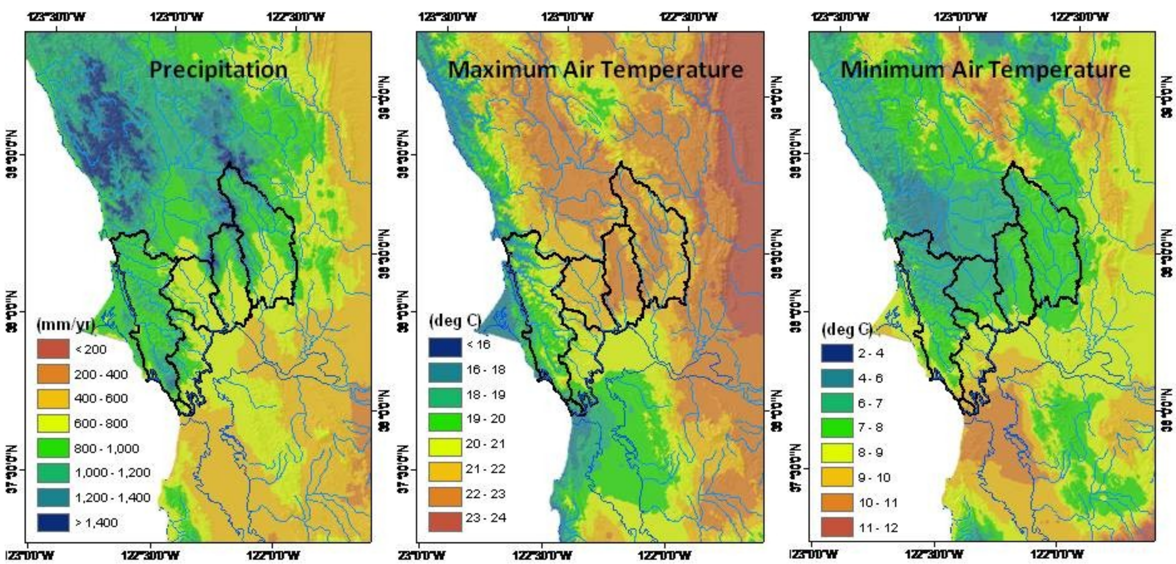
Adapting to Climate Change
State of the Science for North Bay Watersheds

A Guide for Managers

December 2010



Average annual temperatures and precipitation, 1971-2000

A report prepared for the North Bay Watershed Association by the Dwight Center for Conservation Science at Pepperwood in partnership with the US Geological Survey and the Bay Area Open Space Council

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Executive Summary

Adapting to Climate Change: *State of the Science* for North Bay Watersheds

A Guide for Managers, December 2010

The North Bay Watershed Association (NBWA) commissioned this guide to assess and summarize potential climate change impacts to the hydrology of basins draining to the North San Pablo Bay portion of the San Francisco Bay Estuary based on "the state of the science." Results include estimates of climate and hydrology parameters down to the watershed scale (completed as part of this study) combined with a summary of the potential extent of sea level rise anticipated over the next century (completed in an earlier study by US Geological Survey for the Bay Conservation and Development Commission). Relevant technical journal articles cited here provide details on methodologies and results. The purpose of this guide for managers is to summarize research results and implications for water supply, flood control, water quality, and habitat management projects and long-term adaptation strategies. Critical findings include the following.

- The North Bay has already experienced a significant warming trend over the last century with monthly maximum temperatures having increased on average approximately 2.7 °F since approximately the year 1900 to present. Over the last century the Bay has also experienced approximately 0.5 feet of sea level rise.

- The spatial distribution of climate change to date across the region is variable, with a trend towards warming of valley bottoms and in some cases cooling of montane areas. Coastal influences in general mitigate the warming trend, such that effects are more pronounced with increasing distance from the Pacific Coast or the Bay.

- Scientists have reached a consensus regarding a range of projected global temperature scenarios for the next century. For the purpose of this project, these projections have been "downscaled" for the North Bay region to a 270 m grid.

- By the last 30 years of this century, compared to today's climate models project that a "business as usual" emissions scenario would result in an increase of approximately 6 °F in average annual maximum temperature, while a "mitigated" (e.g. significantly reduced) emissions scenario would result in approximately a 4 °F increase for our region.

- Based on the current state of the science, one cannot definitively project whether the North Bay will be faced with consistently more or less precipitation as a result of climate change because there is greater uncertainty in projected precipitation trends than in projected temperature trends.

- The two climate models analyzed in this study represent two precipitation scenarios, one that is comparable in precipitation to today's conditions and one that represents conditions should precipitation increase approximately 20% compared to the last century. We generalize these two scenarios as "warmer drier" versus a "warmer wetter" scenario.

- Under all scenarios (four combinations of emissions (high and low) and precipitation (drier and wetter)), seasonal variability of precipitation, runoff, recharge, and stream discharge is likely to increase, with increased likelihood of previously rare or unprecedented precipitation and drought events.

- For both the "warmer drier" and "warmer wetter" scenarios, hydrologic models predict reduced early and late wet season runoff for the next century, resulting in a potentially extended dry season, regardless of potential increases in precipitation.

- Scenarios that estimate increased precipitation project that precipitation to be concentrated in midwinter months, a trend which could increase risk of floods.

- Evapo-transpiration and associated soil climatic water deficit is projected to steadily increase in both the wetter and drier future scenarios (on the order of 10-20%). In the course of longer summers, soils are likely to experience greater drought stress, which in turn may increase demand for irrigation.

- Extended dry season conditions and the potential for extended drought may serve as additional stressors on water quality and habitat.

- Sea level rise projected over approximately the next century is projected to be on the order of approximately 5 feet for San Pablo Bay which would impact approximately 73,000 acres of North Bay watersheds. The majority of the potentially inundated areas were historically tidally-influenced prior to levee conversion.

- Real-time monitoring of hydrological variables, as laid out in the 2009 NBWA *Watershed Indicators* report and related efforts, will be central to testing hypotheses about potential climate change laid out in this report and equipping managers to respond to climate adaptation challenges in a timely fashion.

- Pursuing a range of integrated regional watershed strategies capable of reducing greenhouse gas emissions, increasing water efficiency, creating distributed storage networks, promoting integrated flood management, and restoring resilient ecosystems is more important than ever.

- Watershed project designs will need to adapt to a greater range of hydrologic variability than represented in the historical record to date. Scenarios presented in the detailed report quantify a reasonable range of potential hydrologic conditions for conceptual design considerations. Project data can be queried at the scale of major planning basins and minor basins defined by CalWater. Higher resolution downscaling (to daily timesteps) may be required to support detailed engineering designs.

In addition to this report and associated published research on watershed hydrology impacts (*Micheli et al in press*), this project produced a PowerPoint presentation on projected localized climate impacts to the North Bay that is available to NBWA members for presentation. For more information, please contact the project lead: Dr. Lisa Micheli, Dwight Center for Conservation Science at Pepperwood, lmicheli@pepperwoodpreserve.org, 707-591-9310 x 203. In addition, project data will be posted online and linked to www.nbwatershed.org.

Adapting to Climate Change
"State of the Science" for North Bay Watersheds

A Guide for Managers

Purpose

A goal of the North Bay Watershed Association (NBWA) is to provide members and associated watershed organizations with comprehensive tools for watershed management informed by a regional perspective. As advised by DWR 2008,

> *Impacts and vulnerability will vary by region, as will the resources available to respond to climate change, necessitating regional solutions to adaptation rather than the proverbial one-size-fits-all approach.*

The purpose of this guide is to advance adaptation planning for North Bay watersheds by providing a summary of potential future climate change and sea level rise vulnerabilities based on current science. While there is inherent uncertainty in generating future climate scenarios, the information provided here, which includes quantitative estimates of model uncertainties expressed as a range of scenarios, is critical to prepare watershed managers to adapt to our changing climate, and in turn, to wisely manage our water resources future. This guide is intended as a first step to enable North Bay watershed managers to take potential future climate change into consideration in planning projects aimed at enhancing water supply, flood protection, water quality, and watershed habitat.

Background

The international climate science community has put the public on notice on two fronts:

1. climate change is already well under way and unavoidable impacts need to be planned for even if we are successful in stabilizing greenhouse gas emissions immediately due to the lag time in climate response;

2. while there is some diversity among global climate general circulation models (GCMs), sufficient convergence among projections allows identification of conservative central tendencies in future climate.

The latest general circulation models (GCMs) have benefited from calibrating model inputs based on recent observed climate, such that today these tools provide a much stronger basis for projecting ranges of potential change today than ever before (see IPCC 2001 and 2007, Knowles and Cayan 2002, Cayan and others 2007 and 2009, Hidalgo and others 2008).

A major recent advance in climate science is the ability to "downscale" GCMs developed by the Intergovernmental Panel on Climate Change (IPCC) to generate meaningful results at a watershed scale. In terms of watershed hydrology, this is achieved by linking future climate scenarios to a Basin Characterization Model (Flint and Flint 2007a, 2007b, 2011) that translates climate parameters into hydrologic impacts on the water cycle for each basin in the study area based on topography, soils, and underlying geology. For sea level rise, this is achieved by combining results from global models with detailed regional information on tides, storm frequency, and wave surge. The work referenced here was overseen by US Geologic Survey principal investigators and prepared for publication in *San Francisco Estuary and Watershed Science,* a journal produced by University of California. Readers interested in detailed methods and analyses used to generate the watershed hydrology and sea level rise scenarios should consult companion research papers (Knowles 2010, Micheli and others *in press*).

The scientific foundation for this guide is grounded in research that projects both sea level rise and watershed hydrology under climate change for NBWA watersheds. While the USGS focuses exclusively on scientific research, our project team translated research results to potential implications for management based on our experience and by consulting national and state level guidelines on climate adaptation (DWR 2008, Lawler and others 2009, State of California 2009, West and others 2009). We are indebted to technical peer reviewers from NBWA member organizations who provided critical input to this report. The project team also included representatives from the Dwight Center for Conservation Science at Pepperwood, Creekside Center for Earth Observation and the Bay Area Open Space Council to augment the perspective of applied watershed managers working in a regional context.

Planning for uncertain futures

Modeled scenarios summarized here at best capture the magnitude and direction of long-term trends. These models are empirical and probabilistic: they utilize observations of hydrologic response to historic climate to generate future scenarios.

While modeled scenarios generate monthly to annual values for projected climate, hydrology and sea level parameters, these values should not be taken as specific predictions for short-term climate impacts. Instead, we focus on reporting approximately 30- to 100-year climate trends in the context of potential seasonal and inter-annual variability. In other words, these models do not aim to predict short term climate fluctuations commonly referred to as "the weather," but speak to long term trends that underlie the high spatial and temporal variability of climate in our region.

There are several sources of "uncertainty" in climate change projections, some of which are a function of actual scientific unknowns while some are simply a function of natural variability of our regional watershed systems. Primary sources of uncertainty in this study include the following.

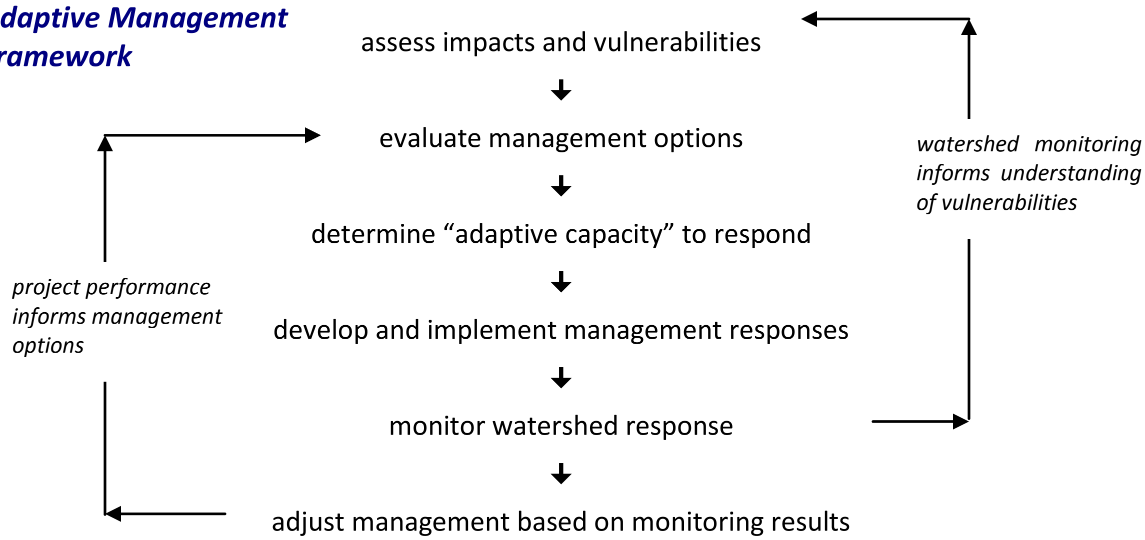
- Actual temporal variability in global and local climate observed in historic records
- Actual spatial variability of watershed and estuary attributes
- Unknown rates of long-term future greenhouse gas emissions
- Variations in sensitivity among GCM models used to generate temperature and precipitation patterns and among sea level rise models
- Uncertainty regarding the precise physical mechanisms of climate change and sea level rise

Watershed managers need to make informed choices to plan in the face of these uncertainties. Critical to a science-based approach is understanding climate projections as defining reasonable ranges for average values with quantified estimates of temporal and spatial cumulative uncertainty. To meet this objective for watershed hydrology, we use four scenarios that represent two different climate modeling approaches and two different greenhouse gas emissions scenarios. Figures and tables provided show quantitative estimates of residual uncertainty. To effectively use these vulnerability assessments, managers need to apply an "adaptive management" framework.

