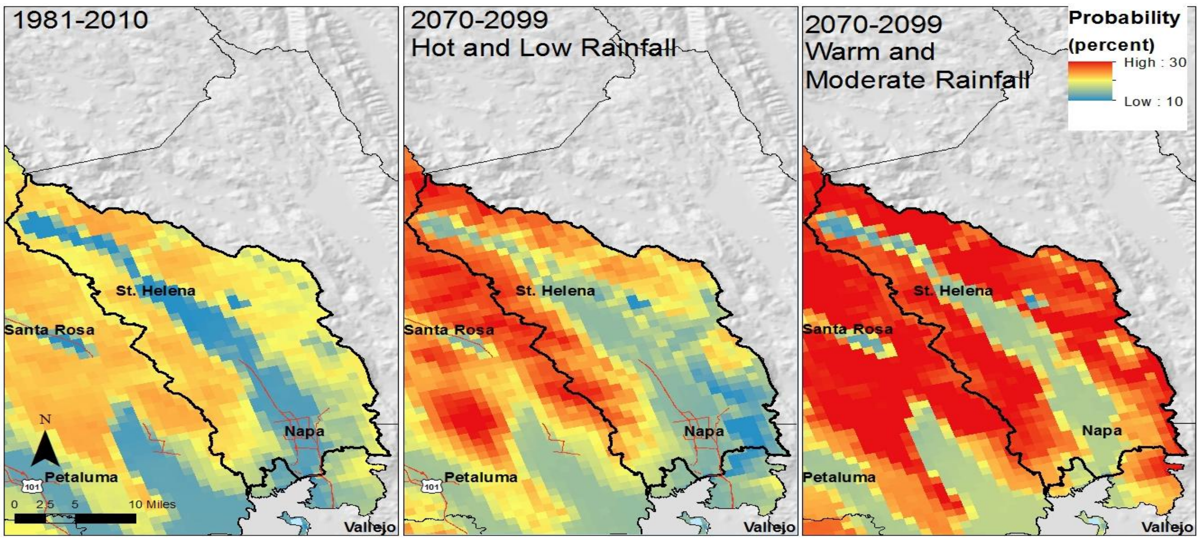
> *Scenario 3: Warm, moderate rainfall* – 87 year average projected return interval, reduced by 33%
>
> *Scenario 6: Hot, low rainfall* – 119 year average projected return interval, reduced by 8%

From 1971-2000, the average historic probability of burning occurring one or more times within 30 years for Napa Valley was 21%. From 2070-2099, the probability of burning doubles in some locations, with the probability throughout the region projected as follows.

Scenario 3: Warm, moderate rainfall – 29% probability
Scenario 6: Hot, low rainfall – 22% probability

We note that these zonal statistics should be complemented by inspection of the maps in Figure 10, which show that in montane locations, in general the probability of burning within a 30-year period approximately doubles from a typical value of 15% to approximately 30%.

Figure 10. Probability of fire one of more times per 30-year time period, 1981-2010, Napa Valley



It's important to note that the probability of fire occurring is actually higher in the warm and moderate rainfall scenario as opposed to the hot and low rainfall scenario due to the impact of more rainfall on the generation of fuels.

PowerPoint slides 81-85 in the companion *CRNB Napa Valley.ppt* illustrate the discussion above.

Bridging Science and Management

Climate Ready North Bay resources developed for Napa Valley are intended to inform specific land and water management actions under the County's jurisdiction today and in the future. In the process of detailed exchanges with Napa County staff, the following potential applications of and audiences for these data sets were identified.

Potential Climate Ready North Bay Data Applications

- Use of localized climate temperature and rainfall data to inform the County's current Climate Action Plan.
- Presentations to raise public awareness regarding the benefits of greenhouse gas

reduction (mitigation) and the need to plan for adaptation.
- Use of hydrologic data to inform partner agencies' long-term planning for surface water supply including the cities of Napa and Saint Helena.
- Use of recharge maps to inform the groundwater management plan underway, as well as planning required by the new Sustainable Groundwater Management Act, in particular, to identify high recharge zones.
- Integration of potential vegetation transition risks and fire hazards into long-term natural resource management plans and fire mitigation planning.
- Use of hydrologic assessments to evaluate potential high value resource streams and riparian zones at risk, as well as development of strategies to build adaptation into maintenance and restoration planning.

