Section 5
Measuring Regional Impacts

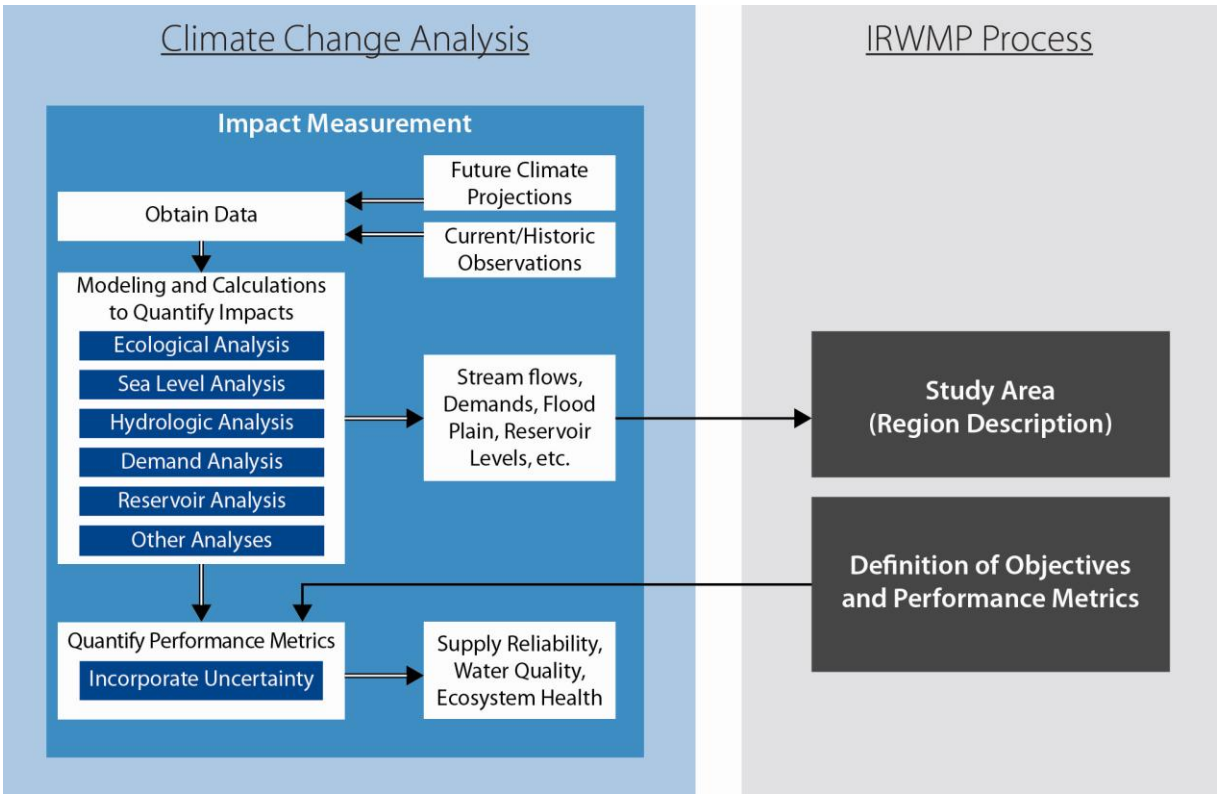


Figure 5-1: Process for Measuring Impacts of Climate Change as part of an IRWMP.

Once a regional planning group has identified and prioritized its key areas of climate change vulnerability, they must determine how to analyze these vulnerabilities and start quantifying the impacts on important resources. The vulnerability assessment discussed in Section 4 provides planners with a way to identify resources with a "warning flag" where they are particularly vulnerable. The analyses discussed in Section 5 are a way of responding to these warning flags. During this step, the climate change analysis becomes fully integrated with traditional planning analyses.

All planning is based on making estimates of future conditions. Planners are familiar with projecting future population or land use trends. Considering climate change involves altering our assumptions about future conditions related to climate. Standard planning exercises have been done in the past assuming that climate conditions in the future will vary in the same way that past climate conditions have varied. This is no longer an appropriate assumption. Incorporating climate change projections into planning analyses increases the uncertainties that need to be taken into account.

This section focuses on:

- Comparing various analytical approaches and determining which approach or approaches will work best for each of the vulnerabilities identified for a region,
- Understanding the data and technical resource requirements associated with various analytical approaches,
- Finding additional references for approaches that look appropriate, and
- Gathering required data and conducting the necessary analysis using the chosen analytical approach.

Several tools are available to assist planners in making assumptions about future climate and using those assumptions to inform analysis of important impacts. This section provides a discussion of the decision-making process required to determine which tools and which analytical approach will work best for a region. Several typical analytical approaches for measuring regional climate change impacts on water resources are presented and discussed. This process is highly specific for each region, and no one-size-fits-all approach can be recommended. Instead, this section lays out the factors that a region should consider when selecting an analytical approach and specific tools. Each region is unique and requires analytical methods that are matched to their specific water resources challenges, local technical and financial capabilities, and priorities of the region. The general elements associated with measuring climate change impacts are depicted in Figure 5-1.

Specific climate change impacts resulting from the analyses discussed in this section can be used to quantify planning performance metrics, help guide planning decisions, and direct development of new projects. For IRWMPs, baseline analyses may feed back into the regional description, as well. The tools discussed in this section are useful in quantifying performance metrics for strategy or project evaluation.

5.1 Overall Approach

This chapter discusses the two main steps in measuring regional climate change impacts:

1) Determining an analytical response and selecting appropriate tools (Section 5.2), and
2) Conducting the analysis (Section 5.3).

Figure 5-2 shows steps to determine the type of impact analysis that is most appropriate and the steps that will be necessary to complete the impact analysis.

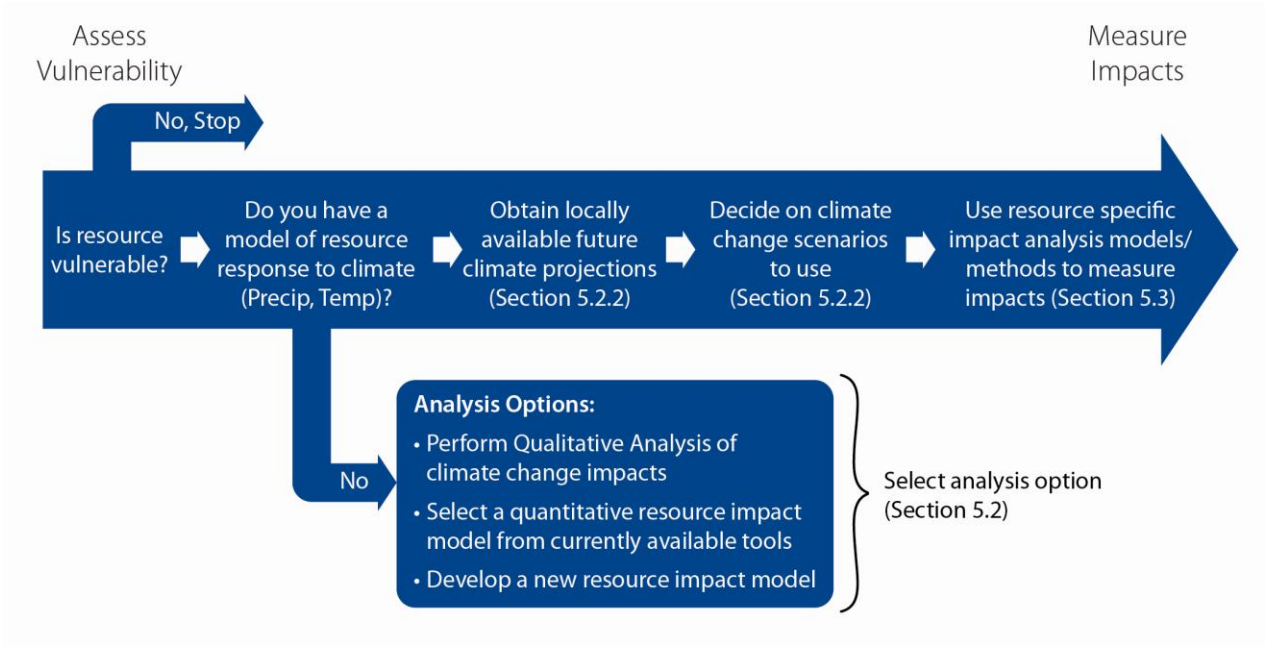


Figure 5-2: Roadmap for Analysis Approach from Assessing Vulnerability to Measuring Impacts

This handbook follows a "bottom-up" approach to climate change analysis, in which local, agency-specific vulnerabilities are prioritized. This approach minimizes conducting costly analyses on water resource sectors that are unlikely to be vulnerable or significant in the region. Therefore, it is imperative that the region complete its Vulnerability Assessment (Section 4) prior to beginning the Measure Regional Impacts step.

5.1.1 Using Existing Studies for Quantitative Analysis

In many regions, studies have already been undertaken to quantify future conditions with climate change taken into account. Whether existing or ongoing studies are being conducted on a local or regional scale, it is prudent to make use of them for an IRWMP or other planning process. Regions that import SWP water are encouraged to make use of DWR's State Water Project Delivery Reliability Report 2009 Update (DWR 2010b) to project supply reliability in the future.

A region with multiple water supply sources may need to combine supply-reliabilities from multiple analyses. For example, the Metropolitan Water District of Southern California (MWD) 2010 Integrated Resource Plan (IRP) combines delivery projections from the SWP and the Colorado River (MWD 2010). These supply-reliability results are compared with water demand study results (see MWD case study on adaptive management in Section 7). The use of multiple studies may be difficult if each analysis uses different emissions scenarios and GCM results as a basis for identifying future conditions.

5.1.2 Additional Resources for Quantitative Analysis

Appendix D-1 presents several large data repositories that may be useful in climate or hydrologic analysis described later in this section. These sources are only a starting point and planners should tap into regional and local sources as well. Much of the observational hydrologic data needed for the resource impact models can be obtained from the California Data Exchange Center maintained by DWR (http://cdec.water.ca.gov/).

Once an analytical technique has been chosen and calibrated for the specific area and purpose for which it will be used, a climate change scenario needs to be selected for the analysis in order to generate information about the system response to potential future climate conditions.

5.2 Selecting Analytical Methods and Tools

There are a multitude of potential analysis methods that could be used to account for climate impacts on regional water resources and planning projects. This section discusses several potential analysis methods. Appendix D-2 contains information on several analysis tools for the various methods discussed in this section; however, new methods are constantly being developed and planners are encouraged to investigate the most current analysis methods available. There is a wide range in sophistication and accuracy of the various methods available, and determining the appropriate way of considering climate change in the planning process is not always straightforward. This section discusses elements of both qualitative and quantitative analysis methods and provides some guidance on selecting an appropriate analysis method. Ultimately, an appropriate analysis can only be determined on a case-by-case basis.

Uncertainty in Planning

Uncertainty influences every aspect of planning, whether climate change is explicitly included or not. Accounting for uncertainty in planning is an established component of good planning practices and needs to reflect uncertainties associated with future population and economic conditions, as well as future technological advances and social trends. Climate change involves added uncertainties associated with future GHG emissions conditions and the hydroclimatic response to current and future emissions. Section 5.3 describes the sources of climate change-related uncertainty and ways to include it with other uncertainties in planning. Additionally, Appendix C presents information on how to quantify uncertainty in climate change analysis. Uncertainty considerations are part of the definition of an analytical approach for climate change impacts.

5.2.1 Considerations for Selecting Analytical Approaches

In many cases, currently used analytical planning tools can be adjusted to incorporate climate change. For example, most hydrologic models used to evaluate streamflows and reservoir levels may be adjusted to account for future temperatures and precipitation. However, where tools currently used by regional planners cannot be used, planners can select analytical methods based on the regional data available, capabilities of existing technologies, potential use of analysis results in the planning effort, uncertainty considerations, and local technical and financial capabilities.

Considerations that should be taken into account when making this decision include:

- The sector's sensitivity to climate change impacts (e.g., if a small change in temperature could have a large impact on the resource). Information from the vulnerability assessment can be useful in this step.
- The sector's exposure to climate change impacts (e.g., if a very large portion of the region's water supply could be affected by climate change). Information from the vulnerability assessment can be useful in this step.
- The sector's adaptive capacity (e.g., would the region have the ability to adapt quickly and with minimal disruption of services or environmental damage if an extreme change in climate were to occur). Information from the vulnerability assessment can be useful in this step.
- Does the region have existing analytical tools that can incorporate projections of future climate and can be effectively deployed to analyze the potential impacts of climate change?
- Do "off-the-shelf" tools exist to effectively analyze the potential impacts of climate change?
- Does the region possess the technical expertise, or the financial resources to engage the technical expertise, necessary to select or create models or other analytical tools for analyzing the potential impacts of climate change?
- Does the region have appropriate data on current/historical conditions to effectively analyze the potential impacts of climate change?
- How could information generated from analyzing the impacts of climate change be used to quantify performance metrics in project evaluation?

Measuring regional climate change impacts can be a highly analytical process—requiring downscaled climate data from GCMs, along with the use of various water resources models (e.g., water demand, hydrologic, water quality, runoff, and coastal). However, if sophisticated climate projections or models are not available and/or are not appropriate, more qualitative assessment of impacts can be used.

Analysis options vary greatly with respect to complexity and sophistication. The various methods included in this handbook are intended to give a representative overview of the most common options that have been used by others. However, it is not possible to include all methods that have been used, as the literature is constantly evolving. This handbook provides descriptions of several methods, and directs the reader to more comprehensive detailed descriptions of the methods, data required, and type of data resulting from the analysis.

Planners are encouraged to use analysis methods that are consistent with the region's prioritization of climate change vulnerabilities (see Section 4), and the quality of data and GCM projections available. Figure 5-3 shows various analysis methods (vertical axis) and climate projection applications (horizontal axis) and how quantitative they can be.

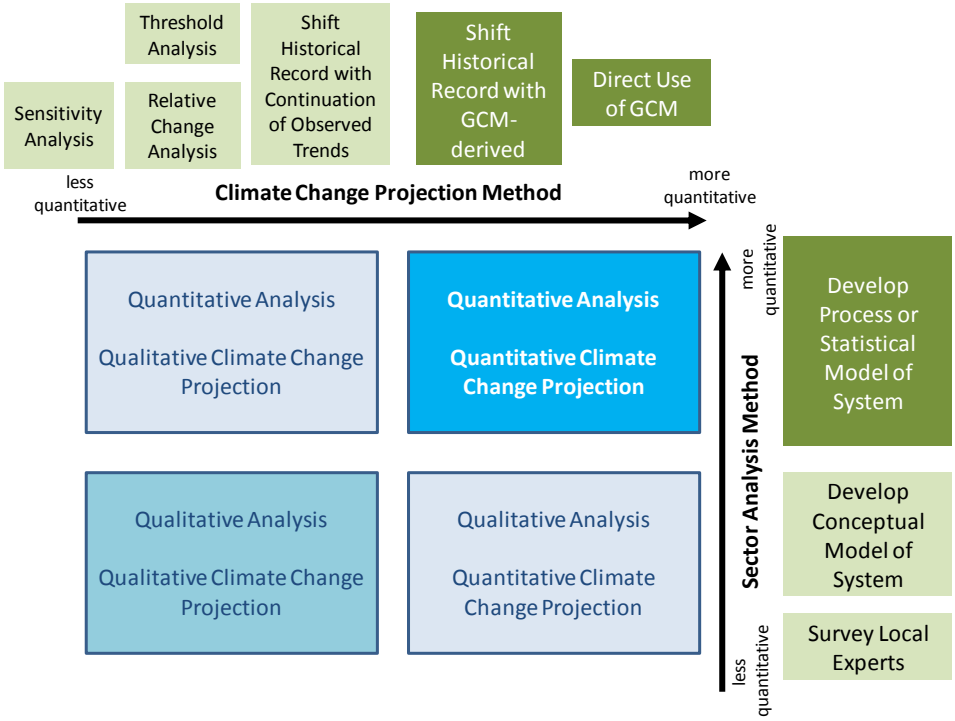


Figure 5-3: Quantitative versus Qualitative Climate Change Analysis.

Each of the sector analysis methods and climate change projection methods shown in the figure are discussed in this section. The sections below are broken up into Quantitative Approach Tools (Section 5.2.2) and Qualitative Approach Tools (Section 5.2.3). This distinction is made between approaches that rely on very specific data or projections, like time series of future daily temperatures, and approaches that rely on more general data or projections, like an assumption such as "droughts will become 20 percent more common or more severe in the future." Many of the tools described below can be combined in various ways to generate hybrid approaches as well. Hybrid approaches are descibed in Section 5.2.4.