Adaptive management is more important that ever

The principle of adaptive management is critical to successfully meeting the challenge of managing watersheds given uncertain climate futures. The scenarios provided here constitute a set of hypotheses regarding how our watersheds may respond to climate change in the decades to come. It will be critical to implement long-term watershed monitoring (per recommendations developed in the 2009 NBWA *Watershed Indicators* report, which include "climate context" indicators) to evaluate the validity of this hypothesis and to adjust predictive models to improve future scenario development in the decades to come. We will also need to more carefully monitor watershed projects over time to see how they actually fare in the course of climate change. Thus we recommend an iterative process of utilizing scientific prediction tools in concert with field-based monitoring that measures actual change in the resource over time. The figure below provides a visualization of how to utilize future climate and hydrology scenarios in the context of an adaptive management framework (following West and others 2009, Lawler and others 2009).

Adaptive Management Framework

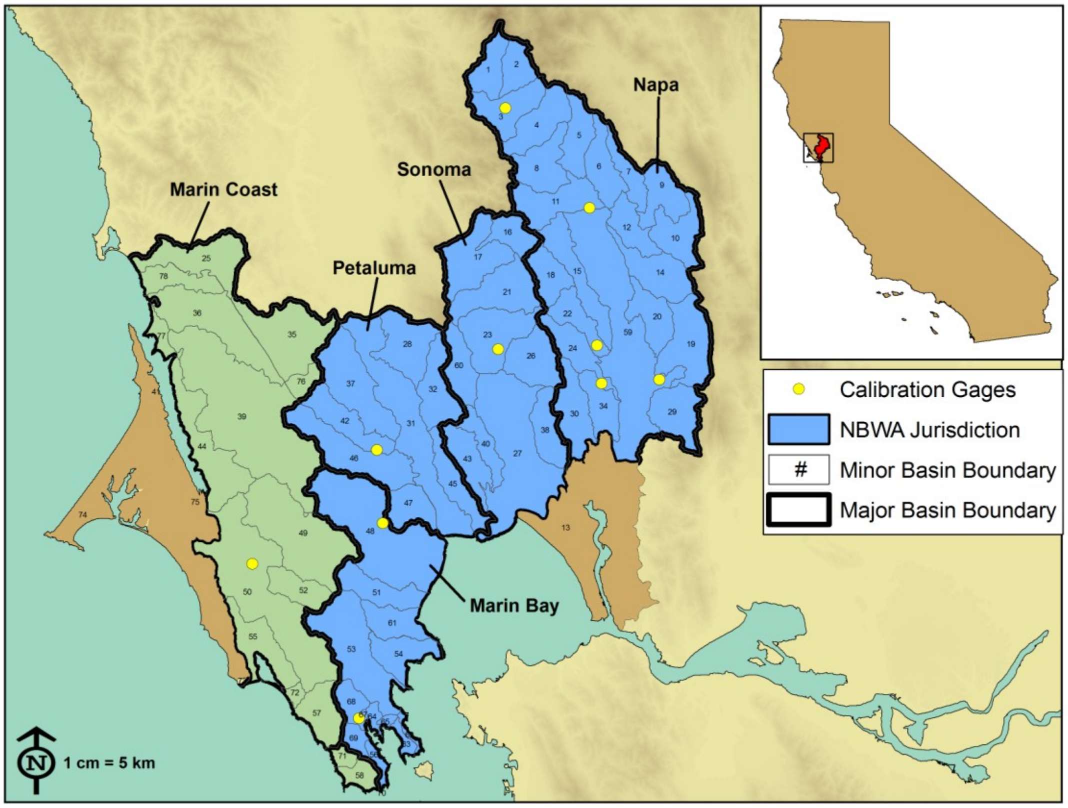


A**daptive capacity** can be defined as "the ability of systems, organizations, and individuals to: adjust to actual or potential adverse changes and events, take advantage of existing and emerging opportunities that support essential functions or relationships, and/or cope with adverse consequences, mitigate damages, and recover from system failures (DWR 2008)." The feedback loops shown above indicate the critical role of monitoring to refine vulnerability assessments and provide feedback on the efficacy of management techniques. Adapting to climate change calls for a comprehensive commitment to adaptive management at a regional scale to maintain flexibility to respond to uncertain futures.

Watershed delineation within the study area

The study area is comprised of the NBWA jurisdiction and environs as shown in Figure 1 below.

Figure 1 Study area and delineated watersheds



Map of study area delineating major and minor basins analyzed using Basin Characterization Model (BCM). Blue shading defines North Bay Watershed Association (NBWA) jurisdiction. Labels with arrows identify major basins. Small numbers label minor basins identified by name in Appendix A. Yellow circles show location of USGS gages used for model calibration.

The major basins defined for this study form a west to east transect across the North Bay and include; "Marin Coast" (comprised primarily of the Lagunitas Creek and Bolinas watersheds that drain to the Pacific Ocean), eastern "Marin Bay" (comprised primarily of the Corte Madera and Miller Creek watersheds draining into the estuary), Petaluma River watershed, Sonoma Creek watershed, and the Napa River watershed. Excluding the Marin Coast basin, the core of the study area is comprised of the geographic jurisdiction of the NBWA. These major planning basins can be further divided into minor basins per watershed delineations generated by the Natural Resources Conservation Service's California Interagency Watershed Mapping Committee (CalWater 1999). For details on major and minor basins, please consult Appendix A.

Historic patterns of climate variability.

The watershed hydrology team analyzed historic PRISM climate data (Daly and others 2004) to understand past patterns of climate variability and to calibrate the model to predict future patterns of variability. These include patterns of spatial variability within and between the major planning basins of the North Bay and temporal variability across seasons and years. Researchers utilized mapped topography, soils, and geology and stream gage records to reproduce historical patterns using the Basin Characterization Model (BCM). Understanding the historic spatial variability of climate, hydrology and sea level at the watershed scale is critical to identifying potentially vulnerable versus resilient regions of North Bay watersheds for the four future scenarios. Figure 2a shows the spatial variability of North Bay climate over a 30 year period ending in 2000.

Figure 2a Average annual precipitation and maximum and minimum temperatures, North Bay region, 1971-2000

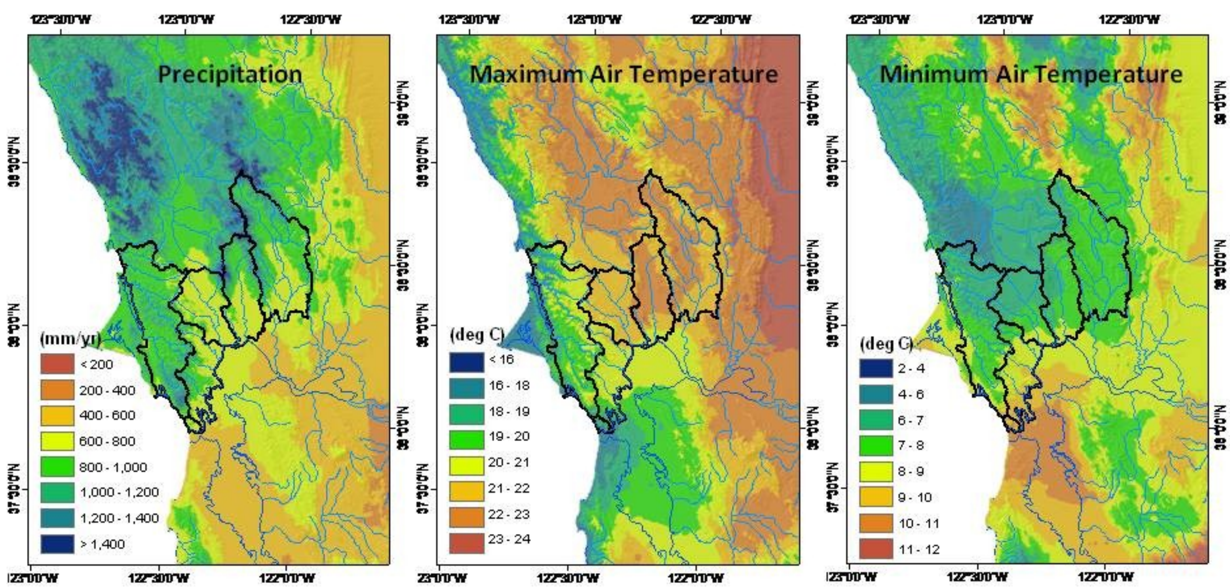
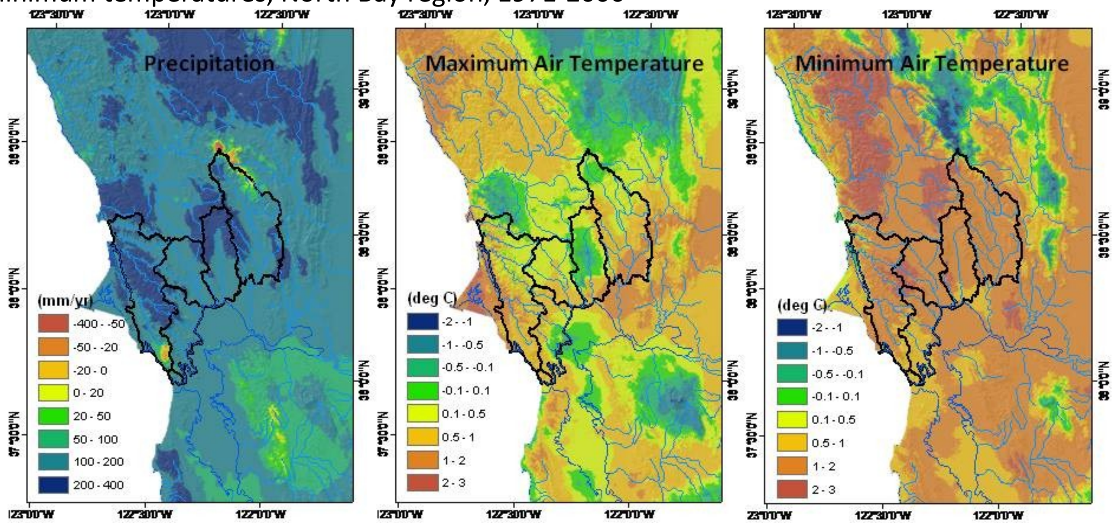


Figure 2a displays a decreasing precipitation gradient from the coast and montane headwaters to inland valleys, an increasing gradient in maximum temperatures from the coast 64-66 °F (18-19 °C) to inland 72-73 °F (22-23 °C), and relatively consistent trends across the region in minimum temperatures. Figure 2b below shows the direction and magnitude of any net change in variables over the same period.

Figure 2b Direction and magnitude of change in annual average precipitation and maximum and minimum temperatures, North Bay region, 1971-2000



Recent climate change trends displayed above show an increase of approximately 2–4 inches (50-200 mm) in average annual precipitation, a variable trend in maximum temperatures, and more intensive increases in minimum temperatures (on the order to 1.8 – 3.8 °F) across the region for the 1971-2000 time period. We can also see that while the overall trend has been towards warming, there are some regions that have experienced a cooling trend (on the order of 0.9 to 1.8 °F).