Potential Climate Ready Data Audiences
- Other County staff
- Elected and other decision makers, including the Watershed Information Conservation Council (WICC)
- Consultants working on other dimensions of natural resource management and climate readiness for the County
- Developers
- Agriculture
- The community at large

Participating Stakeholders
With special thanks to Jeff Sharp for coordination and all participating managers:
- Brian Bordona, Planning, Building and Environmental Services
- Jason Hade, Planner III, Planning, Building and Environmental Services
- Matt Lamborn, Planner III/GIS, Planning, Building and Environmental Services
- Patrick Lowe, Natural Resources Program Manager, Public Works
- David Morrison, Director, Planning, Building and Environmental Services
- Jeremy Sarrow, Watershed & Flood Control Specialist, Flood District
- Jeff Sharp, Principal Planner, Public Works Natural Resources Conservation
- Rick Thomasser, Watershed and Flood Control Operations Manager, Flood District

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APPENDICES

Appendix A: List of Climate Ready Analyses Conducted for Napa Valley

REGIONAL HYDROLOGY GIS DATABASE

Data Product: TBC3 Bay Area Basin Characterization Model Database

An ESRI Geographical Information System (GIS) raster database. This database includes 18-acre monthly resolution data for Sonoma County, including historic data for 1920-2010 and 18 climate future projections selected to cover the full range of internationally peer-reviewed Global Climate Circulation Models (Flint and Flint 2013). This database is the source of all map products and BCM time series represented in the technical memo and PowerPoint slide deck. It may be queried for future analyses by partner agencies.
Filename: *CRNB TBC3 Bay Area BCM 1920-2099.gdb*

NORTH BAY RAINFALL DATABASE

Data Product: Regional Rainfall Analysis

Spreadsheet of annual rainfall totals for North Bay study region and frequency analysis of exceedence of high and low rainfall relative to benchmarks, including minimum and maximum of historic record and 10^{th} and 90^{th} percentiles of assumed "pre-climate change" conditions. Source data is the California BCM (Flint and Flint 2013).
Filename: *CRNB annual regional rainfall.xls*

NAPA VALLEY CLIMATE: HYDROLOGY-FIRE VARIABLES

Data Product: Basin Characterization Model and Fire Model Outputs-Napa Valley Averages

Spreadsheet table of downscaled climate input values (temperature and precipitation) and BCM outputs including runoff, recharge, climatic water deficit, and evapotranspiration averaged over Sonoma County in 30-year time steps for two historic time period and three projected periods for three "bounding" business-as-usual scenarios (with respect to emissions), including maximum, moderate, and minimum rainfall estimates for the region. A separate tab summarizes fire model results for 30-year time steps.
Filename: *CRNB Napa Valley BCM 30-y water supply and fire tables.xls*

NAPA VALLEY BCM: DERIVED ANNUAL TIME SERIES

Data Product: Annual Time Series Plots-Napa River Estimated Flows, Flood-prone Tributaries, and Water Deficits on Agricultural Lands

Spreadsheet plots of aggregated flow including historic and projected estimates for gages at Calistoga, Saint Helena, and the town of Napa on the Napa River, 1920-2100. Queried time periods for flow include winter periods (December, January, February) and summer low flows

(August, September, October). Time series data also provided for winter runoff of flood-prone tributary watersheds and for annual water deficits on agricultural lands.
Filename: *CRNB Napa Valley BCM gages and other annual time series.xls*

WATER SUPPLY DATABASE: RUNOFF AND RECHARGE BY VALLEY SUB AREA

Data Product: Excel Pivot Table-All Models-Runoff and Recharge for Identified Sub-Areas

Pivot table of water supply indicators (runoff and recharge) containing all CRNB model results (historic and projected) for Napa Valley sub-areas, including eastern and western mountains and valley floor.
Filename: *CRNB Napa Valley-sub areas runoff and recharge pivot table.xls*