For some water resources concerns, such as flooding and other extreme events, GCM projections are not accurate enough to yield high-accuracy analysis results. In these cases, it may be more effective to use qualitative methods. The Water Utility Climate Alliance (WUCA) produced a whitepaper in which they identified the relative appropriateness for applying climate model results to various management decisions. The table is repeated here for reference as Table 5-1.

Table 5.1: Climate model variables and relative reliability for water resources analysis (Source: WUCA 2009)

Water Management Issue	Climate Model Variables	Relative Reliability of Climate Model Output
Water Supply		
Long-term supplies - mean annual basin yield	Annual average temperature and precipitation	- High on temperature - Precipitation depends on geographic scale, higher at sub-continental scale - Regional climate model precipitation projections are more reliable than GCM projections
Long-term demand	Warm-season temperature and precipitation	Same as above
Shift in seasonality of runoff in snowmelt-dominated areas	Monthly temperature	Medium-High
Shift in seasonality of runoff in non-snowmelt-dominated areas	Seasonal precipitation	Medium-Low
Long-term supplies - variability in yield	Monthly temperature and precipitation	Medium-Low
Flooding		
Seasonal floods	Winter and spring precipitation	Medium-Low
Major storms/cyclones	Frontal systems; cyclone information and track	Low
Flash floods	Hourly precipitation in small geographic areas	Very Low
Water Quality		
Biological oxygen demand	Annual, seasonal, monthly air temperature (to estimate water temperature)	Medium-High
Dissolved oxygen	Annual, seasonal, monthly air temperature (to estimate water temperature)	Medium-High
Flow reduction	Annual, seasonal, monthly temperature, precipitation	Medium-High
Saline intrusion of groundwater	Sea level rise; annual temperature and precipitation	Medium-High
Algal bloom	Annual, seasonal, monthly temperature	Medium-Low
Turbidity	Daily, hourly precipitation intensity	Low
Cryptosporidium	Daily, hourly precipitation intensity	Low

5.2.2 Quantitative Approach Tools

5.2.2.1 Quantitative Analysis Methods

For each resource sector, there are many ways to quantitatively represent the relationship between climate variables (e.g., temperature and precipitation) and regional water planning variables of interest (e.g., streamflow, water demand, or ecological response).

Process-based models and regression-based models are two of the most commonly used quantitative tools for assessing the impact of climate variables, such as temperature and precipitation, on resources. Both types of models have been in use in academia and industry for many decades, and have traditionally utilized historic climate data. This handbook makes reference to these models since they can be used in climate change assessment once new values for climatic variables are introduced.

Process-based Models

Process-based models simulate the physical processes that are occurring in the real world. These models use mathematical formulas to approximate the effect that a change in one or more variables to the system will have on the resulting behavior of the system. For example, a process-based model of a watershed would use precipitation and temperature data as inputs. The model would calculate how precipitation makes its way through the watershed, falling as snow or rain, percolating through aquifers, evaporating to the atmosphere, and finally flowing down stream channels and, perhaps, into a reservoir.

This method requires sufficient data to understand the underlying physical processes and represent them mathematically. Observational data to test and calibrate the model is also required. However, once the model is constructed and calibrated it should be able to simulate the system's response over a wide range of climate conditions—assuming the climate conditions don't affect the underlying physical processes.

Regression-based models

Regression relationships and other statistical models are based solely on measured data. This method requires more historical data but less understanding of the underlying physical processes. For example, a regression relationship may correlate precipitation data with streamflow data, so that a statistical relationship can be developed which projects the streamflow response of a given precipitation input.

Care should be taken when using a regression-based model to estimate system response for input levels that vary greatly from the observed data used to generate the regression relationship. For example, a regression relationship of temperature vs. agricultural water demand that is based on agricultural water demand at summer time temperatures between 50 and 90 degrees Fahrenheit may not be reliable when temperatures exceed 100 degrees because of factors that have discontinuous effects on water demand.

Specific information and direction on building and calibrating process-based models and developing regression relationships is beyond the scope of this handbook. Regions should exercise care in selecting a modeling approach and developing the approach to represent their systems, considering:

- *Selecting a model that is designed to represent the processes that are important in the region*. Some models do not accurately represent features that are either atypical or occur at a small spatial scale. For example, the Water Supply Forum case study (Box 5-2) discusses a watershed

containing a glacier. The modeled representation of this watershed was developed using a model that had the capability to represent the influence of glacial activity on streamflows.

- *Selecting a model that maximizes information contained in the available data.* Different models make use of different datasets to calculate relationships among variables. For example, if the historic temperature record contains little variability and future projected temperatures are outside of the historic range, a regression analysis may not accurately reflect projected conditions as well as a process-based model could. However, if limited data or understanding is available to develop a process-based model while an extensive historical record of a few variables is available, a regression analysis may be best.

5.2.2.2 Climate Change Projections

This section describes methods for obtaining locally applicable projections of future climate change. This information is required in order to complete a quantitative analysis of future conditions and will be used as an input to drive process-based models, regression relationships, or other analytical tools.

As discussed in Section 2, the most rigorous and readily available source for this information comes from downscaled GCM projections. GCMs generate projections of future climate at very large scales; model grid cells can be hundreds of square miles. Downscaled GCM data can be used with other, more resource-specific models to analyze local impacts. For instance, temperature and precipitation data from a downscaled GCM can be used to drive a rainfall-runoff model to project future streamflow. Alternatively, temperature, precipitation, and humidity data from a downscaled GCM could be used to drive an agricultural water demand model.

The CMIP3 archive of downscaled GCM projections (discussed in Section 2) includes 16 of the 25 models included in the CMIP3, run with three future GHG emissions scenarios (A2, B1, and A1B). The data set contains a total of 112 downscaled climate projections. The downscaled projections use the BCSD downscaling technique to increase the resolution from greater than 1 degree of latitude-longitude for GCM outputs to 1/8th degree of latitude-longitude (approximately 12 km by 12 km). The downscaled outputs cover the time period from 1950 to 2099 at monthly time steps and contain mean daily precipitation and mean monthly surface air temperature values. The data set is available at:
http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.html#About.

There are other sources of locally applicable climate change data that a region could reasonably select and use for performing climate change analyses. However, regional planners should consider using the CMIP3 archive, as it has been widely adopted in the water resource planning field and has been used to study potential climate change impacts on various resources systems, including watershed hydrology and reservoir systems (DWR 2010c).

Planners need to define a limited number of future climate scenarios to use in successive resource-specific models in order to constrain the amount of modeling and analysis that will be done. This section discusses options for developing climate change scenarios using downscaled GCM data. The

recent California Department of Water Resources report on characterizing and analyzing climate change in planning studies (DWR 2010c) outlines two general approaches that have been widely used for selecting climate change scenarios for use in planning studies: selecting discrete projections, and developing ensemble projections. Both methods have strengths and weaknesses, and neither is considered more rigorous than the other.

Selection of Discrete Projections

Selecting a single downscaled GCM projection or a subset of projections from a full set should be based on predetermined selection criteria. These criteria may include how well a given model is able to represent locally important climate processes. For example, in the CAT 2009 study, six GCMs were selected to drive subsequent impact analyses (Cayan et al 2009). These specific GCMs were selected based largely on their ability to simulate historical seasonal precipitation and temperature *patterns*, annual precipitation *variability*, and the El Nino/Southern Oscillation (DWR 2010c). Alternatively, discrete projections might be selected based on a statistical analysis of the available suite of future projections. For example, in their 2010 study of Oklahoma climate change and hydrology, the US Bureau of Reclamation (BOR) selected four discrete GCM projections that "bracket" the changes possible from all considered projections and a fifth that represents the central tendency of those projections (BOR 2010). The four bracketing projections can be viewed as "bookends" of dry and warm, dry and hot, wet and warm, and wet and hot. These discrete scenarios were used in subsequent hydrologic analyses as part of their "Hybrid-Delta" approach (BOR 2010).

Some studies have even selected a single projection from the data set. This may be appropriate for some types of analysis but great caution should be exercised with selecting only a single projection, as it will not provide information about the range of possible impacts from climate change that are more or less extreme than the chosen projection. Selecting a single projection will provide limited information about the range of uncertainty associated with climate change impacts.

The Nature Conservancy's Climate Wizard (http://www.climatewizard.org/#) allows planners and technical experts to view the CMIP3 archive of downscaled GCM results geographically. This tool facilitates visual and quantitative comparisons among emissions scenarios and GCMs, and also facilitates comparison of ensemble projections. SimCLIM (http://www.climsystems.com/simclim/) also allows geographic visualization of GCM projections (downscaled or direct GCM results). SimCLIM interfaces with several impact models and also provides a platform for comparisons between GCM projections and observed data.

Ensemble Scenarios

Developing ensemble projections involves combining multiple climate model projections into a single scenario that reflects model-to-model variability and uncertainty. For example, for the Delta Conservation Plan (BDCP), DWR uses data from 112 individual projections to arrive at five projections that bracket the range of climate projections. For the BDCP study, each of the five projections was formed by aggregating an ensemble of discrete scenarios. The projections used for each ensemble set were identified through a statistical analysis focused on projected average annual

changes in precipitation and temperature using a procedure known as "quantile mapping" (DWR 2010c). For these analyses, percentile distributions were then fit to each ensemble dataset to quantify perturbation factors ("delta values") that were applied to historical data in subsequent hydrologic analyses.

Alternative approaches to generating ensembles also exist. Cox et al (2011) used a selection of six GCMs and two emissions scenarios, for a total of twelve GCM projections. For each model scenario, a "pool" was developed by combining model results within the planning horizon from all of the six GCMs. A projected set of precipitation and temperature conditions for the planning horizon was developed by randomly sampling projections. By using a sampling method of GCM results rather than applying a shift to the historic record, the assumption that the historic record's variability is representative of hydrologic variability in the future is avoided. However, this method also assumes that the full range of hydrologic variability is represented in the GCM results. DWR (2010c) provides an overview of several downscaled GCM projection processing approaches, additional references for obtaining further information on various approaches, and a summary of the strengths and weaknesses of each approach.

Using Downscaled GCM Outputs When Historical Observational Data is Available

In many areas good historical observational datasets of temperature and precipitation are available. In these cases, planners and modelers may wish to use the historical data to help inform projections of future conditions. Conversely, planners and modelers may also choose to ignore these data so as not want to constrain the climate model outputs. There are two primary methodologies that have been used in previous water resource studies to generate projections of future climate: perturbed historical data and direct use of GCM-generated output.

- Perturbed historical data uses observed historical data that is modified by applying a perturbation factor to the observed value (e.g., precipitation from January 1998 is modified to reflect climate change conditions). The perturbation factor is derived statistically from the downscaled GCM outputs. Perturbation factors can be probabilistic or deterministic. BOR (2010) provides additional information on the "Delta Method" for perturbing historical data. This method guarantees that historical climate variability is maintained in future projections.
- GCM-generated output can also be used directly. This means that the temperature and precipitation outputs from the downscaled GCM are taken as-is and used as inputs to drive other resource-specific impact models.

Both of these methods are considered acceptable ways of characterizing future climate conditions. Each of these methods has strengths and weaknesses. Perturbing historical data preserves the historical variability observed in the historical record. However, this may mask increased climatic variability driven by climate change. Conversely, GCM-generated outputs may project levels of variability in the climate system that have no precedent and may be unrealistic.

5.2.3 Qualitative Analysis Methods

Planners are encouraged to use methods that are as quantitative as possible. However, lack of resources, expertise, or appropriate data to complete a quantitative analysis of climate change impacts does not preclude a region from developing useful climate change analysis information. Several qualitative analysis methods exist that do not require as much time, money, technical expertise, or data.

Surveying local experts, shifting historic records based on qualitative studies and uncertainty buffers, threshold analysis, and sensitivity analysis are four of the most common qualitative approaches and are discussed in greater detail below.

5.2.3.1 Surveying Local Experts

In the absence of reliable data for conducting a quantitative analysis, a survey of local expert opinions on potential and likely climate change impacts can be useful in consolidating available information. As part of the EPA's Climate Ready Estuaries program, the Partnership for the Delaware Estuary conducted a drinking water survey to prioritize potential climate impacts to address (Kreeger et al 2010). The survey also identified data gaps and future research needs. Figure 5-4 depicts the general steps needed for surveying local experts.

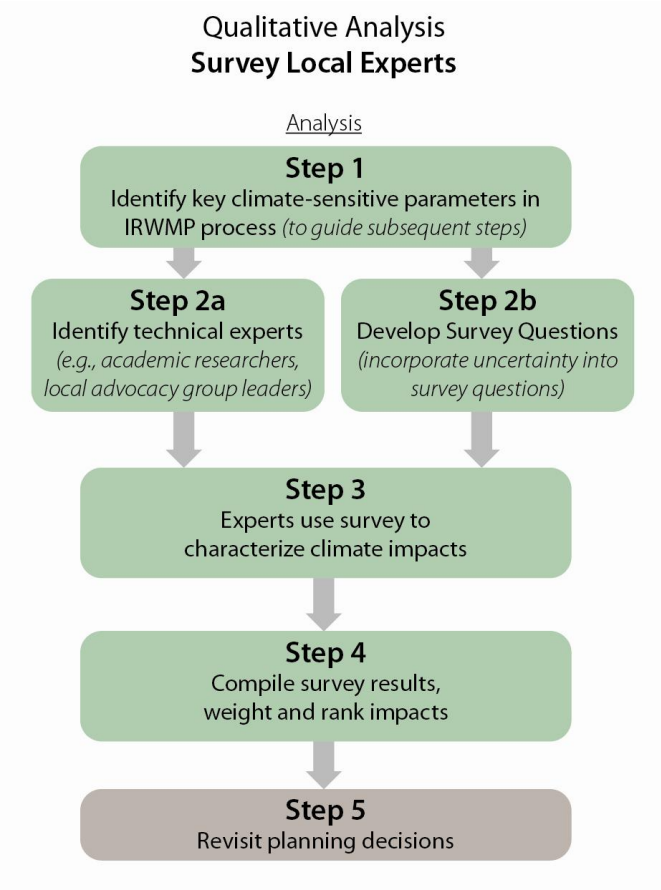


Figure 5-4: Surveying Process Flow-chart

Before conducting the survey, it is necessary to identify a comprehensive list of potential climate change vulnerabilities. Section 4 provides guidance in assembling this list. From the completed list of climate change vulnerabilities, a list of local technical experts can be generated to target the vulnerabilities. The local experts can be from a combination of government and municipal agencies, academia, local consultants, or other relevant entities.

A survey that allows experts to rate their responses, for example, on a scale of 1 to 5, facilitates consolidating survey results into meaningful statistics and scores. Questions included should target both expert opinions and the uncertainties inherent in their opinions. The natural performance metrics to use in this study are the ranked survey results.

5.2.3.2 Other Qualitative Methods

Other qualitative methods for considering climate change impacts exist. Simple conceptual models may help planners to postulate on potential climate change impacts, and simple, "back of the

envelope" model representations of resources may also be useful qualitative tools in assessing climate change impacts (Johnson and Weaver 2009).

For water and wastewater resource sectors, the EPA has developed the Climate Ready Water Utilities (CRWU) website with a number of resources, including the Climate Resilience Evaluation and Assessment Tool (CREAT), which allows users to evaluate potential impacts of climate change on their utility and to evaluate adaptive options to address these impacts using both traditional risk assessment and scenario-based decision making. (http://water.epa.gov/infrastructure/watersecurity/climate/.) This suite of tools and resources from the EPA can provide a region with the ability to conduct a qualitative (semi-quantitative) analysis, at least in terms of the water and wastewater sectors.

5.2.4 Combining Qualitative and Quantitative Methods

As shown in Figure 5.3, there is no sharp distinction between qualitative and quantitative methods; regions should select methods that make sense for the questions relevant to the region and the resources (e.g., data, finance) available. Some methods that may make use of sophisticated existing models (e.g., hydrologic/hydraulic models), but account for climate change in a less quantitative way, are described below.

5.2.4.1 Shifting historic record based on qualitative studies and uncertainty buffers

Some climate change studies have adjusted the historical record by quantities loosely based on GCM or other modeling studies, but without rigorously processing GCM or other data. In many cases, a "buffer" is added to the climate change projection, to estimate climate change impacts in a "worst case" scenario. This method, sometimes referred to as "relative change," may be most appropriate for analyses that require data that is unavailable, such as future flood return periods. For example, the 200-year floodplain has become the planning standard for the Central Valley of California. The size of the "buffer" used to represent climate change is based on analysis of the available data, system properties and response characteristics, and ultimately, expert judgment.