Future climate scenarios

To capture a reasonable range of future projections for watershed hydrology we utilized two different global climate models for Basin Characterization Model inputs and two different models for emissions scenarios. The result is four scenarios that explore the implications of a higher or lower emissions future for scenarios with both greater and lesser amounts of precipitation compared to the historical average. (By contrast to the watershed hydrology scenarios, we summarize just one scenario for sea level rise that conservatively is likely to be realized within a century.)

General Circulation Model (GCM) temperature and precipitation outputs shown below in figures 3a and 3b have been downscaled to the North Bay region based on monthly values averaged over decade intervals (for methods, see Flint and Flint 2011). Historic values are derived from PRISM. Projected data series (2001-2100) represent four combinations of GCM model (GFDL or PCM) and emissions scenario (A2 "business as usual", B1 "mitigated') as identified in legend.

Figure 3a Historic (1911-1999) and GCM-projected values (2000-2100) for maximum temperatures (monthly values averaged over decade intervals), North Bay region

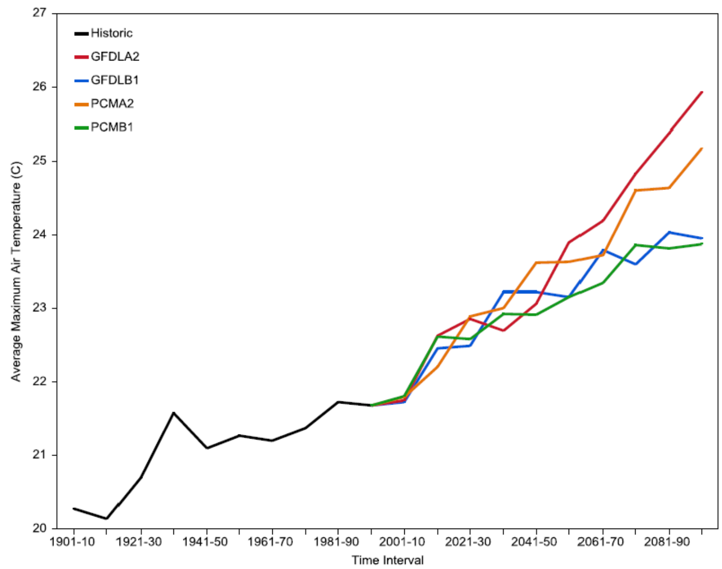
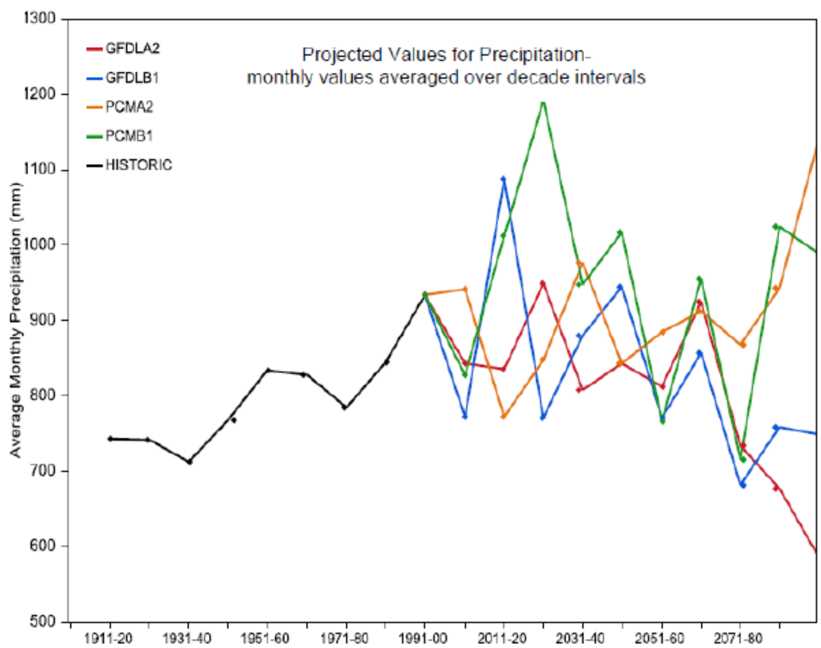


Figure 3b Historic (1911-1999) and GCM-projected values (2000-2100) for precipitation (monthly values averaged over decade intervals), North Bay region



By the century's close the four scenarios evolve into essentially two distinguishable scenarios with equivalent temperature values but divergent precipitation. By the last 30 years of this century (2071-2100), maximum temperature is projected to increase above today's values by 3.8 to 6.1 °F, based on the lower versus higher emissions projections.

By contrast, the long term trend for precipitation is uncertain and driven by model "make" rather than emissions scenario. By the 2071-2100 time interval, the "wetter" PCM model (for both the low and high emissions scenarios) is characterized by a annual precipitation average of approximately 37.4 ± 3.0 inches per year (950 ± 75 mm y^{-1}) versus a "drier" GFDL model (for both the higher and lower emissions scenarios) characterized by a precipitation average of 29.5 ± 3.0 inches per year (750 ± 75 mm y^{-1}). Compared to a historic mean of 30.8 ± 2.0 inches per year (783 ± 47 mm y^{-1}) (1900-1981), the PCM "warmer wetter" model assumes a much more significant shift (21% more than the historic average) in precipitation than the "warmer drier" GFDL model.

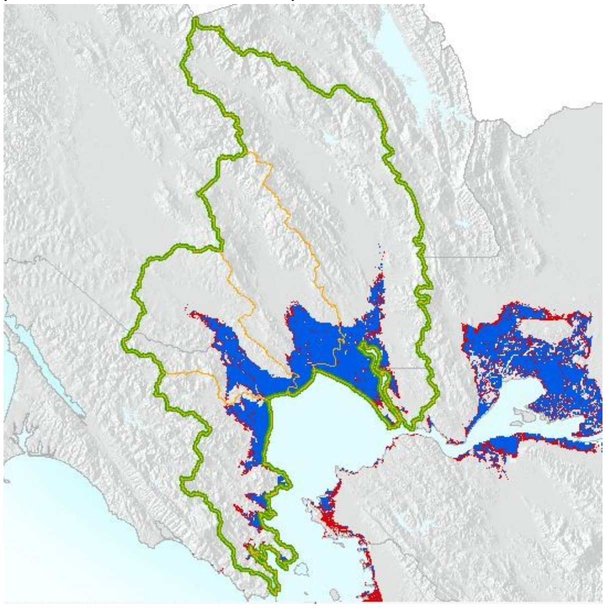
Potential climate change impacts on sea level rise

For sea level rise projections presented here one emissions scenario was applied ("business as usual") using a hydrodynamic model that integrates the effects of global sea level rise and local variability in San Francisco Bay estuary water surface elevations based on underlying topography, tides, storm surge, and flood conditions (Knowles 2010). The model examines the risk of extreme high water levels associated with rare (low-frequency) events that may prove capable of breaching existing protective levees around low lying areas. Thus the model projects potential inundation for current conditions and with approximately 4.9 feet of sea level rise, considered a reasonable estimate by approximately this century's close (Knowles 2010). (The model does not aim to precisely predict the date of this extent of sea level rise, but rather examines the impacts of this relatively conservative estimate for what is likely to occur sometime this next century or early in the next.)

In terms of the potential extent of inundation, the sea level rise model estimates a total of 73,270 acres or 13% of the NBWA jurisdiction area that may prove vulnerable to sea level rise by this century's close. This acreage is distributed relatively evenly between the four major basins, with 21% in the Marin Bay basin, 22% in the Petaluma River basin, 24% in the Sonoma Creek basin, and 33% in the Napa River basin. Appendix B summarizes types and relative rarity of vegetation prone to inundation. Out of a maximum score of 4, the relative rarity of land cover on impacted lands averages 2.74.

In terms of the potential frequency of sea level rise extreme events (when tides, wind fetch, and flooding are all at maximum), Knowles (2010) indicates that for the bay as a whole, as early as mid-century, the one-year peak flooding event will be nearly equal in magnitude to the 100-year peak event currently estimated for the year 2000.

Figure 4a Potential inundation due to sea level rise for NBWA Jurisdiction (based on Knowles 2010)

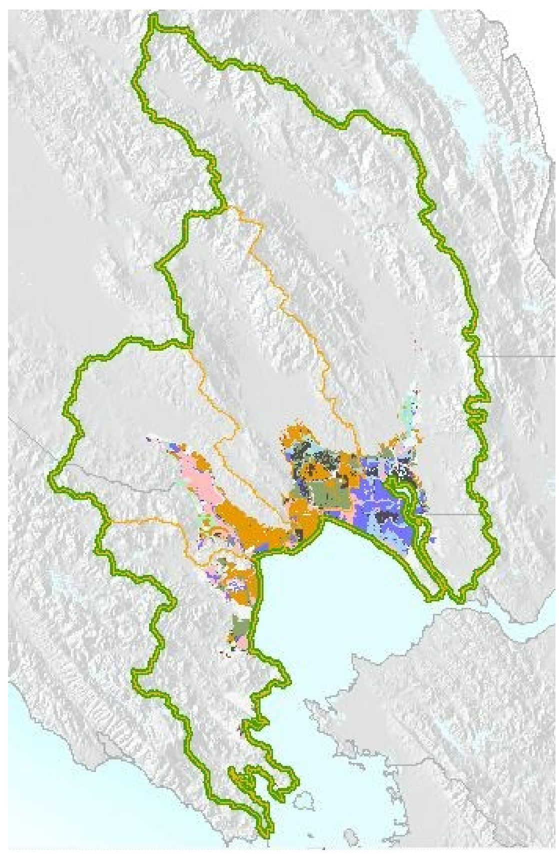


Explanation: in blue are areas vulnerable to inundation at present under worst case scenario (100-yr storm, levee failure) and in red are additional areas prone to inundation during extreme events with 4.9 feet of sea level rise (NBWA jurisdiction outlined in green, major basin boundaries in gold).

Figure 4b Vegetation types at risk of inundation by sea level rise for NBWA Jurisdiction (based on Knowles 2010)

Explanation: diversity of Upland Habitat Goals vegetation types at risk of inundation via sea level rise, (NBWA jurisdiction outlined in green) with types listed by acreage in and rarity rankings in Appendix B. The table below summarizes potential inundation acreage by protection status.

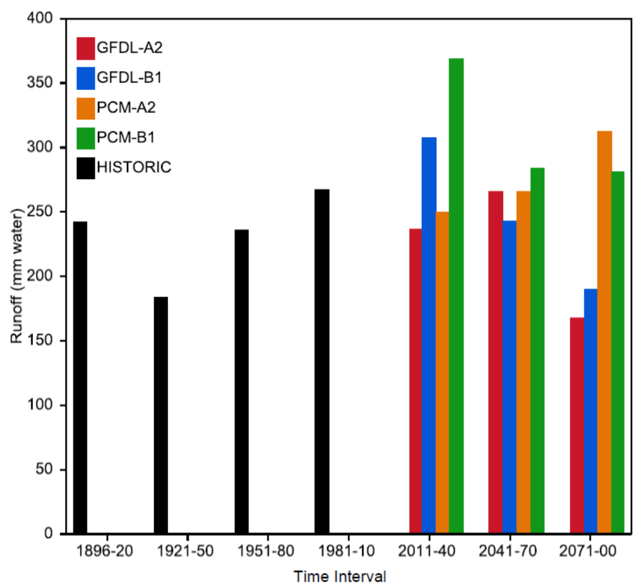
Major Basin	Not Protected (acres)	Protected (acres)	Basin Total (acres)
Marin Bay	9,285	5,833	15,118
Napa River	8,483	16,036	24,520
Petaluma River	7,174	8,760	15,934
Sonoma Creek	15,337	2,361	17,698
Category Totals	**40,279**	**32,991**	**73,270**



Potential Climate Change Impacts on Watershed Hydrology

For watershed hydrology, by exploring both a "warmer drier" and a "warmer wetter" scenario, we can identify common and unique adaptation challenges associated with long terms trends of greater versus less precipitation. The four scenarios analyzed here result in the following estimates of watershed runoff (shown as mm of annual precipitation) for the entire North Bay region.