WATER SUPPLY PROJECTIONS: NAPA VALLEY RESERVOIRS

Data Product: Excel Pivot Table-All Models-Reservoir Analysis

Pivot table of water supply indicators (runoff and recharge) specifically for reservoir drainages with a tab per CRNB model (historic and projected) for 15 reservoirs identified in the Napa Valley for analysis.
Filename: *CRNB Napa Valley reservoirs-detailed analysis.xls*

HYDROLOGY OF FISH BEARING STREAM: NAPA VALLEY

Data Product: Excel Pivot Table-Fisheries tributaries

Pivot table of water supply indicators (runoff and recharge) specifically for fisheries with a tab per CRNB model (historic and projected) for 26 fish-bearing stream drainages identified in the Napa Valley for analysis.
Filename: *CRNB Napa Valley fisheries drainages detailed analysis.xls*

IMPACTS OF CLIMATE CHANGE ON VEGEATION-NAPA VALLEY

Data Product: Standardized 4-page vegetation reports by landscape

Based on the dynamic vegetation model (Ackerly et al. 2015) for all landscape units of the project.
Filename: *CRNB Napa Valley Vegetation Reports.pdf*

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%**

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. IPCC Global Models used in the TBC3 Bay Area California Basin Characterization Model downscaled climate-hydrology knowledge base

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		MPI-ESM-LR	5	RCP 4.5	BCSD

Originating Group(s)	Country	Model Abbreviation	IPCC Assessment Report	Emissions scenario or representative concentration pathway	Downscaling method
Institute for Meteorology)					
Meteorological Research Institute	Japan	MRI-CGCM3	5	RCP 2.6	BCSD
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

* Bias correction/spatial downscaling (Wood and others, 2004)

** Constructed analogues (Hidalgo and others, 2008)

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

Variable	Code	Creation Method	Units	Equation/model	Description
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 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* Historic *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 base flow 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 base flow (stream flows during periods absent precipitation), especially during multi-year droughts. Decreases in recharge results in less groundwater storage and loss of base flow, 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: Napa County Basin Characterization Model, Napa Valley Watershed Summary

Table 1: Basin Characterization Model, Napa Valley Watershed, 1951-2099.

		Historic	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	35.6	36.4	44.8	48.6	35.1	38.2	28.7	27.7
	SD	6.5	5.7	7.6	8.1	6.0	6.4	5.0	4.8
Tmn	Deg F	86.6	39.4	42.8	32.9	41.6	44.4	43.6	46.7
	SD	34.1	32.9	32.9	90.9	32.8	32.8	32.8	32.8
Tmx	Deg F	86.6	86.5	90.9	93.9	90.5	93.1	93.8	98.0
	SD	34.1	34.0	34.0	34.0	34.0	34.0	34.0	34.0
CWD	in	30.2	30.6	31.9	33.4	32.3	33.6	34.3	36.8
	SD	3.3	3.3	3.4	3.4	3.2	3.4	3.1	3.1
Rch	in	10.9	10.6	13.4	6.0	10.5	11.1	7.5	7.8
	SD	5.0	4.7	6.0	13.0	4.8	5.0	3.7	3.9
Run	in	7.1	7.8	13.0	16.1	6.9	9.5	4.3	3.8
	SD	6.8	6.8	9.3	10.7	6.5	7.5	4.5	4.4

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

Table 2: Basin Characterization Model, Napa Valley Watershed – Projected change in temperature (° F) and hydrologic indicators (% change from current), three scenarios.

			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		36.4	23%	34%	-3%	5%	-21%	-24%
Tmn	Deg F		39.4	9%	-17%	5%	13%	11%	19%
Tmx	Deg F		86.5	5%	9%	5%	8%	8%	13%
CWD	in		30.6	4%	9%	6%	10%	12%	20%
Rch	in		10.6	27%	-44%	-1%	5%	-29%	-27%
Run	in		7.8	67%	107%	-11%	22%	-44%	-51%

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