Some useful studies that have identified and measured climate change impacts, with results that can serve regions as a starting point for a local climate change analysis, are listed below:

- State Water Project Reliability reports,
- California Water Plan studies,
- Data from the Climate Action Team reports,
- Pacific Institute coastal flood plain maps that incorporate sea level rise, and
- California Ocean Protection Council sea level rise guidance.

There may be other local analyses that a thorough literature and knowledge search may uncover. Regions are encouraged to make use of previous studies where appropriate.

5.2.4.2 Threshold Analysis

For some regions, rigorously incorporating GCM-based climate change projections is not practical. In these cases a more "bottom-up" approach is to identify system vulnerability thresholds and potential climate conditions that could produce the limiting conditions. For example, after identifying the minimum streamflows that a region considers acceptable or desirable, planners can then identify the temperature increase at which a reduced snowpack would result in streamflows below this threshold. Identifying the likelihood of future climate characteristics that create conditions that exceed identified thresholds may be quite difficult. However, it should be possible to make qualitative judgments about the *change* in likelihood of future climate characteristics that might create conditions that exceed identified thresholds. In the above example relating to minimum streamflows, it should be possible to state that the probability of streamflow falling below the critical threshold is more likely as temperatures rise and snowpack feeding the river diminishes. The Central Valley Flood Management Planning Program is using a threshold analysis to incorporate climate change into the planning process, and the program's Draft Climate Change Threshold Analysis Work Plan (DWR 2010d) could potentially serve as a rough template for regions.

5.2.4.3 Sensitivity Analysis

Sensitivity analysis provides insight into the potential magnitude of impacts. It involves perturbing a single input variable to quantify a model's response to that variable. This method requires a quantitative analysis model or other tool for analyzing the impact of climate change. The perturbation of the variable can be done arbitrarily, just to give an idea of what the impacts might be of various variable values (e.g., analyzing the impact of 2, 4, and 6 degrees of temperature increase). The perturbation can also be done more systematically, using other studies or analyses that suggest the magnitude of change in the variable that climate change would be expected to cause. The Cosumnes, American, Bear, and Yuba Watersheds (CABY) IRWMP (Ecosystem Sciences Foundation 2006) discusses a sensitivity analysis where historical temperature was increased by 2 degrees Celsius to account for climate change in a watershed model. No other variables were altered from the historical record.

5.2.5 Uncertainty

This section describes the sources of climate change-related uncertainty and ways to include it with other uncertainties in planning. Additionally, Appendix C presents information on how to quantify uncertainty in climate change analysis.

There are several methods for incorporating uncertainty into the IRWM planning process, including:

- **Probabilistic Method**: This method involves identifying which variables are most uncertain, and defining these variables in terms of probability functions. The performance of a climate change adaptation strategy, or group of strategies, is measured in terms of joint probability functions based on the selected model projections. The result of this analysis is an overall assessment of risk. This method can be applied at different stages of the plan development. It can be applied at the earliest stages to define temperature, precipitation, and sea level rise data (described in Sections 2

and 5); and can also be applied to assess climate change impacts (described in Sections 5 and 6). The method is described in Section 7, "Implementing Under Uncertainty," given that the probabilistic results of the technical analysis are useful for planners and decision makers during plan implementation.

- **Scenario Planning**: This method is widely used and simple to understand. First, several plausible scenarios of potential future conditions are defined. Then, projects within the IRWMP are evaluated under these different scenarios to determine the most robust strategies.

- **Scenario Planning with Probabilistic Variables:** In some cases, variables with probability distributions are evaluated using scenarios. The result is a probable outcome under specific scenarios. The State Water Project (SWP) provides water delivery projections in this way.

- **Qualitative Uncertainty Assessment:** Some qualitative methods do not provide or use enough data or calculations to evaluate uncertainty, in terms of probabilities or specific scenarios. In these cases, it is important to quantify uncertainty to the extent possible and maintain uncertainty information throughout the planning process.

These methods are discussed in detail in Appendix C, and must be incorporated into any analysis involving climate change.

5.3 Conduct Analysis

Analytical methods vary greatly across the range of sector-specific impact analyses. Therefore, this subsection provides several examples of sector-specific impact analyses. It discusses the level of sophistication involved in each method, and the uses and limitations of each method. In addition, several case studies of analyses are included here. Resource sectors included in this section:

- Water Demands,
- Water Supplies,
- Water Quality,
- Ecosystem and Habitat Vulnerability,
- Sea Level Rise,
- Flooding, and
- Hydropower.

5.3.1 Water Demands

Climate change is expected to influence outdoor urban and agricultural water demands. Many agencies, such as Metropolitan Water District of Southern California (MWD 2010), Irvine Ranch Water District (IRWD, Rodrigo and Heiertz 2009), the San Diego Water Department (CDM 2008), and Central Puget Sound Water Supply Forum (WSF 2009), have developed a regression based on historical records to develop a relationship between climate variations and water usage. This relationship is then projected onto projected future climate conditions to develop future water demands under climate change.

5.3.1.1 Urban Demand

Though there are several options for calculating climate change impacts on urban water demands, many urban demand climate change analyses use regression methods (see discussion of regression methods in Section 5.3.1). The general approach of regression analysis involves developing a regression relationship between water demand versus temperature and precipitation. Planners can then use this relationship to evaluate future conditions.

Case studies for water demand impacts using regression analyses are included at the end of this section. They include the Central Puget Sound Water Supply Outlook (WSO) case study (Box 5-1). The WSO case study reference material provides details on the regression equation used. The MWD case study (Box 7-1) presented in Section 7 also discusses a demand regression analysis, with details provided in the reference materials for the case study.

Data Needed

To develop a regression relationship, it is necessary to obtain both historical data and a projection of future conditions. Historical data needs to span a length of time that can provide a statistically significant relationship among the variables analyzed, and must include all variables that have a significant influence on water demand. While identifying these variables includes step 1 in Figure 5-5, it also includes identifying non-climate change-related variables.

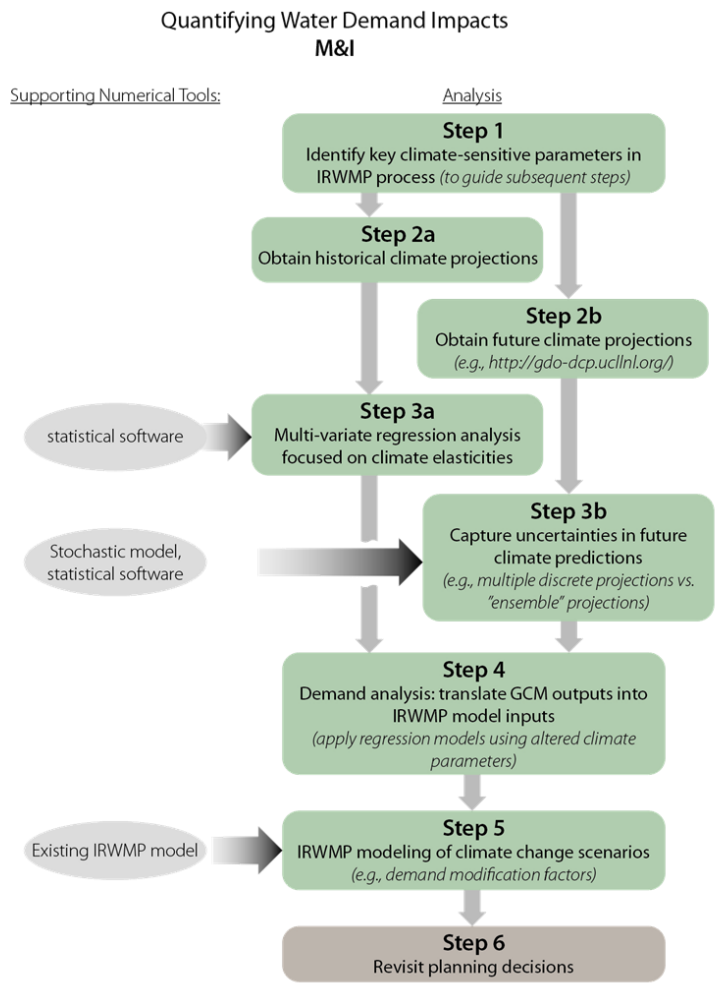


Figure 5-5: Urban Water Demands Process Flow-chart

Historical data may include:

- Water deliveries,
- Temperature,
- Precipitation, and
- Population (or a proxy of population, such as number of connections).

To make use of the regression relationship to project future conditions, the relationship needs to be applied to projected future conditions. Future projections need to include the same variables as those included in the regression relationship, and may include population projections, economic projections, and of course, climate variables (see step 2 in Figure 5-5).

Conducting the Analysis

Estimating future water demands using this method requires first fitting historical water use to a regression curve that relates historical water demand to the variables for which data has been obtained (see step 3a in Figure 5-5). Future water production projections can then be calculated using the regression relationship with future climate and population data incorporated into the calculation (see steps 4 and 5 in Figure 5-5).

Incorporating Uncertainty

Primary sources of uncertainty specific to water demand analyses include:

- The inclusion of predictor variables (i.e., demand drivers) in the regression analysis. This process generally entails selecting factors *a priori* that planners deem to be the strongest drivers of demand and might include population, conservation practices, employment data, and climate variables. While multiple variables are included in the analysis, others are excluded and uncertainty therefore exists over whether all significant drivers of demand have been captured.
- Accuracy of the regression relationship established from the historical record, which is typically quantified in the form of a statistical distribution. A perfect regression fit is never achieved, as parameterized by the correlation coefficient (R^2) or similar, and therefore the model projections are uncertain.
- Future projections of the independent variables used in the regression model. How variables like population and economics will change in the future is highly uncertain. When climate change is included in the analysis, climate variables such as temperature and precipitation (see step 3b in Figure 5-5), also need to be projected with highly uncertain projections.

Two options for quantifying uncertainty in urban water demand analyses are probabilistic modeling and scenario planning. Both options are described in detail in Appendix C. Demand regression models are well-suited for use with probabilistic modeling software since the models are easily written into a spreadsheet or similar tool. Climate variables could be represented as probability functions, or simply a range of equally likely values (i.e., uniform discrete distribution), and stochastic sampling

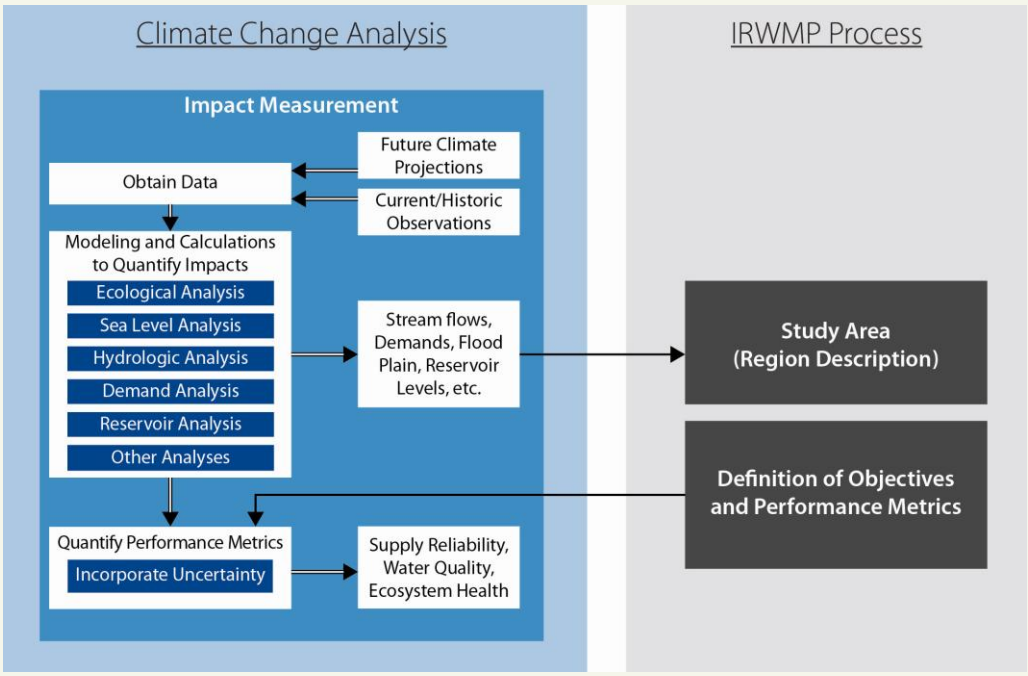
could be used to generate a range of potential outcomes. Expert judgment or climate modeling could be used to guide the distribution fitting. A simpler approach, more in line with scenario planning, is to calculate the regression result for a fixed number of discrete climate inputs representing a range of climate change projections. Results could then be presented as a discrete number of scenarios, differing according to their underlying projection assumptions.

Potential Performance Metrics

Potential performance metrics for urban water demand may include deviation from a threshold of demand that could be met with existing or projected water supplies, or may relate to a targeted water conservation goal. Performance metric evaluation takes places in steps 5 and 6 in Figure 5-5.

Case Study: Measure Impacts

Central Puget Sound Water Supply Outlook – Water Demand Analysis
Snohomish, King and Pierce Counties, WA



Background:

The Central Puget Sound Water Supply Forum developed a Regional Water Supply Outlook that projects water demands and supplies within the region, streamflow issues and potential regional projects. Regional water demand projections through the year 2060 were developed in this process, taking climate change effects into account.

Central Puget Sound (CPS) Vulnerabilities:

- Water supply: snowpack, precipitation runoff
- Water quality
- Water demand

Figure 1: WSF service area. Source: http://www.watersupplyforum.org/home/resource/planning-area-map/.

Box 5-1

Study region includes 3 counties:

- Snohomish
- King
- Pierce

Study region contains several major water providers, including:

- Seattle Public Utilities (SPU)
- City of Tacoma
- City of Everett
- Lakehaven Utility District
- City of Renton
- City of Kent Public Works Department
- Lakewood Water District
- Auburn Water Utility

Step 1: Obtain Locally Applicable Data

Data Obtained:

- GCM Downscaled Data
- Reported Consumption- Water Provider Survey
- Demographic Data and Projections
- Historical Meteorological Observation Data

1. GCM Data

- Select GC/emissions scenario couples (6 emissions scenarios, over 20 models)
- GISS_B1: "warm"
- ECHAM5_A2: "warmer", and
- IPSL_A2: "warmest"
- Reasons for choosing these scenarios:
- GCMs: good replication of Temperature and Precipitation for Pacific Northwest (Mote, 2005)
- Emissions scenarios: range of high (A2) and low (B1) emissions levels included

2. Historical Data

- Included: water use records, demographics, weather
- Data Processing
- Developed *base water use factors* – for SPU, included data from 100+ providers
- Developed *climate change-free* future water use projections based on 1) population trends and base water use factors, and 2) historical weather
- Historical Monthly Water Use Data QA/QC – identify trends from:
- Economic recessions/booms - long-term trends in annual water use minimum levels were determined
- Mandatory water use curtailments (the effects curtailments have on water use are demonstrated by portion of water production that is circled in red in Figure 2)

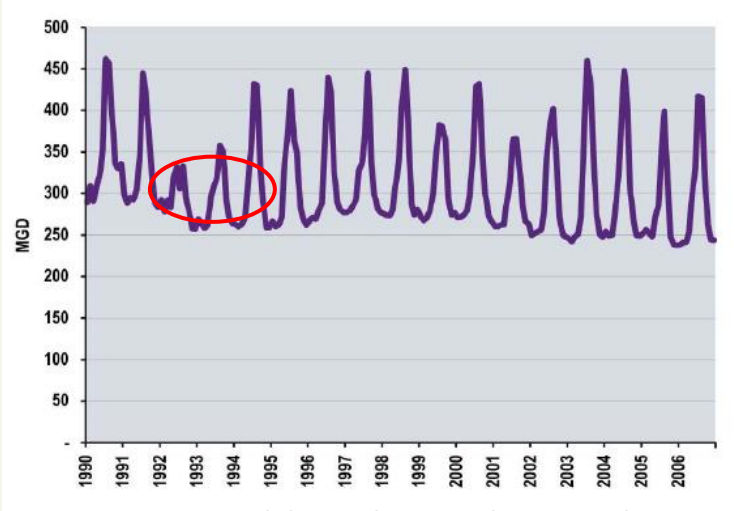


Figure 2: System-wide historical water production record. Source: WSPF, 2009.

Box 5-1 (Continued)

Step 2: Assessment and Analysis

Future Demand Analysis

1. Identify Seasonal Demands

Water demands for the study area were separated into two categories:

- Non-seasonal demands that are relatively constant over the year, and
- Seasonal demands that fluctuate over the course of the year.