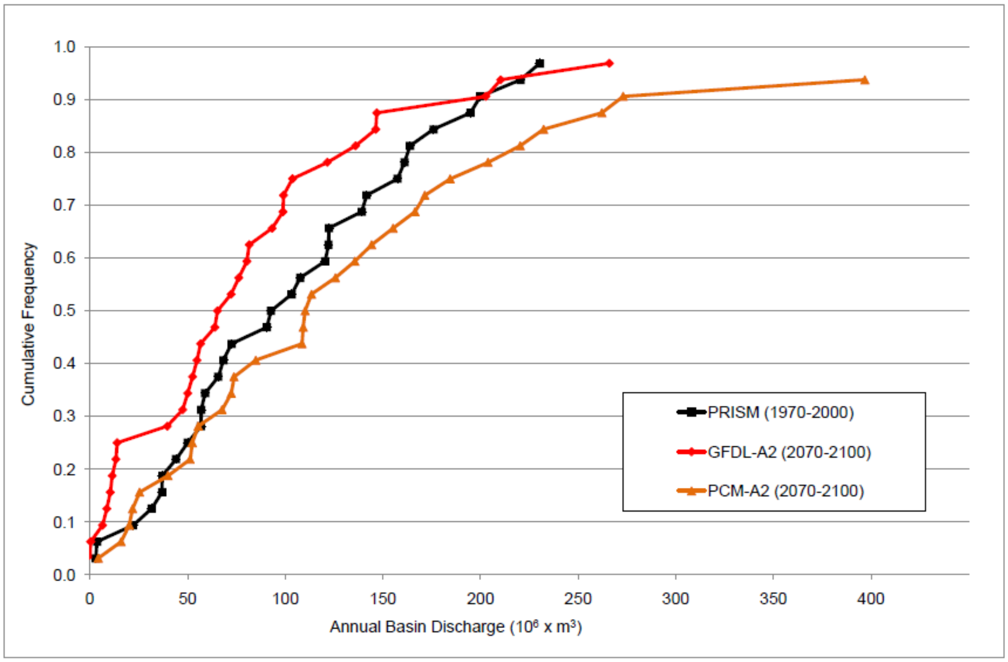
Figure 5 Historical runoff (1896-2009) and projected runoff (2010-2100) for four projected scenarios. (Runoff shown as mm of incoming annual precipitation)



Each bar represents average annual runoff estimated by the Basin Characterization Model (BCM) for the North Bay region (NBWA jurisdiction) over the defined time interval, with black bars derived from PRISM data (1896-2009) and colored bars derived from GCM projections. For the three projected time periods, the first (2011-2040) shows a case where the B1 scenarios are significantly wetter than the A1 scenarios, the second (2041-2070) shows a case where all scenarios are comparable in terms of projected runoff, while the third (2071-2100) demonstrates a case where the PCM projections are significantly wetter than the GFDL projections for both emissions scenarios. These runoff scenarios can be used to essential "bound" a reasonable range of "drier" versus "wetter" hydrology estimates for the next century.

Runoff scenarios can be translated to potential impacts on stream flow. Below is a cumulative discharge plot for the Napa River that compares historic annual discharge to annual discharge projected for both a "warmer wetter" and "warmer drier" scenario.

Figure 6 Historic (1971-2000) versus projected (2071-2100) cumulative probability of annual stream discharge, Napa River at St Helena

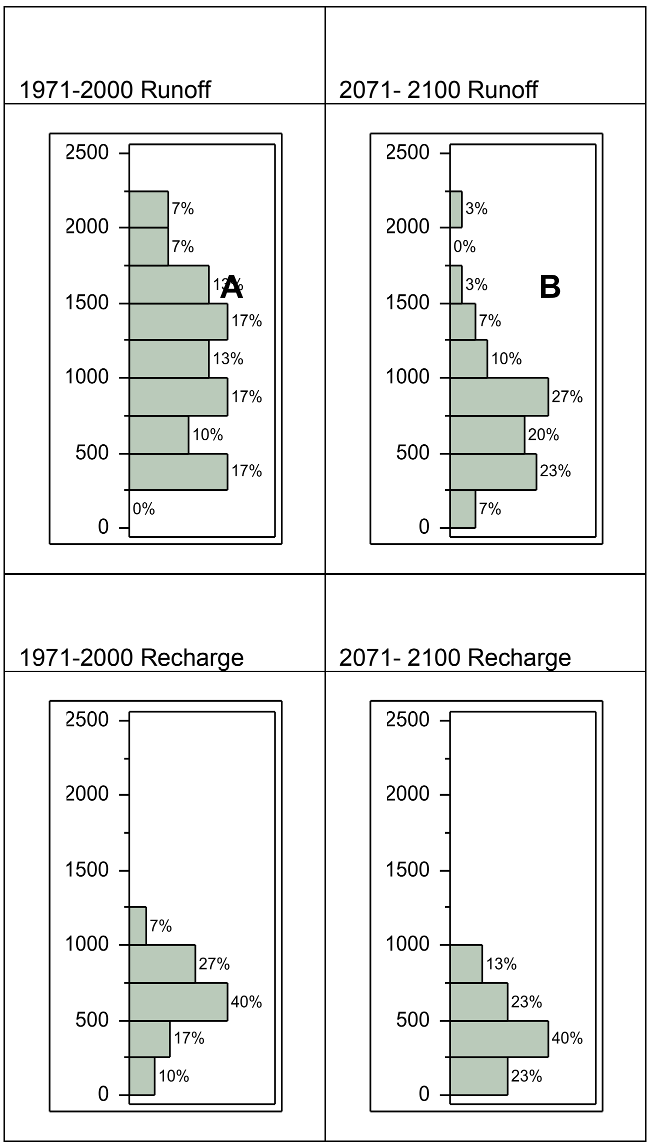


Annual basin discharge versus cumulative frequency for the Napa River at St Helena, where black squares represent historic conditions (1971-2000, derived from PRISM data), red diamonds represent projected GFDL A2 scenario (2071-2100, BCM simulation), and gold triangles represent projected PCM A2 scenario (2071-2100, BCM simulation).

River managers and engineers typically rely on these kinds of frequency plots of cumulative discharge for sizing hydraulic structures and stream channel restorations. Figure 6 shows that future scenarios project shifts in the negative direction under the warmer drier (GFDL A2) scenario and shifts in the positive direction for the warmer wetter (PCM A2) scenario. For example, if one examines values estimated for a return frequency of 0.5, which estimates the average discharge of the system, the historic value is 75,960 acre-feet per year (a-f y^{-1}) (equivalent to 93.7 x 10^6 m^3 y^{-1}) versus a projected value of 52,940 a-f y^{-1} (65.3 x 10^6 m^3 y^{-1}) for the GFDL A2 scenario and a projected value of 89,340 a-f y^{-1} (110.2 x 10^6 m^3) for the PCM A2 scenario. Thus instead of a fixed discharge value for bankfull or a 100-yr return interval event, planners may need to design for a range of values that could approximate plus or minus on the order of 25% of historical flow conditions.

Watershed runoff and recharge can be estimated using the Basin Characterization Model for sub-basins within major basins to facilitate more site-specific assessments of climate change vulnerabilities. Below we show potential shifts in distributions of both runoff and recharge events for the Milliken Creek sub-basin of the Napa River major basin. As conjunctive use of surface and groundwater resources advances within North Bay basins, these types of projections can help clarify tradeoffs between surface flows and groundwater recharge under varying precipitation conditions. Our results indicate that groundwater resources, as represented by recharge rates, may be more resilient to climate change (i.e. less flashy) than surface water represented by runoff estimates.

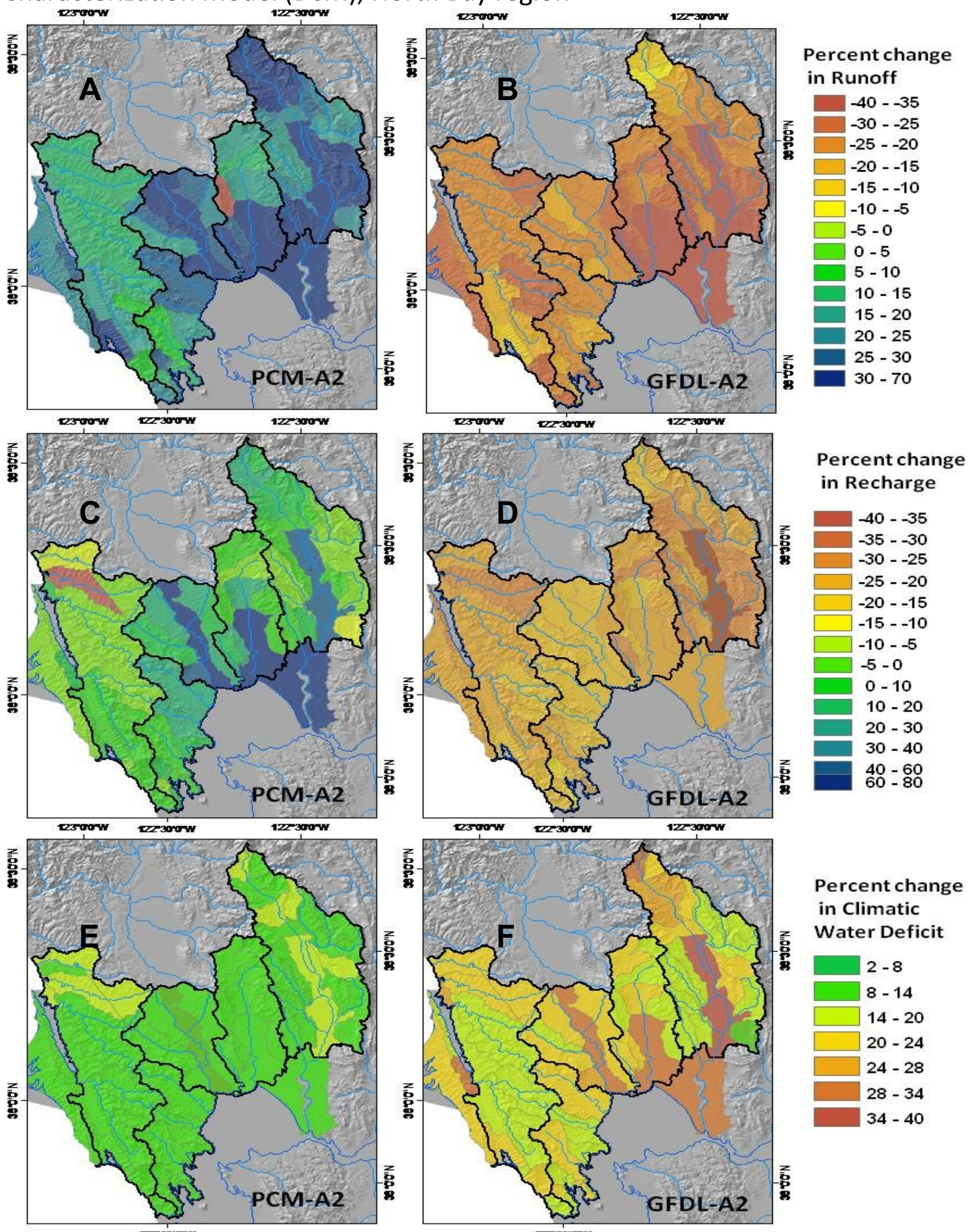
Figure 7 Runoff and recharge, three-year running average values, historic (1971-2000) and GFDL-A2 projections GFDL-A2 (2071-2100), Milliken Creek sub-basin



Explanation: These histograms compare frequency distributions for 1971-2000 (derived from USGS gage data) and 2071-2100 (derived from BCM simulation for GFDL-A2 scenario) for three-year running average values for runoff (A-B) and recharge (C-D). Percent labels show total frequency of values for each histogram interval. Units are $10^3 \times m^3$ of water. This plot shows that while in 1971 to 2000, the three-year runoff average exceeded 1000 x 10^3 m^3 (810 acre-feet) 57% of the time, under the GFDL A2 scenario for 2071-2100, this threshold would be exceeded only 23% of the time. In terms of basin recharge, while for the historic period (1971-2000) three-year average basin recharge exceeded 500 x 10^3 m^3 (405 acre-feet) 74% of the time, under the GFDL A2 scenario for 2071-2100, this threshold would be exceeded only 36% of the time.

Using the Basin Characterization Model, it is possible to map the spatial variability of climate impacts on hydrology. The maps below compare effects of climate change projected by the "warmer-drier" (GFDL) versus the "warmer-wetter" (PCM) scenario.