Seasonal water demands are more likely to be impacted by climate change, because they already exhibit sensitivity to annual seasonal weather

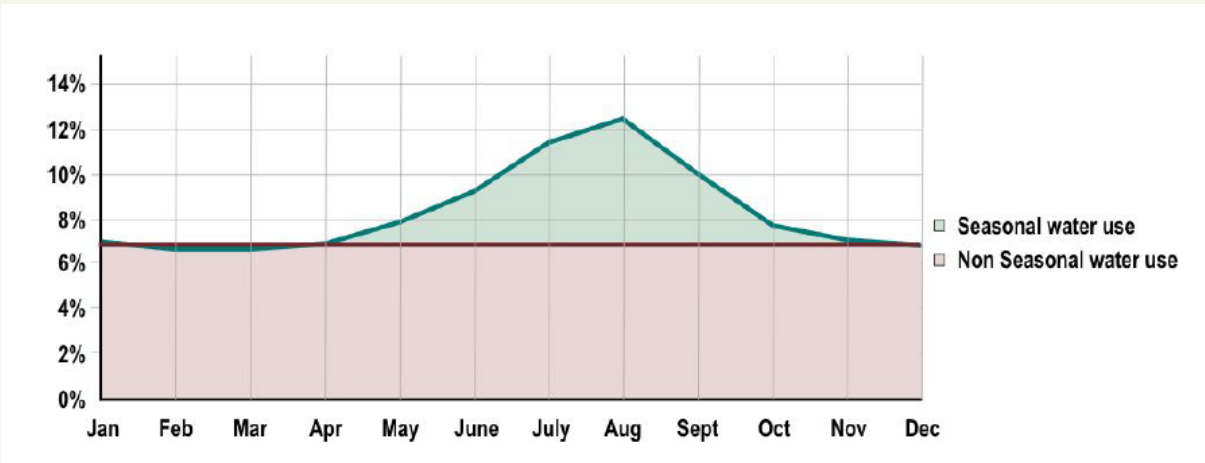


Figure 3: System-wide historical water production record. (Source: WSF, 2009.)

2. Estimate Historical Dependence on Weather: Regression Analysis (Statistical Model)

Model Inputs (all Historical Data):

- Monthly *seasonal* water production (system-wide)
- Monthly average maximum daily temperature
- Monthly total precipitation
- Annual regional employment (for long-term trends)

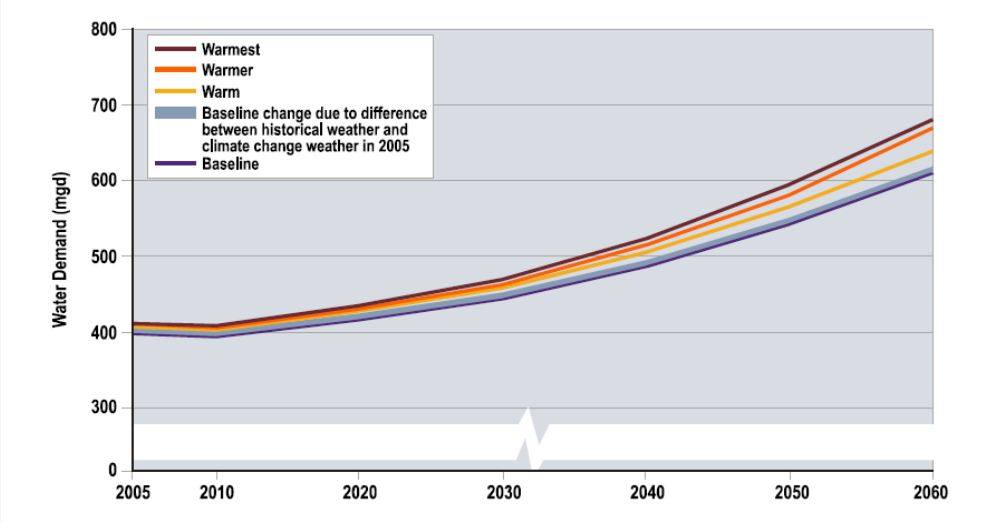


Figure 4: Water use projections using climate variables from various emissions scenarios. (Source: WSF, 2009.)

Box 5-1 (Continued)

Model Output:

- Relationship between weather variables and water use, calibrated to historical data

3. Calculate *Future* Demand: adjust future water demand projections

Inputs:

- Regression relationship from (2)
- Baseline future projection of system-wide monthly water production (from Step 1)
- Monthly average of maximum daily temperature (from GCM downscaled data)
- Monthly total precipitation (from GCM downscaled data)

Output:

- Adjusted seasonal monthly demands system-wide for future scenarios
- Seasonal monthly demands adjusted for climate change can be added to non-seasonal demands to estimate **total future demand with climate change**

Step 3: Performance Metrics

Metric Used: Current Water Demand

1. Demands projected to increase *due to climate change* by 5-12% between 2005 and 2060

2. Other *non-climate*-related changes could be due to:

- Variability in population projections
- Changes in economic demographics
- Changes in water conservation practices
- Mandatory Curtailments

Influence on Regional Water Management: Potential Management Strategies Being Considered to Increase Redundancy:

- Seasonal Reservoir Operation/Operational Protocol Changes
- Additional Supply Projects

For More Information

Climate Change Technical Committee. 2007. Final Report of the Climate Change Technical Committee. http://www.govlink.org/regional-water-planning/tech-committees/climate-change/index.htm

Mote, Philip, Eric Salathé, and Cynthia Peacock. 2005. Scenarios of Future Climate for the Pacific Northwest. Climate Impacts Group, University of Washington. http://cses.washington.edu/db/pdf/kc05scenarios462.pdf

Seattle Public Utilities. 2007. Seattle Public Utilities Water System Plan. http://www.cityofseattle.net/util/About_SPU/Water_System/Plans/2007WaterSystemPlan/SPU01_002126.asp

University of Washington Climate Impacts Group. (n.d.). http://cses.washington.edu/cig/

Water Supply Forum. 2009. Water Supply Forum 2009 Water Supply Outlook. http://www.watersupplyforum.org/outlook

Box 5-1 (Continued)

5.3.1.2 Agricultural Demand

Crop irrigation needs are a function of precipitation, crop type, crop-specific evapotranspiration (ETc), and the growing season length. As the earth's climate changes, all of these factors are changing. However, simultaneously, other changes are taking place. Trends in total irrigated acres of farmland are decreasing, or are projected to decrease in the future in many places in California. Cropping patterns are also likely to shift as the climate changes. At the same time, agricultural water use efficiency is increasing. Two studies have been done at the state-level involving agricultural water demand estimates:

1. California Water Plan Update 2009
2. SWP/CVP Impacts Report 2009

In both the California Water Plan (CWP) 2009 Update (DWR 2009) and the SWP/CVP Impacts Report (Chung et al 2009), a hydrologic model is used to calculate water demand per acre of irrigated land, for each crop type of interest. Once calibrated to historical data, the model can be used to calculate water demand under future hydrologic conditions for a particular crop type. Crop demand per acre of irrigated land is not modified to account for climate change impacts on evapotranspiration (ET) in these studies.

Beyond calculating irrigation demand as it correlates to irrigated area and accounting for climate projections of precipitation, there are several methods for calculating changes in ET from climate variables. DWR has developed the Simulation of Evapotranspiration of Applied Water (SIMETAW) tool and the Consumptive Use Program (CUP+) to help estimate crop and applied water evapotranspiration. CUP+ is an Excel-based application, and SIMETAW is an executable model. Both models use the Penman-Monteith method (described in detail at http://www.fao.org/docrep/X0490E/X0490E00.htm) for calculating reference ET (ETo), from which crop-specific ETc can be calculated. Other potential approaches include directly using the Blaney-Criddle or Penman Monteith equations to estimate ETo as a function of climate variables. It may also be possible to develop a regression relationship based on historical ETo data relating location-specific historical ETo with location-specific historical temperature. Determining which method to use is a component of step 1 in Figure 5-6, which depicts steps for conducting an agricultural water demand analysis.

Evapotranspiration equation

The Blaney-Criddle equation is a very simplified method for calculating ETo based on temperature and season. The Food and Agriculture Organization of the United Nations (FAO) has a manual available for using the Blaney-Criddle equation (http://www.fao.org/docrep/S2022E/S2022E00.htm). Coefficients for several crops are provided in the FAO Blaney-Criddle Manual "Irrigation Water Management: Irrigation Water Needs".

Data Needed

The data required for using the Blaney-Criddle equation to estimate water needs under climate change conditions (steps 2a and 2b in Figure 5-6) include:

- Irrigated area estimate,
- Crop types and their ET coefficients (for converting ETo to Etc), Precipitation projections, and
- Temperature projections.

Conducting the Analysis

Estimating crop water needs involves:

1. Calculating ETc for each crop (step 4 in Figure 5-6),
2. Including precipitation in the estimate of water needs (step 4 in Figure 5-6), and
3. Extrapolating water needs to the irrigated areas (step 5 in Figure 5-6).

Incorporating Uncertainty

Primary sources of uncertainty specific to agricultural water demand analyses include:

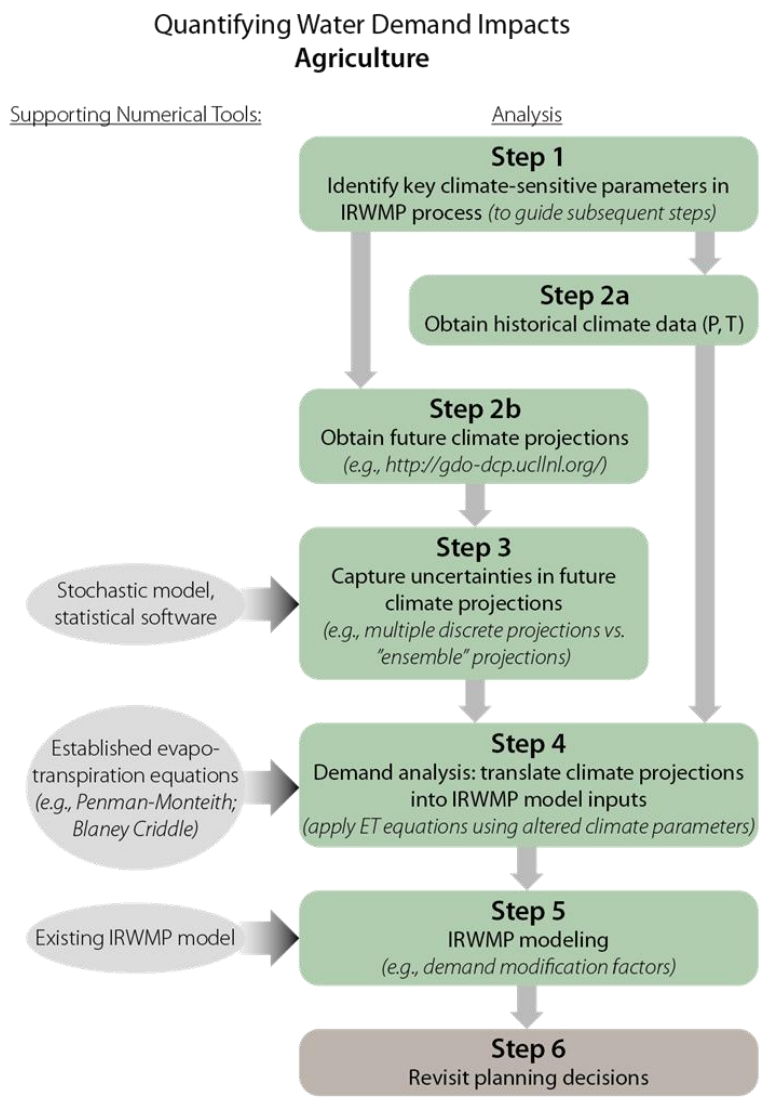


Figure 5-6: Agricultural Demand Climate Change Analysis Process Flow Chart.

- Simplifications and assumptions inherent in the method of calculating both ET (e.g., Blaney-Criddle) and water demand; and
- Future projections of the independent variables used in the ET model, including crop varieties, irrigated land estimates, and climate variables (step 3 in Figure 5-6).

Two options for quantifying uncertainty in agricultural demand analyses are probabilistic modeling and scenario planning. Both options are described in detail in Appendix C. Simple empirical models, like the Blaney-Criddle equation, are well suited for use with probabilistic modeling software since the models are easily written into a spreadsheet or similar tool. Climate variables could be represented as probability functions, or simply as a range of equally likely values (i.e., uniform discrete distribution), and stochastic sampling could be used to generate a range of potential outcomes. Expert judgment or climate modeling could

be used to guide the distribution fitting. A simpler approach, more in line with scenario planning, might be to calculate the regression result for a fixed number of discrete climate inputs representing a range of climate change projections. Results could then be presented as a discrete number of scenarios, differing according to their underlying projection assumptions.

Potential Performance Metrics

Potential performance metrics for the evapotranspiration equations may include deviation from a threshold of demand that could be met with existing or projected water supplies, or may relate to a targeted water conservation goal. Performance metric evaluation takes places in steps 5 and 6 in Figure 5-6.

Models such as SIMETAW and CUP+

Both SIMETAW and CUP+ can be used to impose different climate scenarios on crop ETc rates. The CUP and SIMETAW models are both available at http://www.water.ca.gov/landwateruse/models.cfm. SIMETAW is also discussed in DWR (2006), and also in Volume 4 of the CWP Update 2009 (DWR 2009).

DWR is also developing a new model: Cal-SIMETAW. The main difference between the SIMETAW and Cal-SIMETAW application programs is that SIMETAW is used to determine the daily water balance of individual fields of crops within a region, whereas Cal-SIMETAW is designed to use batch files of input data to compute daily water balance for up to 24 crop categories over the period of record. Cal-SIMETAW is scheduled for release in late 2011.

Data Needed

Obtaining data is included in step 2 in Figure 5-6. SIMETAW and CUP+ both require more data than the Blaney-Criddle method, and both are more accurate where sufficient data is available. Required data includes:

- Monthly total precipitation,
- Daily mean wind speed by month,
- Daily mean solar radiation by month,
- Maximum and minimum daily mean temperatures by month,
- Daily mean dew point temperature by month,
- Rainy days per month,
- Canopy resistance,
- Crop and soil information, and
- Water contributions from seepage of ground water data.

It may be difficult to obtain observed and/or projected estimates for this data. The data sources listed in Appendix D-1 are useful resources. For other parameters, best professional judgment and/or sensitivity analysis may be needed to determine appropriate values and uncertainty brackets.

Conducting the analysis

Both SIMETAW and CUP+ involve assembling data, entering the data into a program, and collecting results (step 4 in Figure 5-6). CUP+ provides water requirements for crops by month, season, or year (Orang et al 2008). CUP+ is Excel-based and includes plotting and multi-scenario comparison capabilities. Water needs can be extracted to irrigated areas in a region (step 5 in Figure 5-6).

Incorporating Uncertainty

Using SIMETAW or CUP+ to estimate agricultural water demand involves estimating future changes in ET, and incorporating this into a water demand calculation for irrigated areas. Uncertainties associated with this method result from the following factors:

- Simplifications and assumptions inherent in the method of calculating both ET and water demand, and
- Projections of future conditions, including crop varieties, irrigated land estimates, and climate variables (step 3 in Figure 5-6).

Because CUP+ incorporates scenario comparison into its framework, this tool facilitates a scenario approach to accounting for uncertainties (see Appendix C).

Potential Performance Metrics

Potential performance metrics for agricultural water demand using CIMETAW or CUP+ may include deviation from a threshold of demand that could be met with existing or projected water supplies, or may relate to a targeted water conservation goal. Performance metric evaluation takes places in steps 5 and 6 in Figure 5-6.

5.3.2 Water Supplies

This section discusses projecting climate change impacts on:

1. Water supply sources within the region for municipal and industrial (M&I) or agricultural use,
2. Water imported into the region, and
3. Streamflow supplies for environmental needs.

For locally-sourced water and instream flows, regions are encouraged to build off of existing tools that are already being applied to study the region's water resources, where possible. Regions that import water are encouraged to rely on studies that have been conducted by the water purveyor, such as the SWP Delivery Reliability Report (DWR 2010b).

5.3.2.1 Rainfall Runoff Modeling

Watershed yields impact all water uses, including environmental instream flow needs, agricultural uses, and M&I demands. Increased temperatures and shifts in precipitation patterns could alter watershed-based water supplies in the future: snowpack is decreasing in the Sierras, seasonal snowmelt timing is shifting, and precipitation changes could also alter a watershed's rainfall capture. For surface water supplies and instream flows that are vulnerable to reduced snow pack and/or changes in precipitation patterns, regions may consider rainfall runoff and/or water system modeling. Rainfall runoff modeling uses watershed characteristics and environmental data to estimate streamflows.

The CABY 2006 IRWMP discusses rainfall runoff modeling that takes climate change into account (Ecosystem Sciences Foundation 2006). The CABY analysis uses the Water Evaluation and Planning (WEAP) model, as does the state-level water supply analysis conducted as part of the CWP 2009 Update (DWR 2009). The Puget Sound case study (Box 5-2) included a watershed modeling analysis using the Distributed Hydrology Soil Vegetation Model (DHSVM). Several hydrologic modeling studies are also discussed in BOR (2011b).

Future streamflows can also be projected using regression relationships developed between historical precipitation and streamflow data (Cox et al 2009, Stewart et al 2003, Nawaz and Adeloye 1999). The regression relationship can be used to relate GCM downscaled precipitation data to a projected corresponding streamflow. The regression method can be combined with a mechanistic model, like WEAP, for streamflow projections in a snowpack-driven watershed (Cox et al 2011). The steps for conducting a water-supply analysis are depicted in Figure 5-7.

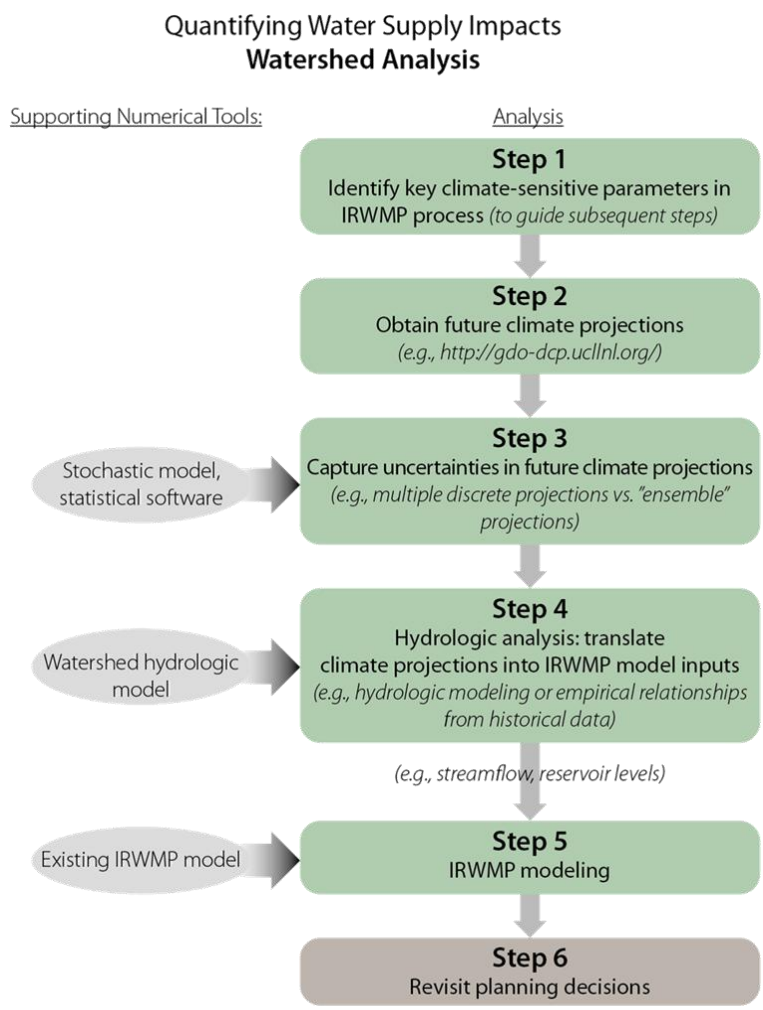


Figure 5-7: Watershed-based water supply climate change analysis process flow chart.

Data Needed

Data describing the watershed, such as topography and soil characteristics, must be included in the hydrologic model. Data describing the existing watershed may include:

- Soil characteristics,
- Vegetation type,
- Topography,
- Land area, and
- Land use / land cover.

Watershed models also include parameters and approximations that need to be calibrated against historical data before future projections can be made. Historical data required may include:

- Temperature,
- Wind records,
- Precipitation, and
- Historical streamflows.

Data representing future conditions can be specific or general, as discussed in Section 5.3. WSF obtained downscaled data from a global climate model (see case study, Box 5-2). As a sensitivity analysis, the CABY IRWMP used a 2 degree Celsius change in temperature only to estimate potential climate change impacts. This temperature change was determined consistent with the warming trends projected by most climate models (Ecosystem Sciences Foundation 2006). Obtaining and processing future climate projections corresponds to steps 2-4 in Figure 5-7.

The projected future variables may include:

- Temperature,
- Precipitation, and
- Land use.

Conducting the Analysis

The process of developing and applying a runoff model to future conditions corresponds to step 5 in Figure 5-7. As with many resource analyses discussed in Section 5, there are several possible methods for incorporating climate change into watershed models. If sufficient hydrologic variability is represented by the model simulation, this technique can provide enough data to develop a probability distribution that reflects natural variability. If using the Delta Method (see Section 5.2.2.2), the variability reflected is the variability captured in the historical record. If unperturbed GCM results are used, variability in runoff model results reflects GCM variability. The Delta Method does not reflect changes in frequency or severity of rare or extreme conditions due to climate change.

Many rainfall runoff models provide streamflow estimates, but not water supply estimates. Because water supply availability is a more useful metric than streamflow, it is therefore useful to couple watershed modeling with some type of water system modeling or water supply analysis tools (e.g., models that include aquifers, reservoirs) where watershed or rainfall runoff models do not provide water system modeling capabilities. The Puget Sound case study (Box 5-2) included water system modeling that translated streamflows into reservoir levels, taking dam operation rules into account. The WEAP model used by CABY and the CWP Update 2009 also include these capabilities.

Incorporating Uncertainty

Uncertainties associated with runoff models result from the following factors:

- Our limited understanding of how the physical system responds to climate and other variables (i.e., gaps in the science of the hydroclimate system).
- Numerical accuracy of the rainfall runoff model. This uncertainty is associated with limitations of the underlying mathematical equations and the way the model solves these equations. There is also uncertainty associated with the assumption that the historical calibration dataset is comprehensive enough to provide a representative calibration for use in projecting the future.
- Hydrologic and climate variability. Fluctuations in climate and hydrology at annual or sub-annual time scales are not predictable and often viewed as effectively "random" for planning purposes.
- Projections of future conditions, including future land use, irrigated land estimates, and climate variables (step 3 in Figure 5-7).

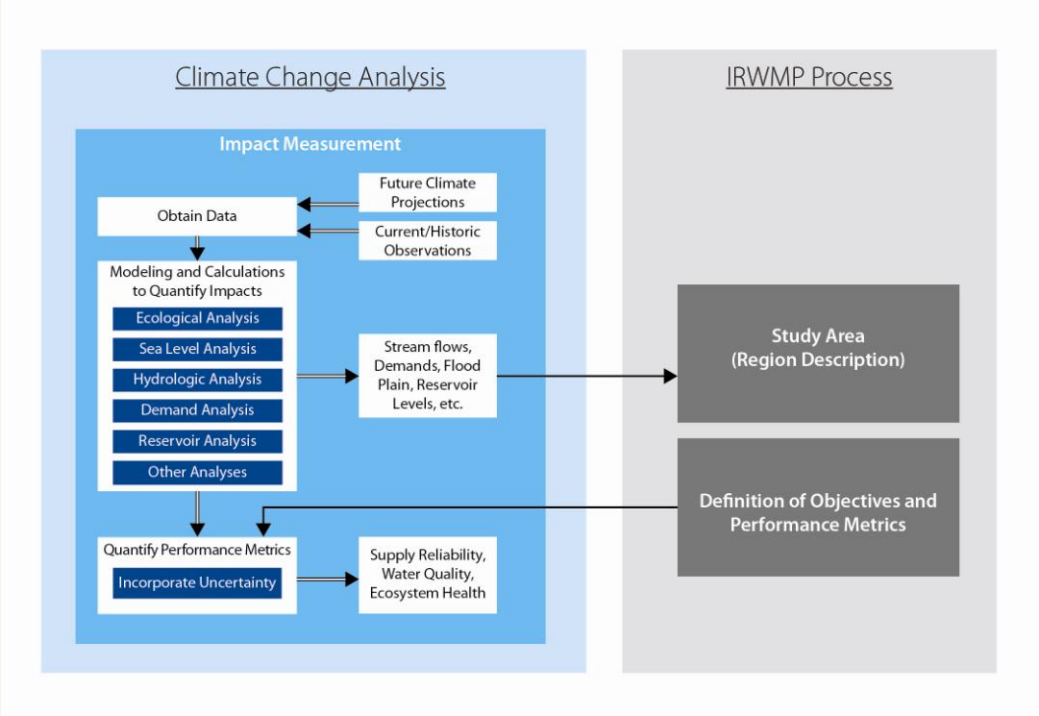
Two options for quantifying uncertainty in water supply analyses are probabilistic modeling and scenario planning. Both are described in detail in Appendix C. For example, hydrologic models could be used to simulate future conditions given a fixed number of discrete climate scenarios, representing dry, wet, and median conditions. These scenarios could be developed with guidance from climate model projections and/or available historical records. A sensitivity analyses to quantify the uncertainty associated with model calibration might also be appropriate to establish error bars for model projections.

Potential Performance Metrics

Performance metrics for water supply may include the probability of a water supply shortfall or unmet demand, or the maximum possible shortfall magnitude. Other potential metrics could include a minimum tolerable reservoir level or a maximum acceptable reliance on imported water. Metrics for water supply should include all water uses including environmental uses or instream flow needs. Evaluating performance metrics takes place in step 6 in Figure 5-7.

Case Study: Measure Impacts

Puget Sound Region – Water Supply Analysis



Background:

- The Water Supply Forum (WSF) was created in 1998 from both public water systems and local governments to address water supply issues. Members represent the King, Pierce and Snohomish Counties. The 2001 Central Puget Sound Regional Water Supply Outlook report developed by the WSF addressed regional water supplies and demands and included information on conservation and potential future supplies. The 2009 Outlook report is an update to the 2001 report which included climate change in the supply assessment and demand projection.

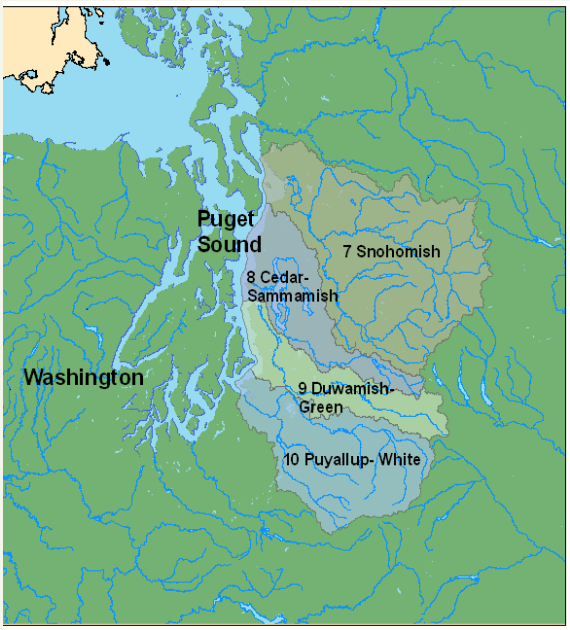


Figure 2: Basin 7: Snohomish, Basin 8: Cedar-Sammamish, Basin 9: Duwamish-Green, Basin 10: Puyallup-White. Source: http://www.climate.tag.washington.edu/regionalmap.html

Box 5-2

- The Climate Change Technical Committee (CCTC) was formed as part of a regional planning effort in 2005. Results from the CCTC analysis of climate change impacts on streamflows in the Central Puget Sound region were used to develop the WSF 2009 Outlook report and have also been used in local planning for Seattle Public Utilities, the City of Everett, and Tacoma Public Utilities.

- Central Puget Sound regional vulnerabilities to climate change:
  - Water supply (focus of this case study) snowpack, precipitation runoff
  - Water quality
  - Water demand

- Streamflow/Surface Water Supply: Four river basins provide roughly 66% of regional water supply (WSF, 2009)
  - Snohomish
  - Cedar-Sammamish
  - Duwamish-Green
  - Puyallup-White (fed by glaciers)

Step 1: Obtain Locally Applicable Data

Data Obtained:

- GCM Downscaled Data
- Historical Observation Data

1. **Select GCM/emissions scenario couples**
   - GISS_B1: "warm"
   - ECHAM5_A2: "warmer"
   - IPSL_A2: "warmest"
2. **Reasons for choosing these scenarios**
   - Good replication of Temperature and Precipitation for the Pacific Northwest (Mote, 2005)
   - Emissions Scenarios:
   - Two chosen out of six
   - Represents high (A2) and low (B1) emissions levels
   - GCMs:
   - Three chosen (out of "more than 20")
   - All three represent PNW temperature and precipitation well historically
3. **Obtain local historical/current data**
   - Maximum and minimum daily temperature
   - Local wind records
   - Total daily precipitation
   - Observation station elevation & geographic position
   - Soil characteristics (porosity, etc.)
   - Vegetation type

Step 2: Assessment and Analysis

Analyses Conducted:

- Watershed Modeling
- Water System Modeling

1. **Model Description - The Distributed Hydrology Soil Vegetation Model (DHSVM)**

Inputs:

- Air temperature
- Wind speed

Box 5-2 (Continued)

- Relative humidity
- Incoming shortwave radiation
- Outgoing longwave radiation
- Precipitation
- Temperature lapse rate

Other data needed:

- Soil porosity, type, thickness
- Vegetation cover
- Topography

Special Model Features:

- Glacier component
- Snowpack component

2. Calibration

Historical flows measured at USGS streamgages were reproduced with the model. Historical weather data was used as model input. Statistical properties of both measured and modeled streamflows were compared to verify model calibration. Values compared include:

- Daily flows –averaged from 1945-2004 (Figure 3)
- Monthly flows –averaged over various time periods
- Cumulative flows–totaled over several years
- Hydrograph comparisons–over several years – monthly, daily
- Annual Mass Accumulation Error
- Reservoir Storage level

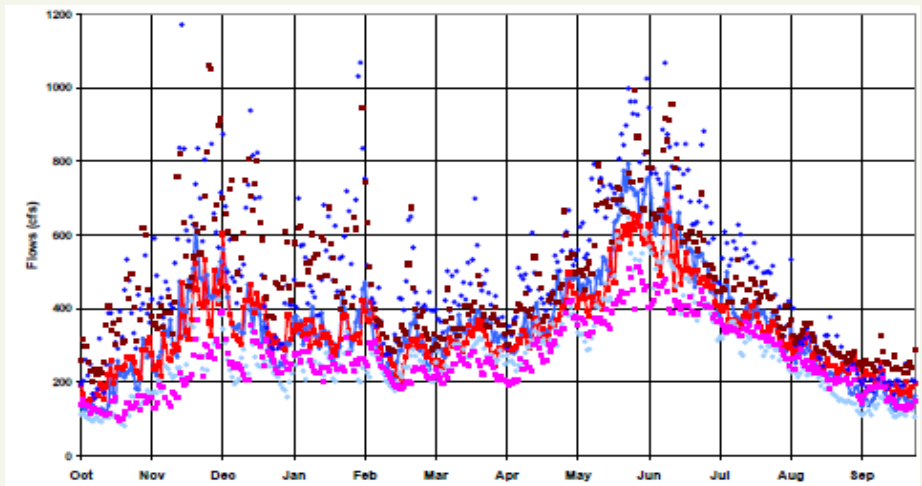


Figure 2: Annual streamflow calibration results at USGS Streamgage 12094000. (Source: CCTC 2007a)

3. Model Analysis and Results

Model Runs Based on:

- Historical Data
  - Year 2000
- GCM Downscaled Data
  - Years 2000-2075

Results Analysis:

- Bias check: Compared GCM-based watershed results for the year 2000 with

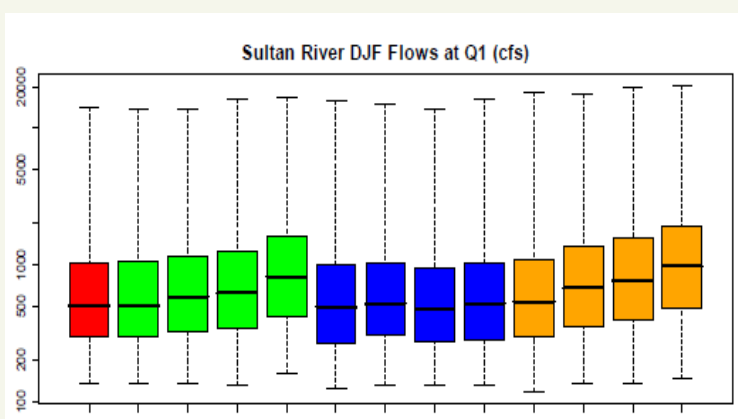


Figure 3: Model-predicted future flows compared among emissions scenarios and against the historical record (red). (Source: CCTC 2007a)

Box 5-2 (Continued)

historical data-based model runs to identify baseline biases that are a carry-over from the GCM data itself. The main variable used for this step was streamflow at various locations.