Figure 8 Spatial distribution of projected climate impacts on hydrology estimated using Basin Characterization Model (BCM), North Bay region

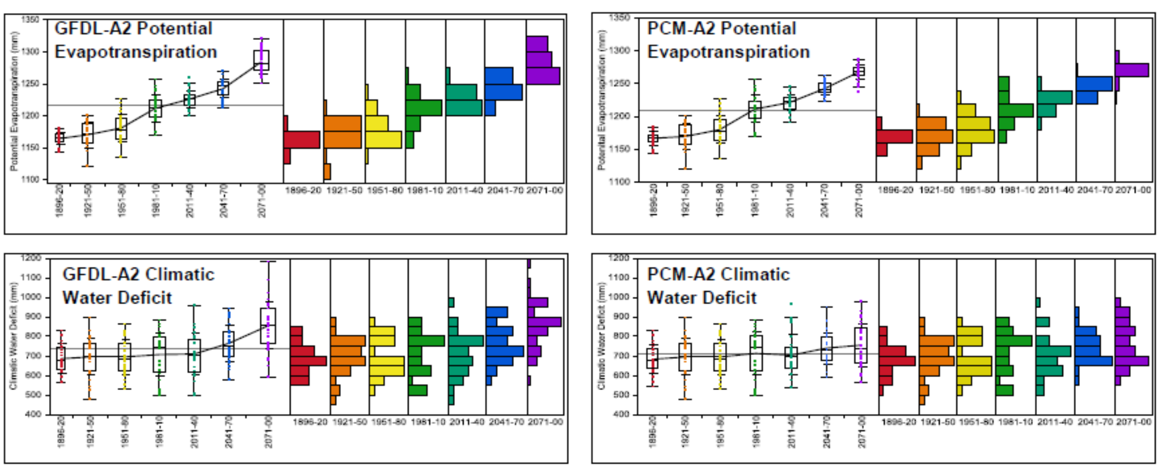


Maps A-F display the diversity of potential hydrologic response to climate change within major basins by showing the spatial distribution of differences between the 1971-2000 and 2071-2100 time intervals. A-B displays runoff, C-D displays recharge, and E-F displays water deficit for the PCM A2 "warmer wetter" scenario (A, C, E) and the GFDL A2 "warmer drier" scenario (B, D, F).

In general, valley bottoms typified by thick layers of alluvium show the greatest magnitude of potential change due to high storage capacity. While runoff and recharge generally trend in opposite directions for the two models (in the positive direction for PCM and the negative direction for GFDL), both models predict increases in water deficit ranging from 8 to greater than 34% in some locations.

What we find is that despite a range of precipitation scenarios, warmer temperatures over time drive higher rates of evapotranspiration during the dry season. Using the Basin Characterization Model, we can model the effects of more or less precipitation in combination with higher evapotranspiration using a term called "climatic water deficit" (Johnson 1998) hereafter referred to as "water deficit." The water deficit calculates how much more water would have been evaporated had it been available in the soil, and effectively estimates drought stress on soils and plants. Another way to think of deficit is that it is the amount of water that would need to be added to the soils to maintain crops or natural cover, and thus it can be thought of as a surrogate for potential irrigation demand. In all scenarios water deficit is anticipated to increase on the order of 6-20% across the region.

Figure 9 Historic (1896-2009) and projected (2010-2100) annual average potential evapotranspiration and climatic water deficit, North Bay region

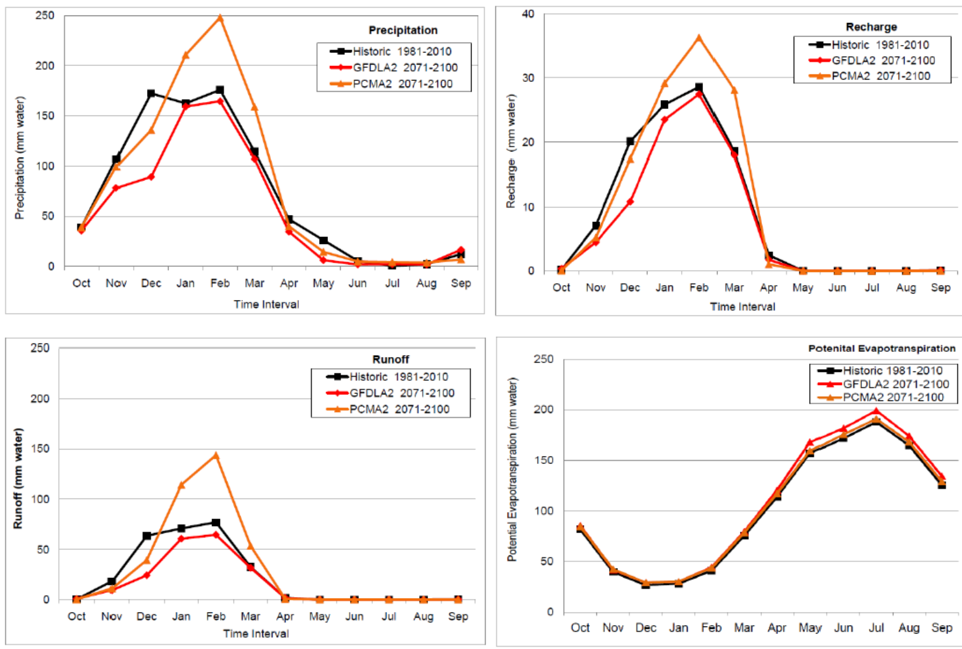


Thus as conditions trend toward those typified by the driest decade predicted here, a larger fraction of the total water available is "lost" to evapotranspiration, leaving approximately 10% less of the full water balance, on the order of 2.4-3.5 inches (60-90 mm water), per year available for recharge and runoff. This could be considered a rough approximation of the additional amount of water that would be needed to maintain current agricultural or natural land cover.

Projected Climate Change Impacts on Timing of Water Availability

Our results included monthly estimates for all hydrologic parameters, which facilitates an examination of the potential impacts of climate change on hydrologic seasonality. Figure 10 below compares average values by month for precipitation, runoff, recharge, and potential evapotranspiration for recent conditions (1981-2010) and projected conditions under the warmer drier (GFDL A2) and warmer wetter (PCM A2) (2071-2100) scenarios.

Figure 10A-D Projected climate impacts on seasonality of climate hydrology parameters, North Bay region



Both projected scenarios display significant reductions in early wet season rainfall, and while PCM A2 projects significantly higher rainfall in January, February and March, it joins the GFDL A2 scenario in projecting drier conditions in April, May and June than for the recent time period. This pattern is reiterated in seasonal patterns of runoff and recharge. Both the warmer wetter and the warmer drier future scenarios show increased potential evapotranspiration during the months of May through September, which is likely to increase water demand regardless of variations in rainfall during antecedent winter months. Thus potential increases in precipitation and runoff under a wetter future scenario may increase supply, but demand is likely to also increase in future wet years compared to historic conditions because of late summer drought stress on soils.

Implications for NBWA categories of management

Water Supply

Watershed hydrology models for the North Bay cannot definitively answer whether there will be a long-term trend towards increased or decreased supply, but they do indicate that supply from in-basin sources may be more variable than we have experienced historically. What they do definitively point to is that regardless or more or less precipitation, increased temperatures are likely to generate increased demand for available water resources to serve irrigation needs for outdoor landscapes and agriculture, given increased drought stress on soils and vegetation.

Sea level rise estimates suggest that low lying portions of North San Pablo baylands (the majority of which were likely to have been tidal or intertidal wetlands prior to agricultural conversion) may be episodically inundated with increasing frequency over the next century. Groundwater studies for watersheds with significant aquifers including Sonoma and Napa suggest that freshwater resources in low-lying regions of the North Bay are in some places already subject to water-table draw down and saline intrusion (although sources of saline water are not always necessarily the Bay itself, but in some cases ancient subsurface saline deposits).

During recent droughts cities reliant on imported water have shifted to increased use of local groundwater resources (where available) to make up for reductions in imports, and this is a trend that may potentially intensify. Many of these critical subsurface basins are poorly characterized. In order to effectively realize the benefits of conjunctive use, communities may benefit from a better technical understanding of this resource to support management approaches that aim to keep groundwater basins "full."

Adaptation strategies summarized below indicate that progress must continue in maximizing conservation approaches to managing water supply. Reducing consumer demand, exploring distributed storage, domestic catchment and reuse, water recycling, and groundwater banking—all need to be pursued as pressures increase on an increasingly variable local water supply.

Flood Protection

The watershed hydrology scenarios summarized here are based on monthly average estimates for watershed runoff and streamflow. These models are not adequate to estimate impacts on a flood hydrograph, since the flood risk is a function of not only total runoff but the intensity of runoff, sometimes at the temporal scale of hours. The same amount of runoff averaged over a month might or might not result in flooding based on storm intensity, or the depth of precipitation per unit time (typically measured as inches per hour). In order to better assess potential flood impacts, ideally these models would be further calibrated to estimate daily flows, as is presently underway for the Russian River.

However, it is likely that peak runoff months are to some degree correlated to peak flood events. We tested this idea on the Napa River basin and found that maximum monthly runoff estimates were correlated with peak flood events approximately 60% of the time. Monthly projected values for runoff do show maximum runoff values concentrated in mid-winter months, rather than distributed evenly over wet season. Thus our watershed hydrology results indicate that increased flood frequency is likely, particularly under the wetter model scenario, but merits closer inspection using a finer temporal scale of analysis.

Flood risks associated with maximum sea level rise can be estimated based on the hydrodynamic modeling approach used for the Bay by projecting the coincidence of peak flood events, high tides, and significant storm surge (Knowles 2010). Knowles (2010) estimates that by the end of the century, what used to be a 100-year storm event in terms of water surface elevations in 2000 may become an event with more like a one-year recurrence interval. Thus there is relative certainty about the intensification of flooding in the low lying portions of North Bay watersheds, while uncertainty remains about how far upstream this effect may propagate. The interaction of watershed hydrology and bay water levels merits far greater investigation that exceeds the scope of this present study.

Water Quality

There are two primary risks to water quality due to climate change: 1) dry weather will reduce flows and will in turn increase concentrations of non-point and other sources of pollution; 2) salinity intrusion attributable to a combination of sea level rise and pressure on surface and groundwater supply sources will degrade water quality. Water quality treatment facility managers will need to take into account potentially higher variability in quantities of storm water and resultant impacts on wastewater treatment facilities. Understanding impacts to water quality as a function of climate can be vastly improved if we move forward with concurrent monitoring of water quality relative to climate and flow conditions as prescribed by the *NBWA Watershed Indicators* report.

Other water quality risks that should be taken into account are the implications of catastrophic events and our responses to those events, particularly in terms of drought, flood, and fire response. It is clear that since the impacts of climate change will probably be experienced at least in part via these kinds of extreme events, successful watershed adaptation efforts will need to engage emergency preparedness and response teams at the local government level far in advance of an event to evaluate and advise on proposed emergency response methods in terms of potential impacts to water quality.

Watershed Habitat

Habitat managers need to design restoration projects that can succeed despite increased climate stresses on ecosystems. Besides planning for ecosystem resilience (ability to recover following disturbance), managers also need to prepare for long-term transformation of ecosystems in response to increasing water deficit pressures. Examples include:

- adapting streams and riparian restoration projects to potentially reduced in-stream baseflows due to variable precipitation and potential exacerbation by increased pressure from human water use
- planning for a broader range of hydrological conditions in riparian restoration, and use a more diverse planting palette (see Seavy and others 2009)
- projecting sea level rise, potential changes in sedimentation, and impacts on reclamation of historic baylands and tidal and inter-tidal restoration projects
- considering potential vegetation conversion due to drier soils in managing upland habitats and defending against weed invasions
- creating habitat corridors to increase ecosystem flexibility and to allow for organism migration during transition periods
- developing ecosystem management plans that take into account increased fire risks
- advocating for ecosystem protection as a component of emergency response plans and measures

Overall our approach to regional restoration ecology needs to shift towards designing more flexible ecosystems which will rely on increasing the diversity of seed sources and vegetation types used in restoration design (see Seavy and others 2009). In turn, the ecosystem services enhanced via restoration may provide valuable buffers between local communities and potential climate change impacts. For example, in portions of the North Bay where wetlands still provide a transition from bay to watershed, there is far greater adaptation flexibility than in places where hard infrastructure has been installed.

Integrative adaptation strategies

The current guiding principle of "integrated regional water management" (IRWM) holds significant promise in terms of adaptive capacity for North Bay watersheds in the face of climate change. Many of the recommended strategies below are adapted from DWR 2008 and others listed in the reference section.