- Compared modeled average monthly flows with 2000 historic record for
  - each scenario
  - multiple years
- Box Plots of seasonal averages – There are significant levels of uncertainty in future climate data and significant variability in natural climate characteristics. Comparing statistical properties of the model results is therefore more informative than examining absolute numbers. Some of the box plots used for this analysis are shown in Figure 4.
- General Results
  - All basins, all three scenarios – earlier peak in spring, lower early summer flows (lower by 37% with all scenarios averaged) – higher winter flows by 48% on average
  - Least pronounced change: B1 scenario (driest scenario, but smallest temp increase)
  - Most pronounced change: basins with more snow

Step 3: Performance Metrics

Metric Used:

- System Yield

1. From Modeled Streamflows to Reservoir Levels

- Streamflows were input into water system models (for City of Everett, SPU, and Tacoma Water)
- Analysis used fixed reservoir operation rules

Water District	Projected Yield Impact in 2075
Everett	6-13% Decline
Seattle	13-25% Decline
Tacoma	4-8% Decline

Source: WSF, 2009

2. Planning-Level Performance Metric: *Yield vs Demand*

- Model results used for years 2020, 2040
- Ensemble average flows used for planning (average of all 3 scenarios)

Year	Flow Reduction	Projected Yield	Impact
2020	12 mgd	159 mgd	None, even accounting for uncertainties associated with demand calculations
2040	24 mgd	147 mgd	20% chance of demands exceeding supplies

Source: SPU, 2007

Box 5-2 (Continued)

Influence on Regional Water Management: Potential Management Strategies Being Considered to Increase Supply/Redundancy

SPU

- Seasonal reservoir operation/Operational protocol changes
- Conservation
- Infrastructure improvements
- Additional supply projects

City of Everett

- Seasonal reservoir operation/Operational protocol changes
- Snohomish River water
- Groundwater sources
- Enhanced conservation
- Reclaimed water
- Intertie with SPU

Tacoma Public Utilities

- Reservoir operational management changes
- Regional interties
- Aquifer recharge projects
- Additional storage projects

For More Information

City of Everett. 2007. City of Everett Comprehensive Water Plan. http://www.ci.everett.wa.us/Get_PDF.aspx?pdfID=3875

Climate Change Technical Committee. 2007a. Final Report of the Climate Change Technical Committee. http://www.govlink.org/regional-water-planning/tech-committees/climate-change/index.htm

Climate Change Technical Committee. 2007b. Technical Memorandum #4: Approach for Developing Climate Impacted Meteorological Data and its Quality Assurance/Quality Control. http://www.govlink.org/regional-water-planning/tech-committees/climate-change/index.htm

Climate Change Technical Committee. 2007c. Technical Memorandum #5: Approach for Developing Climate Impacted Streamflow Data and its Quality Assurance/Quality Control. http://www.govlink.org/regional-water-planning/tech-committees/climate-change/index.htm

Mote, Philip, Eric Salathé, and Cynthia Peacock. 2005. Scenarios of Future Climate for the Pacific Northwest. Climate Impacts Group, University of Washington. http://cses.washington.edu/db/pdf/kc05scenarios462.pdf

Seattle Public Utilities. 2007. Seattle Public Utilities Water System Plan. http://www.cityofseattle.net/util/About_SPU/Water_System/Plans/2007WaterSystemPlan/SPU01_002126.asp

University of Washington Climate Impacts Group. (n.d.). http://cses.washington.edu/cig/

Water Supply Forum. 2009. Water Supply Forum 2009 Water Supply Outlook. http://www.watersupplyforum.org/outlook

Box 5-2 (Continued)

5.3.2.2 Imported Water Reliability

More than 23 million people in California rely on water from either the CVP or from the SWP (Chung et al 2009). In addition, many people in Southern California also rely on water imported from the Colorado River Aqueduct (CRA) through MWD.

The three major imported water supplies in the State of California (SWP, CVP, and CRA) either have current reliability studies that account for climate change, or are in the process of conducting such a study. This handbook recommends that regions incorporate results from these reliability studies with respect to climate change in the planning process, rather than develop an independent assessment of imported water reliability. This recommendation is consistent with Urban Water Management Plan (UWMP) requirements.

Data Needed

Projected supplies from water purveyors and projected supplies from all other sources (or assumptions about availability from them).

State Water Project: "The State Water Project Delivery Reliability Report 2009" contains information on obtaining and using water reliability projections that take into account both climate change and environmental flow restrictions. The MWD and IRWD, among others, have conducted supply reliability studies based on data from the SWP Reliability Report (Rodrigo and Heiertz 2009, MWD 2010) (see also MWD case study, Box 7-1).

Central Valley Project: The California Climate Change Center 2009 report "Using Future Climate Projections to Support Water Resources Decision Making in California" (http://www.water.ca.gov/pubs/climate/using_future_climate_projections_to_support_water_resources_decision_making_in_california/usingfutureclimateprojtosuppwater_jun09_web.pdf) discusses impacts of climate change to both the Central Valley Project and the State Water Project.

Colorado River Aqueduct: Because MWD also obtains water from the Colorado River, MWD used data from the BOR's water supply model, CRSS, to estimate reliability from this source (see Appendix A-1 of MWD (2009), and the MWD case study). The USBR is currently conducting a Colorado River Basin Water Supply and Demand Study. The interim report is available at http://www.usbr.gov/lc/region/programs/crbstudy.html. Characterizing demand-supply imbalances resulting from climate change impacts is one of the objectives of the study, which is scheduled to be complete in July 2012.

Conducting the Analysis

"The State Water Project Delivery Reliability Report 2009" contains guidance on applying supply reliability projections to local and regional planning efforts. The SWP and CVP both provide delivery reliability in terms of an exceedence frequency. Projected deliveries can be

combined with other regional water sources to estimate overall regional water supply reliability.

Incorporating Uncertainty

The SWP and CVP both provide delivery reliability estimates in the form of a cumulative probability distribution that reflects hydrologic variability. Other uncertainties are associated with climate change, future demands, environmental flow restrictions, and natural disasters, among others. Many of these uncertainty sources cannot be modeled probabilistically and scenario planning may be the best option for assessing uncertainty. Regions that rely on imported water are encouraged to read documentation associated with published delivery reliability and incorporate this uncertainty into regional supply reliability studies.

Potential Performance Metrics

Potential performance metrics for evaluating climate change impacts on imported water supply and reliability might include an agency's threshold of acceptable regional supply certainty, or a percent decrease from existing supplies. Projected future supply need, associated with the imported source, may also be a performance metric.

5.3.3 Surface Water Quality

Water quality is critical to both drinking water supplies and ecological needs. Near-coastal drinking water intakes and estuarine habitats are both susceptible to salt water intrusion. Fish in riverine environments are susceptible to higher temperatures. Rivers, reservoirs, lakes, and coastal areas are all susceptible to low dissolved oxygen that can easily accompany higher temperatures.

Surface water systems susceptible to water quality impacts from climate change vary in configuration and require analyses tailored to their unique features. The EPA Watershed and Water Quality Modeling Technical Support Center (http://www.epa.gov/athens/wwqtsc/index.html) contains information on several EPA-supported water flow and transport models that range in complexity from 1-Dimensional (1D) (e.g., the Storm Water Management Model (SWMM) model) to 3D (e.g., the Environmental Fluid Dynamics Computer Code (EFDC) model). Several of the watershed models discussed in Section 5.4.3 can also be used to study water quality. This section specifically discusses salinity studies, and generally refers to inland water quality studies. The methods discussed in this section can be applied to many other water quality studies.

As with other resources areas, in some instances a numerical model is not necessary to develop a complex model. For example, a regression relationship can be developed between air temperature and stream temperature to estimate future stream temperatures (Rehana and Mujumdar 2011). In addition, mass balance-based box models can be developed to estimate concentrations and loadings.

5.3.3.1 Coastal Surface Water: Hydrodynamic Studies of Salinity Infiltration and Sea Level Rise

For drinking water source intakes that are located upstream of estuarine systems, vulnerabilities to salinity intrusion from downstream may be a concern. Estuarine hydrodynamic modeling is a useful tool for evaluating water quality. In some instances, a simple 1 or 2D model will suffice. In the Delaware Estuary, a 3D hydrodynamic modeling study was conducted to assess impacts of climate change on the salt wedge in the Delaware River (Kreeger et al 2010). There are many hydrodynamic models that can be used to evaluate coastal systems. Some examples include:

- EFDC (http://www.epa.gov/athens/wwqtsc/html/efdc.html
- ELCOM (http://www.cwr.uwa.edu.au/software1/models1.php?mdid=5) and
- MIKE 3D (http://www.mikebydhi.com/Training/CourseTopics/CoastandSea.aspx).

Common 2D models include ADCIRC (http://www.adcirc.org/) and RMA2 (http://chl.erdc.usace.army.mil/rma2).

Because developing a hydrodynamic model is labor-intensive and requires a high level of technical expertise, regions should thoroughly evaluate the potential benefits of such an investment. Where resources are not available for a modeling study, more qualitative methods, such as surveying local experts, may provide useful information for guiding planning decisions. The EPA's Climate Ready Estuaries program (CRE, http://www.epa.gov/climatereadyestuaries/) provides several resources that may support this type of analysis. Where models are already developed, they can be useful tools for assessing impacts of sea level rise and other climate change impacts on a coastal system. Figure 5-8 depicts the steps to create an example coastal surface water impacts analysis.

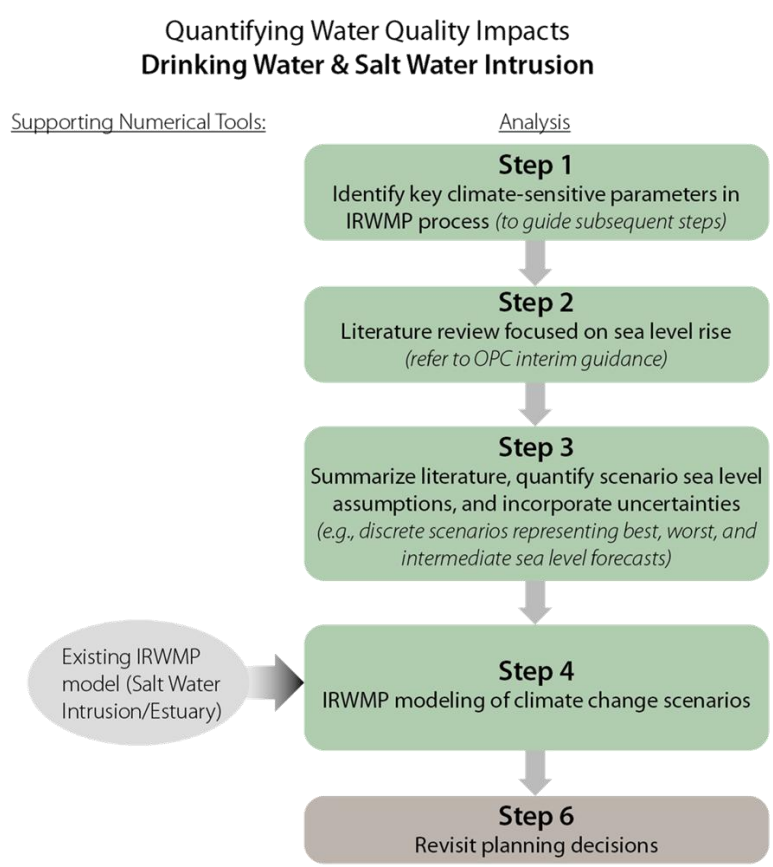


Figure 5-8: Water Quality Salt Intrusion Climate Change Analysis Process Flow Chart.

Data Needed

Regardless of the dimensions modeled, hydrodynamic modeling requires data that characterizes the estuary and points of concern upstream; such as bathymetry data (river and estuary topography), the coastline delineation, and streamflow data. Depending on the morphology of the estuary system, it can be necessary to include large spatial domains in the model set-up if multiple-dimensional modeling is used. In addition to data on the physical shape of the system, hydrodynamic modeling also requires variables, such as atmospheric data (including wind and precipitation), tidal data, historical streamflow data, and historical salinity data.

Other data required for taking climate change into account may include projected levels of sea level rise (see section 5.4.4), anticipated changes in streamflows (see Section 5.4.3), and atmospheric variables such as air temperature, possibly from downscaled GCM results. Determining which model input variables to alter to account for climate change, and obtaining relevant variable projections, involves steps 1 and 2 in Figure 5-8.

Conducting the Analysis

After gathering data, configuring a model for a region, and calibrating/validating it against observed field data; a hydrodynamic model's boundary conditions can be altered to reflect a warmer climate (step 4 in Figure 5-8). Where regions have existing hydrodynamic estuary models, they are encouraged to modify existing models to account for climate change. Variables reflecting climate change may include:

- Tidal elevations reflecting sea level rise;
- Streamflows reflecting seasonal flow patterns altered by climate change; and
- Atmospheric variables downscaled from GCM results; such as evaporation, temperature, wind, and atmospheric pressure).

Incorporating Uncertainty

Primary sources of uncertainty specific to hydrodynamic modeling of saltwater intrusion include:

- Our limited understanding of how the physical system responds to climate and other variables.
- Numerical accuracy of the hydrodynamic model. This uncertainty is associated with limitations of the underlying mathematical equations and the way the model solves these equations. Uncertainty is also associated with the assumption that the historical calibration dataset provides a representative calibration for use in projecting the future.
- Hydrologic and climate variability. Fluctuations in climate and hydrology at annual or sub-annual time scales are not predictable and often viewed as effectively "random" for planning purposes.
- Projections of future conditions, including climate variables (step 3 in Figure 5-8) and other boundary conditions influenced by climate, such as streamflows and sea levels. Future oceanic boundary conditions also serve as a source of uncertainty.

Two options for quantifying uncertainty in hydrodynamic modeling are probabilistic modeling and scenario planning; both described in detail in Appendix C. It is challenging to integrate complex hydrodynamic models into full probabilistic analyses. Therefore, scenario planning may be the better option than probabilistic modeling. A suite of model simulations could be developed assessing sea level rise and intrusion for a range of assumed climate projections. As with hydrologic models, sensitivity analyses are recommended to quantify uncertainty associated with model parameterization.

Potential Performance Metrics

Useful performance metrics for this type of study may include salinity levels relative to acceptable thresholds for drinking water or marine life, or storm surge flooding damage or extent. Various water quality performance metrics can also be addressed with surface water models; these are discussed in the next subsection. Evaluating performance metrics using a coastal water model is represented by step 6 in Figure 5-8.

5.3.3.2 Inland Surface Water Quality Modeling

Inland water systems are also vulnerable to water quality problems exacerbated by climate change. This section discusses water quality modeling generally, and can be relevant to watershed, riverine, or surface water body systems. A common water quality constituent of concern is Dissolved oxygen, which is critical to aquatic life. Dissolved oxygen levels generally decrease with increased water temperature, decreased flow velocity, increases in biologic activity and oxygen demand, and changes in re-aeration. Therefore, this parameter is particularly impacted by climate change in California. Figure 5-9 depicts the general steps for an inland surface water quality impacts assessment.

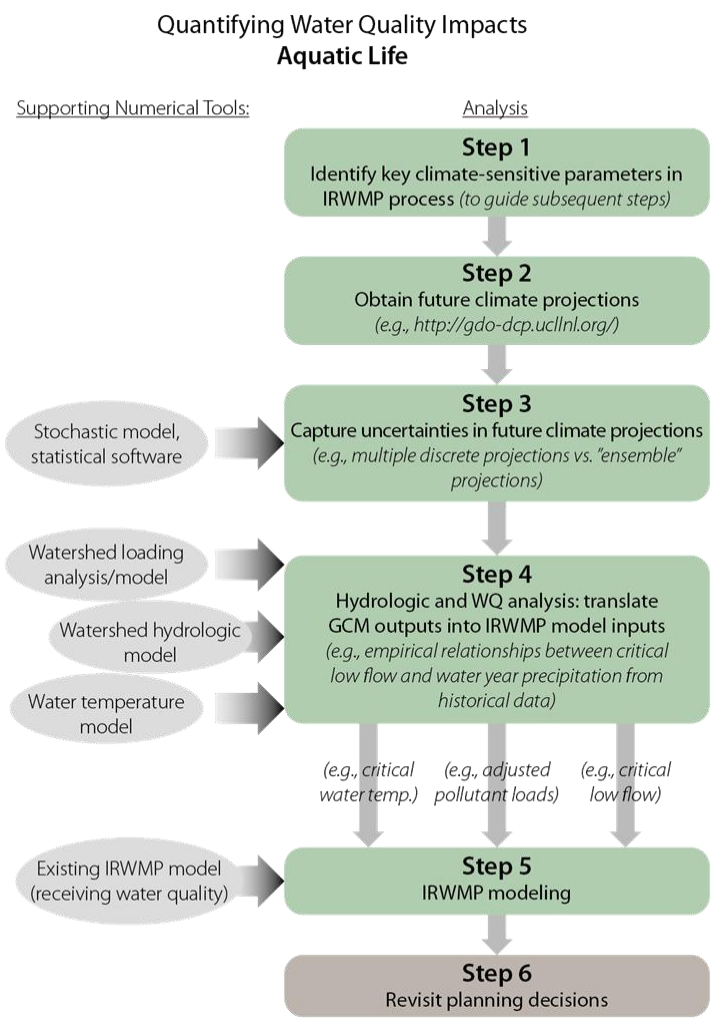


Figure 5-9: Water Quality Climate Change Impacts Process Flow Chart.

Other inland surface water quality concerns may include bacteria, temperature, and pollutants. Temperature lowers dissolved oxygen solubility, which can impact fish viability. Other pollutants may be identified from the State's 303(d) list of impacted waters, or from established total maximum daily loads (TMDLs) in a region's water bodies. Streamflow temperatures will be impacted by both snowmelt and ambient air temperature. Identifying water quality constituents to study is part of step 1 in Figure 5-9.

Data Needed

Flow and hydraulic data are critical to any surface water quality model. For the majority of dissolved oxygen studies, the critical condition corresponds to periods of low flows. Quantifying the low flows used in water quality modeling is often guided by regulatory mandate (e.g., 7Q10 low flow). Therefore, flow data acquisition can often focus on short-term low flows. Other data required to develop a water quality model depends on the system included in the model. Data needs for watershed models are discussed in Section 5.3.2, and may be applicable to a watershed scale surface water quality model. Data needs for a river/water body system also include:

- Watershed area and land use,
- River elevation and cross sectional data,
- Climate data (e.g., precipitation and temperature), and
- Pollutant loadings.

Values for all variables are needed both for current/historical conditions, for calibration purposes (for new models developed as part of the planning study), and for reflecting projected future conditions. Obtaining relevant data and future climate variable projections is represented by step 2 in Figure 5-9. Using GCM results to estimate extremes, such as low flows can be tenuous. Some statistical analyses have been used to estimate low flows from hydrologic studies directly using GCM results (Cox and Tummuri 2010).

Conducting the Analysis

Some well-known surface water quality models include:

- QUAL2K (http://www.epa.gov/athens/wwqtsc/html/qual2k.html),
- RMA4 (http://chl.erdc.usace.army.mil/rma4)
- WASP (http://www.epa.gov/athens/wwqtsc/html/wasp.html), and
- CAEDYM (http://www.cwr.uwa.edu.au/software1/models1.php?mdid=3).

As with most water system process models, it is necessary to calibrate a model to historical data before evaluating the impact of climate change on the system. After calibration, altering variables, such as streamflows and temperature, according to future climate projections provides an estimate of future water quality conditions. A link between climate projections and

streamflow and water temperature will likely be required in this process. The watershed hydrologic models described in Section 5.3.2 can provide streamflow projections. External stream or lake temperature models may be required to simulate temperature impacts. Watersheds with snowpack may need to consider cold water releases from snowmelt. Steps 4 and 5 in Figure 5-9 include simulating future water quality impacts from climate change.

Incorporating Uncertainty

Primary sources of uncertainty specific to surface water quality modeling include:

- Our limited understanding of how the physical system responds to climate and other variables.
- Numerical accuracy of the water quality model. This uncertainty is associated with limitations of the underlying mathematical equations and the way the model solves these equations. There is also uncertainty associated with the assumption that the historical calibration dataset is comprehensive enough to provide a representative calibration for use in projecting the future.
- Hydrologic and climate variability. Fluctuations in climate and hydrology at annual or sub-annual time scales are not predictable and are often viewed as effectively "random" for planning purposes.
- Projections of future conditions, including pollutant loading, land use, climate variables (step 3 in Figure 5-9) and other boundary conditions influenced by climate, such as streamflows.

Two options for quantifying uncertainty in water quality modeling are probabilistic modeling and scenario planning. Both options are described in detail in Appendix C. It is challenging to integrate complex water quality models into full probabilistic analyses, although many new water quality modeling tools include probabilistic and/or stochastic simulation modes. Alternatively, scenario planning techniques could be applied. Under scenario planning, a suite of model simulations are developed for a range of assumed uncertain variables (like future climate conditions). For example, a range of critical low-flow and air temperature inputs might be used in the analysis of future dissolved oxygen conditions in a stream. Both of these inputs might be informed by site-specific climate change model projections. Sensitivity analyses are recommended to quantify uncertainty associated with model parameterization.

Potential Performance Metrics

Performance metrics may include comparing modeling results with thresholds of acceptable pollutant concentrations, such as water quality standards. Water quality standards will define minimum acceptable dissolved oxygen concentrations, or acceptable ranges of instream temperatures. Evaluating performance metrics is represented by step 6 in Figure 5-9.

5.3.4 Ecosystem and Habitat Vulnerability

Ecosystems and habitats are varied. The approaches to measuring potential impacts of climate change on these systems are equally varied. While more vulnerability metrics and methods for assessing them can be found in the literature, this section addresses stream water temperature, water quantity, estuarine salinity, coastal habitat loss from sea level rise, and threats to individual species.

5.3.4.1 Estuarine Salt Intrusion: Hydrodynamic Modeling

Just as salt intrusion into estuarine systems can impact drinking water supplies, it can also have a significant ecological impact. The approach described in Section 5.3.3 also applies to ecosystem habitat vulnerability.

5.3.4.2 Streamflow Water Quality and Quantity

Changes instream flow and water quality could have a significant impact on aquatic life. For streamflow estimation, the rainfall runoff modeling methods described in Section 5.3.2 and the water quality modeling methods described in Section 5.3.3 can be used to assess potential ecosystem impacts. In some cases, ecological response models can be used to further estimate more specific impacts on species, habitats and ecosystems (see NWF 2011).

5.3.4.3 Wetland Habitat Loss from Sea Level Rise

Coastal marsh habitats are particularly vulnerable to sea level rise. Where data is available, it may be advantageous to use modeling tools to estimate future marsh and wetland migration or loss. This information could be used to prioritize protection of land that could accommodate wetland migration. Where these modeling tools and/or data are not available, it is also possible to compare existing coastal habitat with projected sea level rise impacts. Figure 5-10 depicts the steps for a wetland habitat loss/migration study.

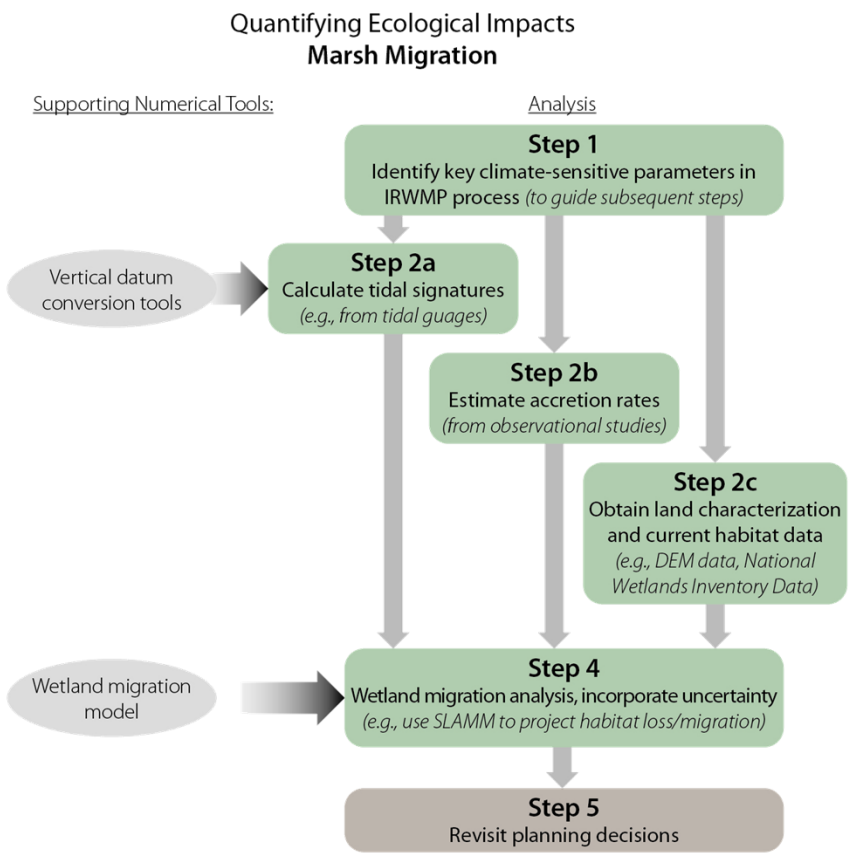


Figure 5-10: Marsh Migration Process Flow-chart

Marsh Migration Modeling

The National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center (http://www.csc.noaa.gov/digitalcoast/index.html) provides several tools for coastal data management, calculations, and decision making. Among these tools is the Sea Level Affecting Marshes Model (SLAMM). SLAMM allows the user to estimate impacts of long-term sea level rise on wetlands, including factors such as erosion and sedimentation.

Data Needed

SLAMM incorporates several options for sea level rise estimates. Other data required include:

- National Wetlands Inventory data (http://www.csc.noaa.gov/digitalcoast/data/nwi/index.html),
- Digital elevation data for the region of interest (http://www.csc.noaa.gov/digitalcoast/data/ned/index.html),
- Local tidal data,
- Local accretion data, and
- Local erosion rates.

Assembling data may take some processing and datum conversion. The tool VDatum is useful for datum conversion (http://vdatum.noaa.gov/). Data processing is also simplified by using Geographic Information Systems (GIS). Step 2 in Figure 5-10 illustrates some components of assembling necessary data.

Conducting the Analysis

SLAMM allows model simulations far into the future. The Delaware Estuary Wetland Work Group used SLAMM to assess tidal wetland habitat loss (Kreeger et al 2010), estimating effects going out to 2100. This analysis is represented by step 4 in Figure 5-10.

Incorporating Uncertainty

Primary sources of uncertainty specific to marsh migration modeling include:

- Our limited understanding of how the physical system responds to climate and other variables.
- Numerical accuracy of the marsh migration model. This uncertainty is associated with limitations of the underlying mathematical equations and the way the model solves these equations. There is also uncertainty associated with the assumption that the historical calibration dataset is comprehensive enough to provide a representative calibration for use in projecting the future.

- Hydrologic and climate variability. Fluctuations in climate and hydrology at annual or sub-annual time scales are not predictable and often viewed as effectively "random" for planning purposes.
- Projections of future conditions, including pollutant loading, land use, climate variables (step 3 in Figure 5-10) and other boundary conditions influenced by climate, such as streamflows.

Due to the complexity of the SLAMM model, scenario planning is likely a better fit for quantifying uncertainty compared to full probabilistic modeling. Scenario planning should be coupled with sensitivity analyses to quantify the uncertainty attributable to model parameterization.

Potential Performance Metrics

Performance metrics for wetland habitat loss may include estimates, such as the percent of the total existing habitat that is at risk, or the total acreage of habitat that may be lost (or preserved). As SLAMM estimates shifts from one marsh type to another, metrics may be qualified by conversion to specific classes of similar wetlands.

Qualitative Land Footprint Comparison

A simpler method than using SLAMM may involve a qualitative analysis, such as comparing projected coastlines under future conditions based upon previous studies with the existing location of wetlands. For this analysis, the descriptions in Section 5.3.5 may apply.

5.3.4.4 Individual Species

Endangered and threatened species can be especially vulnerable to climate change. Figure 5-11 depicts the steps for an individual species impact analysis. While projecting impacts for some species is necessarily qualitative, the US EPA Framework for Categorizing the Relative Vulnerability of Threatened and Endangered Species to Climate Change (EPA 2009b) ("Framework") provides comprehensive guidance in evaluating the projected impacts of climate change on a species. The Framework takes into account "baseline" vulnerability, irrespective of climate change, and accounts for variables specifically related to climate change. The Framework is included in the Literature Review in Appendix A.

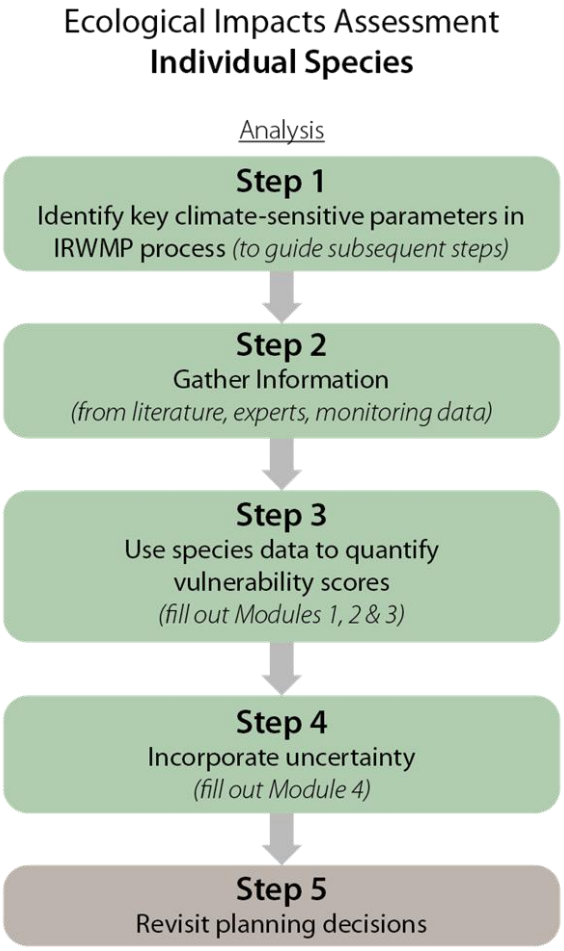


Figure 5-11: Species Process Flow-chart

The Framework analysis includes four modules that assess:

- Background vulnerability,
- Species vulnerability to climate change,
- Overall vulnerability, and
- Uncertainty associated with the vulnerability assessment.

The Framework includes example cases where the modules have been applied to threatened and endangered species.

Other qualitative and quantitative methods can be used for evaluating climate change impacts on individual species. The Southwest Climate Change Initiative (SWCCI) uses a conceptual model to evaluate relationships between climate factors and ecological processes (see case study, Box 5-3). The National Wildlife Federation (NWF) report "Scanning the Conservation Horizon" provides information on other ecological response models and uncertainty associated with them (NWF 2011).

Data Needed

The modules included in the Framework require the user to make qualitative assessments of many variables related to physiological requirements and behavioral characteristics of the species being assessed. If this data is not readily available, and experts are not readily available for consultation, a thorough literature review may be required (see step 2 in Figure 5-11). Implicit in the data required is a qualitative understanding of projected temperature and precipitation changes due to climate change. This assessment is not based on a specific future scenario, rather the planner's judgment about the direction and magnitude of the future under climate change. Information needed to complete the assessment includes:

- Species population size and range, and trends of both;
- Vulnerability to external (non-climate change-related) variables, such as policy and management decisions, stochastic events, and other stressors;
- Species attributes, such as individual replacement time, dispersive capacity, dependence on other species, and dependence on temporal inter-relationships;
- Habitat resiliency; and
- Vulnerability to changes in temperature and precipitation and extreme weather events.

Conducting the Analysis

Use of the EPA Framework involves of filling out a one-page form for modules 1-3. Modules 1 and 2 require data entry. Module 3 requires analyzing the data provided in Modules 1 and 2 to categorize the species as "critically vulnerable", "highly vulnerable", "less vulnerable", "least vulnerable", or "likely to benefit from climate change".

Incorporating Uncertainty

Module 4 of the Framework consists of approximating the certainty of the Module 3 assessment as high, medium, or low. Because the assessment is qualitative in nature, the uncertainty is also qualitatively assessed. This uncertainty is weighed against the severity of potential climate impacts to determine overall climate impacts. Uncertainties are associated with:

- Our limited understanding of how species will respond to climate and other variables.
- Natural hydrologic and climatologic variability.
- Projections of future conditions, including habitat land availability and connectivity, climate variables and other boundary conditions influenced by climate, such as streamflows and water quality.