Strategy 1: Maximize the potential of Integrated Regional Water Management to protect and enhance water supplies

Regional plans for the North Bay should identify strategies that improve the coordination of local groundwater storage and banking with local surface storage and other water supplies such as recycled municipal water, surface runoff, and imported water. Key elements include:

- aggressive conservation and increased efficiency measures
- maximizing reuse and recycling of water where appropriate
- increasing distributed storage, including residential roof catchment
- integrating flood management with land use policies that:
    - restore natural watershed processes to increase infiltration, slow runoff, improve water quality and augment the natural storage of water
    - encourage low-impact development that reduces water demand, captures and reuses stormwater and urban runoff, and increases water supply reliability
- consistently and rigorously apply watershed indicators to monitor watershed "vital signs."

Strategy 2: Prepare for increased frequency of extreme events, coordinate with urban adaptation plans and processes, including emergency response

Local water management agencies need a coordinated plan for entities within our region to share water supplies and infrastructure during emergencies such as droughts, floods, and fire. All at-risk communities should develop, adopt, practice and regularly evaluate formal emergency preparedness, response, evacuation and recovery plans. Key elements include:

- drought preparedness planning that assume a 20 percent increase in the frequency and duration of future dry conditions (pending more accurate information)
- emergency flood response that anticipates potentially unprecedented frequency and intensity of events, shifting to a 200-yr event baseline rather than 100-yr event baseline
- advance fire response planning that integrates considerations of watershed sensitivity, potential water quality, and ecosystem service impacts of control treatments.

Strategy 3: Practice and promote integrated flood management

Flood management should better utilize natural floodplain processes and be integrated with watershed management on open space, agricultural, wildlife areas, and other low density lands to lessen flood peaks, reduce sedimentation, temporarily store floodwaters and recharge aquifers, and restore environmental flows. Elements include:

- increased use of setbacks, flood easements, zoning, and land acquisitions to provide greater public safety, floodplain storage, habitat and system flexibility
- flood insurance requirements to address residual risk
- extensive, grassroots public outreach and education; and
- integration of flood management with all aspects of water resources management and environmental stewardship.

Strategy 4: Restore ecosystems to maximize climate resiliency

Ecosystem-based adaptation utilizes "ecosystem services" to buffer the effect of climate change on humans and biodiversity. Emerging approaches to meet this objective include:

- designing stream and riparian restorations based on a broader range of flow estimates
- increasing species and genetic diversity of vegetation used in ecological restoration
- creating a mosaic of connected habitats, including working landscapes, suitable for a broad range of native target species
- aggressively pursuing invasive species control to ensure transformations in ecosystems occur within our "native" species palette
- monitoring ecosystem response in concert with climate and hydrology indicators.

Strategy 5: Commit to long-term watershed monitoring

Long-term collection of watershed monitoring data will be key to evaluating watershed impacts of climate change in "real time" over the decades to come. Key indicators include:

- stream flow indicators that capture climate impacts on flood peaks, base flows, and total cumulative flow in concert with ongoing changes in land use
- stream temperature and dissolved oxygen indicators that capture sensitive aspects of water quality
- monitoring stream biota, particularly cold-water fisheries (steelhead and Chinook salmon) and riparian bird populations, to provide real-time data on ecosystem response
- tracking potential vegetation changes to inform management concerns regarding fire risk, habitat structure, and potential land cover changes due to vegetation adaptation increased drought stress on soils.

Conclusions

Integrating climate change considerations in watershed project planning in many cases simply means doing a more effective job of what we already know are sound, integrated approaches to managing precious freshwater resources in a Mediterranean climate. Key elements include the following.

- Refine vulnerability assessments: use sub-basin data and sea level rise data posted as part of this guide in project planning, monitor results to improve our understanding of climate vulnerability.

- Commit to real-time monitoring to provide critical "vital signs" indicators for watershed resources.

- Bridge watershed planning and emergency response protocols: integrate water resources considerations with local plans for drought, flood, and fire response.

- Increase priority on conservation, conjunctive use and development of supplementary water supply resources, including spatially distributed as well as centralized storage facilities.

- Minimize development in flood prone and sea level rise zones and anticipate risk of higher frequency/magnitude of extreme events as part of flood protection plans.

- Focus on water quality of dry-season in-stream flows and resulting concentrations of pollutants, prepare for higher salinities in low lying areas.

- Restore habitat for a range of conditions from that include overall drier soils, extended droughts and anticipate extreme precipitation events.

In addition to this report, data posted on-line, and associated published research on watershed hydrology impacts, this project produced a PowerPoint presentation on projected localized climate impacts to the North Bay that is available to NBWA members for presentation. For more information, please contact the project representative listed below.

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References

CalWater. 1999. California Interagency Watershed Map of 1999 (CalWater Version 2.2.1). Prepared by the Natural Resources Conservation Service California Interagency Watershed Mapping Committee. *http://www.ca.nrcs.usda.gov/Features/calwater.*

Cayan DR, Maurer EP, Dettinger MD , Tyree M, Hayhoe K. 2007. Climate change scenarios for the California region. Climatic Change. DOI 10.1007/s10584-007-9377-6.

Cayan DR, Tyree M, Dettinger MD, Hidalgo H, Das T. 2009. California climate change scenarios and sea level rise estimates for the California 2008 Climate Change Scenarios Assessment. California Energy Commission Report No. CEC-500-2009-014-F. *http://www.energy.ca.gov/2009publications/CEC-500-2009-014/CEC-500-2009-014-F.PDF*

Daly C, Gibson WP, Doggett M, Smith J, Taylor G. 2004. Up-to-date monthly climate maps for the conterminous United States. Proc., 14th AMS Conf. on Applied Climatology, 84th AMS Annual Meeting Combined Preprints, Amer. Meteorological Soc., Seattle, WA, January 13-16, 2004, Paper P5.1, CD-ROM. *http://www.prism.oregonstate.edu/pub/prism/docs/appclim04-uptodate_monthly_climate_maps-daly.pdf*

DWR (State of California, The Resources Agency, Department of Water Resources). 2008. *Managing an Uncertain Future: Climate Change Adaptation Strategies for California's Water.* Sacramento, CA. http://www.water.ca.gov/climatechange/docs/ClimateChangeWhitePaper.pdf

Flint AL, Flint LE. 2007a. Application of the Basin Characterization Model to estimate in-place recharge and runoff potential in the Basin and Range carbonate-rock aquifer system, White Pine County, Nevada, and adjacent areas in Nevada and Utah. U.S. Geological Survey Scientific Investigations Report 2007-5099. *http://pubs.water.usgs.gov/sir20075099*

Flint LE, Flint AL *in* Stonestrom DA, Constantz J, Ferré TPA and Leake SA (eds). 2007b. Ground-Water Recharge in the Arid and Semiarid Southwestern United States. Professional Paper 1703. U.S. Geological Survey, Reston, Virginia. *http://pubs.usgs.gov/pp/pp1703/pp1703*

Flint LE, Flint AL. 2011. Downscaling future climate scenarios to fine scales for hydrologic and ecologic modeling and analysis. *(unpublished manuscript in review)*

Hidalgo H, Dettinger MD, and Cayan DR. 2008. Downscaling with constructed analogues-Daily precipitation and temperature fields over the United States. California Energy

Commission Report No. CEC-500-2007-123.
http://meteora.ucsd.edu/cap/pdffiles/analog_pier_report.pdf

[IPCC] Intergovernmental Panel on Climate Change. 2001. Climate change 2001, the third assessment report (AR3) of the United Nations Intergovernmental Panel on Climate Change.
http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm

[IPCC] Intergovernmental Panel on Climate Change. 2007. Climate Change 2007, the fourth assessment report (AR4) of the United Nations Intergovernmental Panel on Climate Change.
http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm

Knowles N, Cayan D. 2002. Potential effects of global warming on the Sacramento-San Joaquin watershed and the San Francisco Estuary. Geophysical Research Letters 29:38-1–38-4. *http://tenaya.ucsd.edu/~knowles/papers/knowles_grl_2002.pdf*

Knowles, N. 2010. Potential inundation due to rising sea levels in the San Francisco Bay. *San Francisco Estuary and Watershed Science*, 8 (1).
http://escholarship.org/uc/item/8ck5h3qn

Lawler J, T Tear, C Pyke, M R Shaw, P Gonzalez, P Kareiva, L Hansen, L Hannah, K Klausmeyer, A Aldous, C Bienz, and S Pearsall. 2009. Resource management in a changing and uncertain climate. *Frontiers in Ecology and the Environment,* 2009; 7. doi:10.1890/070146.

Matthews, J. 2010. *Embracing Uncertainty: Sustainable water resource management in a shifting climate.*
http://siteresources.worldbank.org/EXTWAT/Resources/4602122-1213366294492/5106220-1234469721549/28.3_Climate_Change_Water_Infrastructure_WWF.pdf

Micheli E, Flint, L, Flint A, Weiss S, and Kennedy, M. *In Press. Downscaling future climate scenarios to the watershed scale: a North San Francisco Bay Estuary case study.*

North Bay Watershed Association (NBWA). 2003. North Bay Watershed Stewardship Plan. Novato, CA.

Ridolfi K, Vorster P, Micheli L. 2010. *Indicators and Performance Measures for North Bay Watersheds.* Prepared for the North Bay Watershed Association by the San Francisco Estuary Institute. Alameda, CA. 36 pp.

Seavy, N, T Gardali, G Golet, T Griggs, C Howell, R Kelsey, S Small, J Viers, J Wiegand. 2009. Why climate change makes riparian restoration more important than ever: recommendations for practice and research. *Ecological Restoration* 27:3.

State of California (Natural Resources Agency). 2009. *2009 California Climate Adaptation Strategy: a report to the Governor of the State of California in response to Executive Order S-13-2008.* Sacramento, CA. http://www.energy.ca.gov/2009publications/CNRA-1000-2009-027/CNRA-1000-2009-027-F.PDF

Stephenson NL. 1998. Actual evapotranspiration and deficit: Biologically meaningful correlates of vegetation distribution across spatial scales: Journal of Biogeography, Vol. 25, No. 5, pp. 855-870.

Weiss SB, Schaefer N, Branciforte R. 2007. Upland Habitat Goals: Study Design and Methodology. Prepared for Bay Area Open Space Council, Berkeley, CA. 33 pp.

West J, Julius S, Karieva P, Enquist C, Lawler J, Petersen B, Johnson A, Shaw, R. 2009. U.S. natural resources and climate change: concepts and approaches for management adaptation. *Environmental Management*. DOI 10.1007/s00267-009-9345-1.

WWF (World Wildlife Federation). 2010. Flowing Forward: Freshwater ecosystem adaptation to climate change in water resources management and biodiversity conservation. Le Quesne T, Matthews JH, Von der Heyden C, Wickel AJ, Wilby R, Hartmann J, Pegram G, Kistin E, Blate G, Kimura de Freitas G, Levine E, Guthrie C, McSweeney C, Sindorf N. Water Working Notes, Note No. 28, August 2010.

APPENDIX A Major and Minor Basin Attributes

MAJOR BASINS

Major Basin Name	Selected Drainages Included	Area (km2)	Area (acres)
Marin Coast	Lagunitas and San Geronimo Creeks, Bolinas	833.7	206,012
Marin Bay	Miller and Corte Madera Creeks	341.5	84,396
Petaluma River	Stage Gulch Creek	384.9	95,114
Napa River	Conn, York, Milliken, Soda and other Creeks	829.2	204,890
Sonoma Creek	Bear, Calabazas, Carriger, and Nathanson Creeks	431.4	106,593

MINOR BASINS

Minor Basin ID (HRC)	Minor Basin (CalWater CDFPWSNAME)	CalWater HANAME	Major Basin	Area (km2)	Area (acres)
1	Upper Napa River	Napa River	Napa River	24.9	6,165
2	Garnett Creek	Napa River	Napa River	20.6	5,088
3	Simmons Canyon	Napa River	Napa River	34.6	8,560
4	Ritchie Creek	Napa River	Napa River	35.5	8,772
5	Bell Canyon Reservoir	Napa River	Napa River	27.6	6,830
6	Conn Creek	Napa River	Napa River	29.5	7,297
7	Moore Creek	Napa River	Napa River	19.5	4,819
8	York Creek	Napa River	Napa River	34.2	8,451
9	Chiles Creek	Napa River	Napa River	29.5	7,293
10	Fir Canyon	Napa River	Napa River	33.2	8,195
11	Heath Canyon	Napa River	Napa River	41.0	10,139
12	Lake Hennessey	Napa River	Napa River	23.3	5,761
14	Rector Reservation	Napa River	Napa River	37.7	9,325

MINOR BASINS (cont'd)

Minor Basin ID (HRC)	Minor Basin (CalWater CDFPWSNAME)	CalWater HANAME	Major Basin	Area (km2)	Area (acres)
15	Bear Canyon	Napa River	Napa River	37.9	9,371
18	Upper Dry Creek	Napa River	Napa River	24.7	6,101
19	Milliken Reservoir	Napa River	Napa River	50.3	12,439
20	Soda Creek	Napa River	Napa River	28.6	7,070
22	Lower Dry Creek	Napa River	Napa River	23.0	5,679
24	Redwood Creek	Napa River	Napa River	28.2	6,978
29	Spencer Creek	Napa River	Napa River	36.6	9,039
30	undefined	Napa River	Napa River	38.7	9,565
34	Browns Valley Creek	Napa River	Napa River	24.6	6,068
59	Mouth of Napa River	Napa River	Napa River	145.2	35,883
13	Mouth of Napa River	Napa River	N/A (adjacent Napa River)	174.6	43,146
16	Bear Creek	Sonoma Creek	Sonoma Creek	21.4	5,296
17	Upper Sonoma Creek	Sonoma Creek	Sonoma Creek	49.1	12,140
21	Upper Calabazas	Sonoma Creek	Sonoma Creek	46.8	11,571
23	Lower Calabazas	Sonoma Creek	Sonoma Creek	48.9	12,073
26	Nathanson Creek	Sonoma Creek	Sonoma Creek	37.2	9,183
27	Mouth of Sonoma Creek	Sonoma Creek	Sonoma Creek	122.5	30,259
38	Haraszthy Creek	Sonoma Creek	Sonoma Creek	28.6	7,068

MINOR BASINS (cont'd)

Minor Basin ID (HRC)	Minor Basin (CalWater CDFPWSNAME)	CalWater HANAME	Major Basin	Area (km2)	Area (acres)
40	Champlin Creek	Sonoma Creek	Sonoma Creek	19.0	4,686
43	undefined	Sonoma Creek	Sonoma Creek	30.4	7,513
60	Mouth of Sonoma Creek	Sonoma Creek	Sonoma Creek	27.5	6,804
28	Lynch Creek	Petaluma River	Petaluma River	42.4	10,485
31	undefined	Petaluma River	Petaluma River	96.9	23,948
32	Adobe Creek	Petaluma River	Petaluma River	36.5	9,016
37	undefined	Petaluma River	Petaluma River	60.2	14,869
42	Upper San Antonio Creek	Petaluma River	Petaluma River	33.0	8,156
45	Stage Gulch	Petaluma River	Petaluma River	30.3	7,476
46	Lower San Antonio Creek	Petaluma River	Petaluma River	60.2	14,864
47	undefined	Petaluma River	Petaluma River	25.5	6,301
48	Stafford Lake	Novato	Marin Bay	126.0	31,128
51	Miller Creek	Novato	Marin Bay	30.9	7,626
53	San Anselmo Creek	San Rafael	Marin Bay	74.0	18,277
54	San Rafael Creek	San Rafael	Marin Bay	29.3	7,252
56	Old Mill Creek	San Rafael	Marin Bay	8.4	2,081
61	Gallinas Creek	Novato	Marin Bay	26.5	6,549
62	Belvedere Lagoon	San Rafael	Marin Bay	4.8	1,182
63	Belvedere Lagoon	San Rafael	Marin Bay	6.9	1,698
64	Belvedere Lagoon	San Rafael	Marin Bay	5.0	1,246

MINOR BASINS (cont'd)

Minor Basin ID (HRC)	Minor Basin (CalWater CDFPWSNAME)	CalWater HANAME	Major Basin	Area (km2)	Area (acres)
65	Belvedere Lagoon	San Rafael	Marin Bay	3.7	902
67	Old Mill Creek	San Rafael	Marin Bay	0.8	197
68	Old Mill Creek	San Rafael	Marin Bay	15.7	3,888
69	Old Mill Creek	San Rafael	Marin Bay	9.6	2,378
25	Ebabias Creek	Estero Americano	Marin Coast	50.2	12,393
35	Upper Stemple	Estero San Antonio	Marin Coast	65.5	16,187
36	Lower Stemple	Estero San Antonio	Marin Coast	69.1	17,072
39	Keys Creek	Tomales Bay	Marin Coast	181.2	44,785
44	Nicks Cove	Tomales Bay	Marin Coast	61.9	15,302
49	Nicasio Reservoir	Tomales Bay	Marin Coast	95.7	23,638
50	Tomasini Canyon	Tomales Bay	Marin Coast	138.7	34,273
52	San Geronomo Creek	Tomales Bay	Marin Coast	24.3	6,000
55	Pine Gulch Creek	Bolinas	Marin Coast	40.7	10,066
57	Fern Creek	Bolinas	Marin Coast	31.8	7,869
58	Rodeo Lagoon	Bolinas	Marin Coast	14.3	3,542
71	Rodeo Lagoon	Bolinas	Marin Coast	7.6	1,884
72	Audobon Canyon	Bolinas	Marin Coast	5.8	1,436
73	Pine Gulch Creek	Bolinas	Marin Coast	1.1	284
76	Laguna Lake	Tomales Bay	Marin Coast	11.1	2,747
77	Keys Creek	Tomales Bay	Marin Coast	12.4	3,055
78	Ebabias Creek	Estero Americano	Marin Coast	23.6	5,824

APPENDIX B Upland Habitat Goals Vegetation Types and Rarity Ranking for Acreage Vulnerable to Inundation via Sea Level Rise

(after Knowles 2010 and the Upland Habitat Goals methodology report)

Upland Goals Vegetation Type	UHG Rarity Rank	Marin Bay (acres)	Napa River (acres)	Petaluma River (acres)	Sonoma Creek (acres)	Total (acres)
Barren/Rock	2		2,456	186		5,577
California Bay Forest	3	9		1		10
Central Coast Riparian Forests	1	23	19	0	1	44
Coast Live Oak Forest / Woodland	2	54	2	26		82
Coastal Salt Marsh / Coastal Brackish Marsh	1	2,701	3,657	4,767	1,228	12,352
Coastal Scrub	3	17	6		1	23
Cool Grasslands	1	4				4
Cultivated	4	2,294	797	6,699	6,378	16,169
Eucalyptus	4	5	1	4	11	20
Moderate Grasslands	3	1,893	976	456	4,780	8,105
Montane Hardwoods	2			2		2
Non-Native Ornamental Conifer-Hardwood Mixture	4	3	12	7		22
Non-Native/Ornamental Conifer	4	1				1
Non-native/Ornamental Grass	4	109	6			115
Non-native/Ornamental Hardwood	4			6		6
Oregon Oak Woodland	2			3		3
Permanent Freshwater Marsh	1	10	3,865		1,135	5,011
Redwood Forest	1	0				0
Rural Residential	4	180	117	81	109	488
Semi-Desert Scrub / Desert Scrub	2			1		1
Urban	4	7,015	3,947	1,295	324	12,581
Warm Grasslands	3		1,112	1,293	371	2,776
Water	4	757	7,549	1,107	466	9,879
Total		**15,118**	**24,520**	**15,934**	**17,698**	**73,270**
average rarity ranking (out of maximum of 4)	2.74					

Summary Table by Rarity Ranking

UG Rarity	Marin Bay	Napa River	Petaluma River	Sonoma Creek	Grand Total
1	2,736	7,541	4,768	2,364	17,409
2	118	2,463	218	2,894	5,693
3	1,900	2,088	1,750	5,151	10,889
4	10,364	12,428	9,199	7,289	39,280
Category Totals	**15,118**	**24,520**	**15,934**	**17,698**	**73,270**

APPENDIX C Climate Projection Tables and Major Basin Plots

Table 1 Projected climate and hydrology of NBWA study area, 2011-2100 (monthly values averaged per 30-yr interval, four scenarios)

	Time Interval	Tmax		PPT		Runoff		Recharge		PET		CWD	
Model		**°C**	**SE**	**(mm)**	**SE**	**(mm)**	**SE**	**(mm)**	**SE**	**(mm)**	**SE**	**(mm)**	**SE**
GFDL A2	2011-40	22.6	0.1	864	56	236	27	117	12	1226	3	710	20
	2041-70	23.2	0.1	860	68	266	38	122	16	1242	3	766	17
	2071-00	25.1	0.1	699	54	187	27	89	10	1286	3	855	19
GFDL B1	2011-40	22.7	0.1	913	84	308	49	132	18	1228	3	750	19
	2041-70	23.4	0.1	858	56	243	32	118	12	1244	2	742	15
	2071-00	23.9	0.1	729	52	189	28	86	11	1253	2	792	16
PCM A2	2011-40	22.7	0.1	882	67	250	37	121	14	1221	2	706	19
	2041-70	23.7	0.1	882	58	266	36	119	13	1243	2	740	15
	2071-00	24.8	0.1	943	82	313	50	131	17	1268	2	758	21
PCM B1	2011-40	22.7	0.1	1051	78	369	45	160	18	1220	2	692	19
	2041-70	23.1	0.1	913	77	284	47	121	16	1229	2	717	20
	2071-00	23.8	0.1	907	65	281	39	120	13	1243	2	732	18

APPENDIX C Climate Projection Tables and Major Basin Plots cont'd

Table 2 Historic and Projected Climate by Major Basin.
Each table summarizes historic climate and hydrology and four climate projection models for each major basin of the North Bay Watershed Association study area.

Marin Coast Major Basin

		Tmax		Tmin		PPT		Runoff		Recharge		PET		CWD	
Model	**Time Interval**	**oC**	**SE**	**oC**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**
Historic *	1896-20	18.3	0.1	6.5	0.1	876	258	323	43	88	7	1122	2	655	12
	1921-50	19.1	0.1	6.8	0.1	820	260	265	33	86	7	1129	4	657	14
	1951-80	19.2	0.1	6.9	0.1	911	296	346	41	96	8	1129	4	658	13
	1981-10	19.8	0.1	7.7	0.1	960	357	383	49	92	8	1160	4	684	14
GFDL A2**	2011-40	20.5	0.1	8.2	0.1	955	72	400	54	77	8	1175	2	696	15
	2041-70	21.4	0.1	9.2	0.1	907	62	387	52	72	6	1197	3	746	11
	2071-00	23.0	0.1	11.0	0.1	790	72	318	54	58	7	1236	3	818	18
GFDL B1**	2011-40	20.5	0.1	8.3	0.1	998	91	474	72	75	8	1172	2	722	12
	2041-70	21.1	0.1	8.9	0.1	952	59	396	48	78	6	1188	2	710	11
	2071-00	21.6	0.1	9.3	0.1	790	56	287	43	57	7	1197	2	748	11
PCM A2**	2011-40	20.5	0.1	7.7	0.1	974	71	401	56	79	8	1166	2	671	14
	2041-70	21.3	0.1	8.5	0.1	963	65	418	54	74	7	1186	2	713	11
	2071-00	22.4	0.1	9.6	0.1	1023	88	477	72	73	7	1210	2	737	14
PCM B1**	2011-40	20.5	0.1	7.7	0.1	1156	86	586	69	89	8	1164	2	684	15
	2041-70	20.9	0.1	8.0	0.1	1025	82	463	70	74	7	1174	2	685	14
	2071-00	21.5	0.1	8.5	0.1	999	67	446	57	72	7	1186	2	703	13

* Derived from PRISM climate data (Daly and others 2004) and Basin Characterization Model (BCM) watershed simulations for historic time steps
** Derived from referenced General Circulation Models climate projections and Basin Characterization Model (BCM) watershed simulations

APPENDIX C Climate Projection Tables and Major Basin Plots cont'd

Table 2 Historic and Projected Climate by Major Basin cont'd

Marin Bay Major Basin

		Tmax		Tmin		PPT		Runoff		Recharge		PET		CWD	
Model	**Time Interval**	**oC**	**SE**	**oC**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**
Historic*	1896-20	19.1	0.1	7.3	0.1	771	46	251	32	76	34	1,146	2	672	12
	1921-50	20.0	0.1	7.5	0.1	702	42	200	24	67	33	1,148	3	681	14
	1951-80	20.0	0.1	8.2	0.1	786	48	259	30	80	40	1,157	4	682	14
	1981-10	20.4	0.1	8.9	0.1	818	61	289	36	81	49	1,184	3	707	17
GFDL A2**	2011-40	21.4	0.1	9.5	0.1	856	68	313	41	80	11	1,203	10	713	17
	2041-70	22.3	0.1	10.5	0.1	803	56	301	38	72	8	1,226	14	765	12
	2071-00	24.0	0.1	12.2	0.1	687	64	242	40	58	8	1,267	16	839	18
GFDL B1**	2011-40	21.3	0.1	9.5	0.1	879	82	361	54	82	11	1,200	2	738	14
	2041-70	22.0	0.1	10.1	0.1	831	53	299	36	75	8	1,217	2	731	11
	2071-00	22.4	0.1	10.5	0.1	691	50	220	31	55	7	1,225	2	772	12
PCM A2**	2011-40	21.3	0.1	9.0	0.1	866	67	309	43	81	10	1,194	2	692	15
	2041-70	22.2	0.1	9.8	0.1	856	61	321	42	77	9	1,215	2	729	11
	2071-00	23.4	0.1	10.9	0.1	914	80	366	54	83	10	1,240	2	748	16
PCM B1**	2011-40	21.3	0.1	8.9	0.1	1,024	80	442	54	102	12	1,192	2	693	15
	2041-70	21.7	0.1	9.2	0.1	902	75	349	53	81	10	1,202	2	704	14
	2071-00	22.4	0.1	9.8	0.1	879	64	338	45	75	9	1,214	2	721	13

* Derived from PRISM climate data (Daly and others 2004) and Basin Characterization Model (BCM) watershed simulations for historic time steps

** Derived from referenced General Circulation Models climate projections and Basin Characterization Model (BCM) watershed simulations

APPENDIX C Climate Projection Tables and Major Basin Plots cont'd

Table 2 Historic and Projected Climate by Major Basin cont'd

Petaluma River Major Basin

		Tmax		Tmin		PPT		Runoff		Recharge		PET		CWD	
Model	**Time Interval**	**oC**	**SE**	**oC**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**
Historic *	1896-20	20.0	0.1	5.8	0.1	700	42	138	21	72	8	1155	2	663	18
	1921-50	21.0	0.1	6.1	0.1	664	39	115	15	66	7	1161	4	680	19
	1951-80	21.1	0.1	6.4	0.1	710	42	140	17	77	8	1166	4	676	19
	1981-10	21.5	0.1	7.5	0.1	745	54	162	23	80	11	1201	4	698	23
GFDL A2**	2011-40	22.5	0.1	8.1	0.1	771	58	166	23	94	14	1218	2	708	24
	2041-70	23.4	0.1	9.2	0.1	719	49	153	23	82	12	1242	3	760	17
	2071-00	25.1	0.1	11.2	0.2	619	58	126	23	66	12	1284	3	857	26
GFDL B1**	2011-40	22.5	0.1	8.1	0.2	805	73	208	34	108	99	1216	3	728	23
	2041-70	23.1	0.1	8.8	0.1	769	49	167	23	90	63	1233	2	721	18
	2071-00	23.6	0.1	9.3	0.1	649	46	124	20	64	50	1243	2	783	19
PCM A2**	2011-40	22.4	0.1	7.5	0.1	785	58	166	25	91	13	1209	2	682	22
	2041-70	23.3	0.1	8.4	0.1	779	51	174	24	91	13	1230	2	717	18
	2071-00	24.4	0.1	9.6	0.1	836	72	209	36	104	17	1256	2	734	25
PCM B1**	2011-40	22.5	0.1	0.1	0.2	805	73	208	34	108	18	1216	3	728	23
	2041-70	23.1	0.1	0.1	0.1	769	49	167	23	90	11	1233	2	721	18
	2071-00	23.6	0.1	0.1	0.1	649	46	124	20	64	9	1243	2	783	19

* Derived from PRISM climate data (Daly and others 2004) and Basin Characterization Model (BCM) watershed simulations for historic time steps

** Derived from referenced General Circulation Models climate projections and Basin Characterization Model (BCM) watershed simulations

APPENDIX C Climate Projection Tables and Major Basin Plots cont'd

Table 2 Historic and Projected Climate by Major Basin cont'd

Sonoma Creek Major Basin

		Tmax		Tmin		PPT		Runoff		Recharge		PET		CWD	
Model	**Time Interval**	**oC**	**SE**	**oC**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**
Historic *	1896-20	20.7	0.1	5.7	0.1	812	48	253	31	84	7	1,173	2	697	16
	1921-50	21.4	0.1	6.0	0.1	759	44	214	23	81	6	1,173	4	713	18
	1951-80	21.7	0.1	6.6	0.1	830	48	262	26	90	8	1,186	4	710	18
	1981-10	22.0	0.1	7.7	0.1	876	62	289	33	94	10	1,220	4	727	23
GFDL A2**	2011-40	23.2	0.1	8.2	0.1	883	66	269	33	118	15	1,240	13	746	22
	2041-70	24.2	0.1	9.2	0.1	840	57	262	34	107	12	1,263	15	792	17
	2071-00	25.9	0.1	11	0.2	706	65	207	32	85	12	1,301	17	886	24
GFDL B1**	2011-40	23.1	0.1	8.4	0.1	931	86	325	49	130	18	1,240	3	764	20
	2041-70	23.8	0.1	9.1	0.1	875	57	261	32	114	12	1,255	2	756	16
	2071-00	24.3	0.1	9.5	0.1	747	53	209	29	84	10	1,265	2	810	18
PCM A2**	2011-40	22.1	0.1	7.6	0.1	878	62	289	33	95	10	1,219	4	726	22
	2041-70	23.6	0.1	8.0	0.1	897	45	276	26	116	9	1,241	2	736	13
	2071-00	25.2	0.1	9.6	0.1	961	84	329	50	128	17	1,277	2	773	22
PCM B1**	2011-40	23.1	0.1	7.6	0.1	1,073	78	389	44	156	18	1,229	2	701	20
	2041-70	23.6	0.1	7.9	0.1	931	79	300	47	121	16	1,238	2	728	22
	2071-00	24.3	0.1	8.5	0.1	923	65	297	39	116	12	1,252	2	742	19

* Derived from PRISM climate data (Daly and others 2004) and Basin Characterization Model (BCM) watershed simulations for historic time steps

** Derived from referenced General Circulation Models climate projections and Basin Characterization Model (BCM) watershed simulations

APPENDIX C Climate Projection Tables and Major Basin Plots cont'd

Table 2 Historic and Projected Climate by Major Basin cont'd

Napa River Major Basin

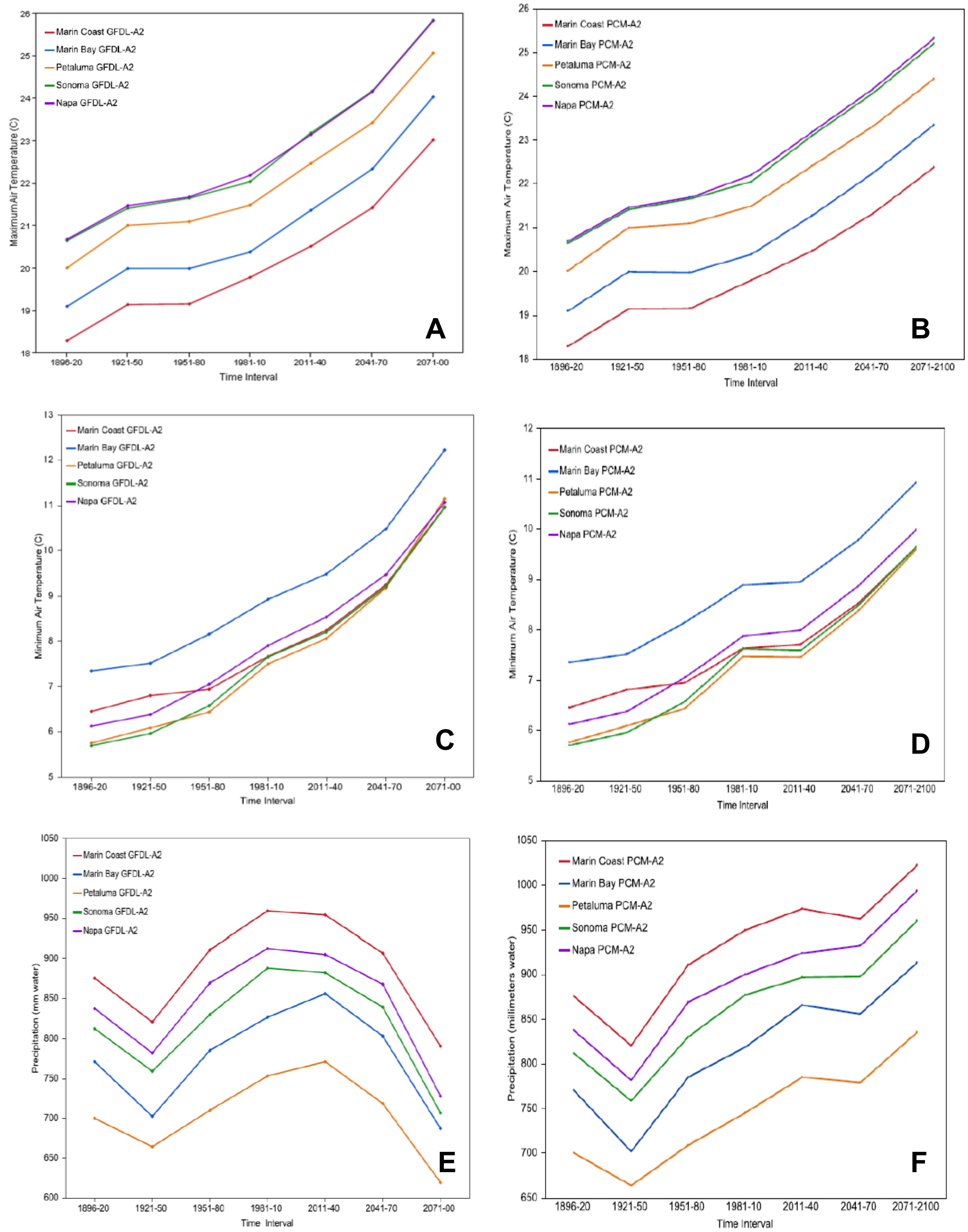
		Tmax		Tmin		PPT		Runoff		Recharge		PET		CWD	
Model	**Time Interval**	**oC**	**SE**	**oC**	**SE**	**mm y-1**	**SE**	**m m y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**	**mm y-1**	**SE**
Historic *	1896-20	20.7	0.1	6.1	0.1	837	51	243	34	109	9	1178	2	691	15
	1921-50	21.5	0.2	6.4	0.1	782	46	195	25	104	9	1181	4	702	17
	1951-80	21.7	0.1	7.1	0.1	870	50	257	29	120	11	1194	4	702	16
	1981-10	22.2	0.1	7.9	0.1	913	61	282	35	123	12	1224	4	715	20
GFDL A2**	2011-40	23.2	0.1	8.5	0.1	905	70	250	36	153	19	1242	3	739	20
	2041-70	24.2	0.1	9.5	0.1	868	61	249	37	142	14	1264	3	785	16
	2071-00	25.8	0.1	11.1	0.1	728	67	194	35	109	15	1300	3	873	23
GFDL B1**	2011-40	23.2	0.1	8.4	0.1	967	90	323	54	164	21	1239	3	758	18
	2041-70	23.9	0.1	9.1	0.1	901	59	246	35	151	15	1254	3	749	14
	2071-00	24.3	0.1	9.5	0.1	772	56	197	32	110	13	1264	2	796	16
PCM A2**	2011-40	23.2	0.1	8.0	0.1	925	72	254	40	153	18	1234	2	716	19
	2041-70	24.2	0.1	8.9	0.1	932	62	276	40	150	15	1256	2	749	14
	2071-00	25.3	0.1	10.0	0.1	994	88	331	55	160	19	1280	2	774	20
PCM B1**	2011-40	23.2	0.1	8.0	0.1	1106	81	382	49	194	19	1233	2	703	18
	2041-70	23.7	0.1	8.3	0.1	955	82	292	51	150	18	1242	2	728	20
	2071-00	24.4	0.1	8.9	0.1	965	71	297	44	153	16	1257	2	740	18

* Derived from PRISM climate data (Daly and others 2004) and Basin Characterization Model (BCM) watershed simulations for historic time steps

** Derived from referenced General Circulation Models climate projections and Basin Characterization Model (BCM) watershed simulations

APPENDIX C Climate Projection Tables and Major Basin Plots cont'd

Figures Historic (1896-2009) and projected (2010-2100) maximum and minimum temperatures and precipitation by major basin, North Bay region, GFDL-A2 and PCM-A2 scenarios



Figures Historic (1896-2009) and projected (2010-2100) hydrology by major basin, North Bay region, GFDL-A2 and PCM-A2 scenarios