Scenario planning could be applied through the use of variable climate and hydrologic condition assumptions within the EPA framework.

Potential Performance Metrics

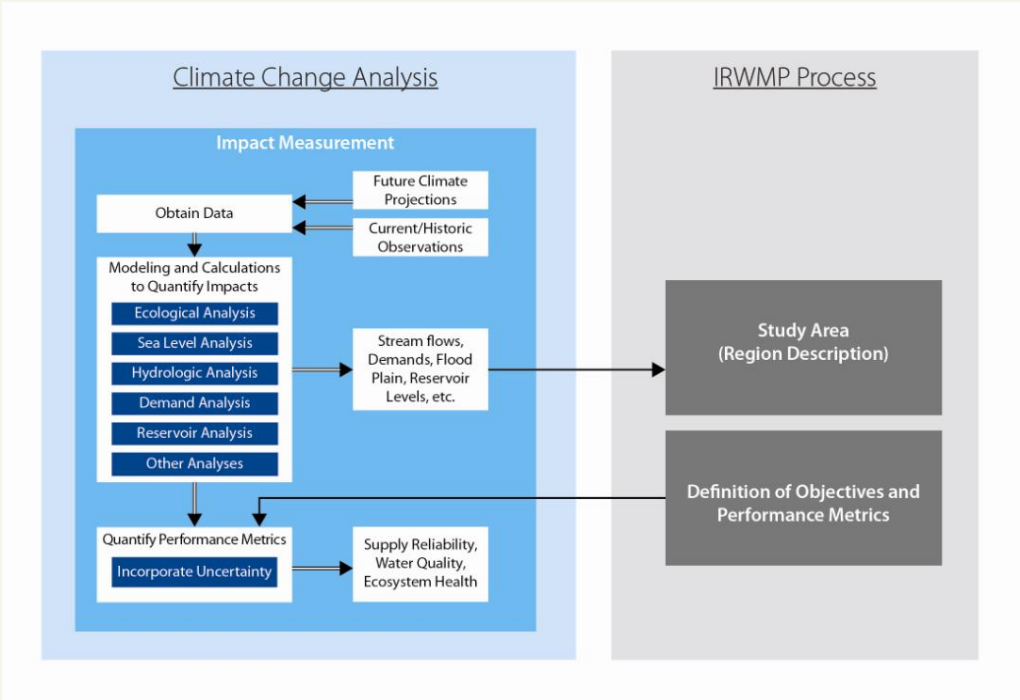
Uncertainty is explicitly included in module 4 of the Framework, which facilitates evaluation of Framework results. A comparison of module 1 and module 2 results facilitates identification of climate-related vulnerability.

The results of this analysis are qualitative, which simplifies performance metrics. Metrics may be set to overall vulnerability ratings. For example, a region could determine to use a “medium” vulnerability as a threshold of performance acceptability. Alternatively, the score from an individual module or question within the Framework may be of particular importance to a region. For example, a region could use a projected habitat availability under climate change of “medium” with a high level of certainty as a threshold of performance acceptability.

Case Study: Measure Impacts

Bonneville Cutthroat Trout – Ecological Impacts Analysis

Southwest Climate Change Initiative



Background:

- The Southwest Climate Change Initiative (SWCCI) was launched in 2009 to provide tools to assess the impacts of climate change on conservation objectives, and build partnerships between scientists and managers for adaptation planning. SWCCI is a partnership of The Nature Conservancy, the Wildlife Conservation Society, the Climate Assessment for the Southwest at the University of Arizona, the National Center for Atmospheric Research, and the Western Water Assessment at the University of Colorado.
- The Bear River Basin spans parts of Utah, Idaho and Wyoming, and is the largest tributary to the Great Salt Lake. Figure 1 shows a map of the Bear River watershed.
- The Bonneville Cutthroat Trout's (BCT) last large river habitat is the Bear River. The BCT is affected by irrigation diversions and hydropower facilities, and is a focus of

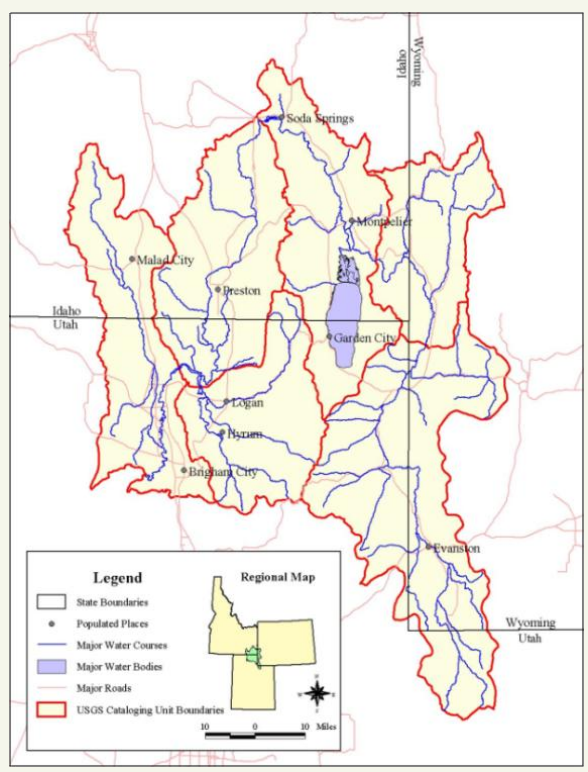


Figure 1: Bear River Watershed. (Source: BRWIS 2011). For larger image please see http://www.bearriverinfo.org/mapping/images/watershedmap.jpg

Box 5-3

conservation efforts through the Utah State Wildlife Action Plan (Utah Division of Wildlife Services 2010). Water temperatures in the main stem of the river are already close to the BCT's tolerance level, raising concern about the potential effects of climate change.

Key Questions:

1. What temperature and moisture changes are likely in the future?
   - The analysis approach included hydrologic modeling with GCM downscaled climate projections
2. How will climate change impact systems of interest in the Bear River?
   - The analysis approach include developing a conceptual ecological model

The Nature Conservancy (TNC) held a 2-day workshop in 2010 to identify climate adaptation strategies for species and ecosystems in the Bear River. The workshop focused on both the Bear River wetlands ecosystem and the BCT subspecies. This case study focuses on BCT-related analyses.

Step 1: Obtain Locally Applicable Data and Preliminary Analysis

Data Obtained:

- *Develop future climate scenarios*
- *Develop future streamflow projections (hydrologic modeling)*

---

1) Develop future climate scenarios

- A2 emissions scenario
- Examine distribution of model results for Bear River area, select two model results
  - NCAR CCSM GCM (model results represent more moderate climate change in the Bear River area)
  - CRCM GCM (model results represent more challenging climate change in the Bear River area)
- GCM results obtained from CMIP3 archive

2) Run a hydrologic model:

a. Variable Infiltration Capacity Model (VIC).
   i. Obtain historical and current data needed for runoff modeling
   ii. GCM results used to adjust historical record

b. Results: streamflow conditions 2041-2070
   i. Earlier springmelt
   ii. Lower summer low flows
   iii. Lower summer high flows
   iv. Higher winter flows

Box 5-3 (Continued)

Step 2: Assessment and Analysis

Analyses Conducted at the workshop:
- *Conceptual model*
- *Workshop discussion*

Workshop Details

- 13 participants examining BCT:
  - Public agencies
  - Private organizations
  - Academic institutions
- Two days long

Develop BCT Conceptual Model

Start with draft developed before workshop

Elements included in the final conceptual model (Figure 2):

- Relationships among key features:
  - Habitat
  - Biological agents
  - Ecological processes
  - Climate parameters
  - Human management
- Elements critical for BCT viability
  - Genetic diversity/gene flow
  - Population demography
  - Habitat connectivity
- Critical habitat elements
  - Flow regime
  - Water quality regime
  - Physical habitat characteristics

Box 5-3 (Continued)

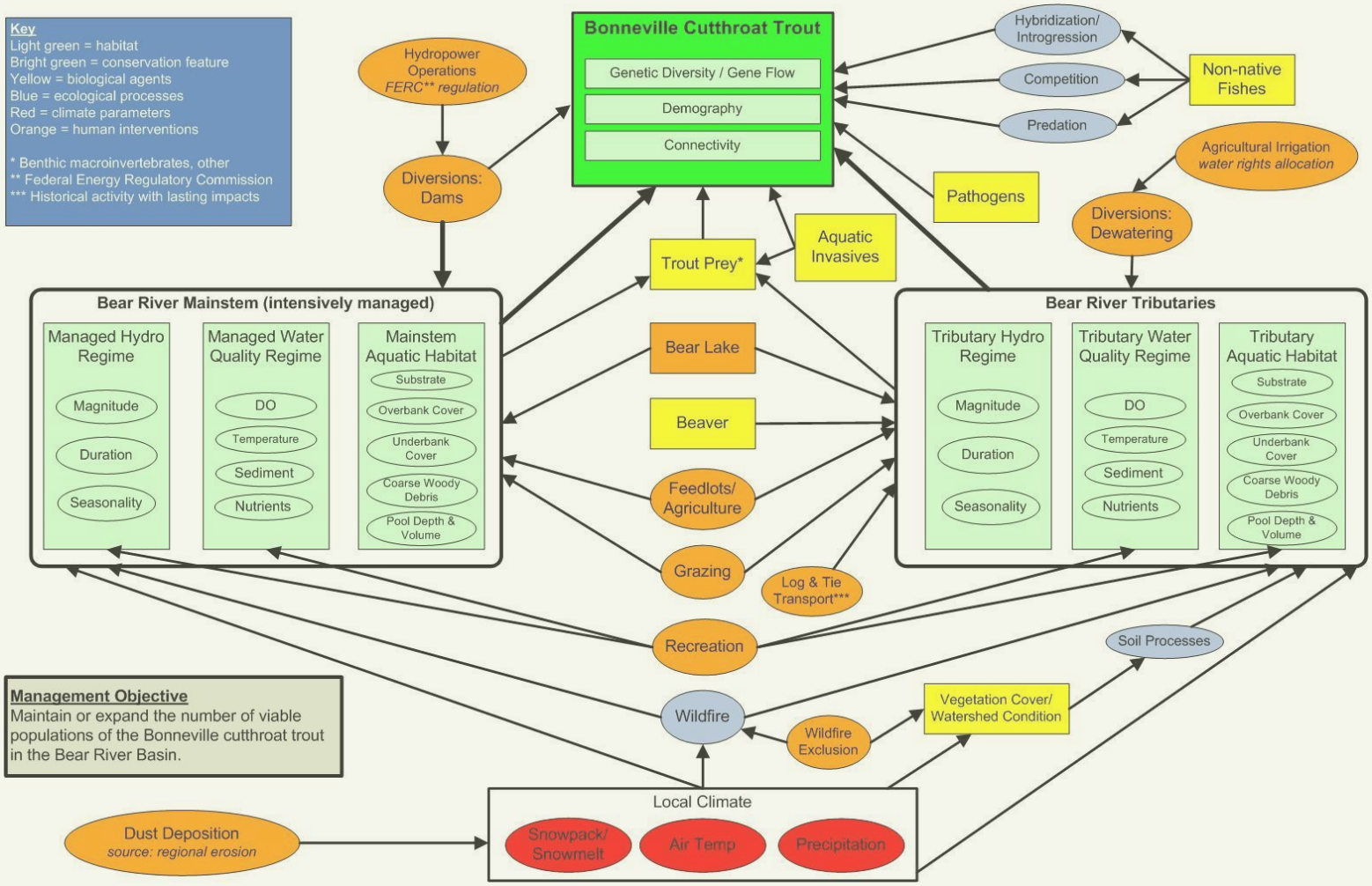


Figure 2: Bonneville Cutthroat Trout Conceptual Ecological Model. (Source: SWCCI 2010).

Box 5-3 (Continued)

Using conceptual model, identify climate change impacts and drivers (direct and indirect)

Physical climate change impacts and their effects on the BCT (modified from SWCCI 2010 Appendix 5) include:

Climate Change Impact	Effect on Bonneville Cutthroat Trout
Increased sediment loading, changes in channel morphology	Decrease in viability
Decreased dissolved oxygen	Physiological stress
Flow regime changes (due to shifts in vegetation)	Decrease in viability
Increased agricultural water demands	Water quantity, stranding
Increased water temperatures	Physiological stress Increase in pathogens Increase in non-native fish species
Less stream ice	Expanded habitat Fewer thermal refugia
Lower base flows, changes in riparian zone	Decreased water quantity Habitat loss Increased water temperature Stranding
Earlier snowmelt runoff	Phenological changes Stranding
Decreased infiltration to soil layers	Decreased water quantity Habitat loss Physiological stress
Increased droughts	Habitat loss Physiological stress Decreased viability
Cattle migration to riparian zones during drought	Habitat loss Physiological stress Decreased viability

---

Step 3: Relation to Management Objectives

Metric Used:

Challenges posed for accomplishing management objectives

The workshop was not a part of a formal planning process and no performance metrics were formalized or evaluated. However, the management objectives were used as a basis for identifying climate change impacts and potential management strategies.

1) 5-10 year Management Objective:
   "Maintain or expand the number of viable populations of the Bonneville cutthroat trout in the Bear River Basin." (SWCCI 2010)

   Subobjectives were to maintain or restore:
   - Connectivity between mainstream and tributaries
   - Flows in actual and potential habitat
   - Habitat quality
   - Genetic diversity
   - Aquatic community
   - Water quality

Impacts posing the largest threat relate to habitat loss:
- Fewer thermal winter refugia
- Loss of ice bridges in tributary streams
- Fewer summer-time streams within the BCT thermal tolerance
- Tributary dewatering/decreases in flows

Box 5-3 (Continued)

Potential Adaptation Measures and Research/Data Needs

The workshop identified potential management strategies that would address the climate change impacts identified for the BCT. This provided steps for moving forward.

Recommended Strategies

- Reducing/removing non-native fish
- Maintaining and creating cool water refugia and connectivity among refugia
- Improving riparian and aquatic habitat
- Removing physical barriers in priority reaches

Data/Research Needs

- River hydrology and fluvial morphology
- BCT biology
  - Demography
  - Life history
  - Phenology
  - Genetics
  - Habitat requirements
- Watershed condition
- Habitat

For More Information

BRWIS. 2011. Bear River Watershed Information System website. http://www.bearriverinfo.org/mapping/images/watershedmap.jpg

SWCCI. 2010. Bear River Climate Change Adaptation Workshop Summary. May 26 and 27, 2010. Salt Lake City, Utah. http://conserveonline.org/workspaces/climateadaptation/documents/southwestern-us-pilot-sites/view.html

Utah Comprehensive Wildlife Conservation Strategy http://wildlife.utah.gov/cwcs/

VIC model website http://www.hydro.washington.edu/Lettenmaier/Models/VIC/

Box 5-3 (Continued)

5.3.5 Sea Level Rise

Sea level rise impacts many water resources; including wildlife habitats, water quality, and coastal infrastructure. Coastal estuaries, wetlands, and marshes will be impacted by changing freshwater-ocean water balances; and may also migrate inland where unimpeded. Estuarine and river delta modeling methods are discussed in Section 5.3.3, along with coastal habitat migration modeling techniques. As sea level rises, coastal flood plains will also move inland; which has impacts for local infrastructure and coastal property. Rising sea levels are necessary inputs to many of the models discussed in these sections.

Planners are encouraged to familiarize themselves with coastal data. Bathymetry and coastal elevation data is available through the NOAA Coastal Inundation Toolkit (http://www.csc.noaa.gov/digitalcoast/inundation/index.html).

5.3.5.1 Future Sea Level Estimates

Studies have been conducted on future sea level rise estimates encompassing the California coast and beyond, reducing the burden on individual planning entities to assess predicted levels of sea level rise. Planners should take advantage of existing studies where possible. The NAS is developing a Sea Level Rise Assessment Report, which is expected to be released in the spring of 2012. The CO-CAT has developed interim guidance on taking sea level rise into account (http://www.water.ca.gov/climatechange/docs/SLR_GuidanceDocument_SAT_Responses.pdf), which the OPC supports (http://www.opc.ca.gov/2011/04/resolution-of-the-california-ocean-protection-council-on-sea-level-rise/). The CO-CAT guidance recommends following the Vermeer and Rahmstorf (2009) method for projecting sea level rise (http://www.pnas.org/content/106/51/21527.full.pdf+html). All future guidance updates will be available at the OPC web site (www.opc.ca.gov).

> *The CO-CAT guidance document provides sea level rise estimates that are applicable to the California Coast for the years 2030, 2050, 2070 and 2100. Planners are encouraged to utilize these existing projections, which are supported by the OPC.*

In California, the OPC guidance supersedes other sea level rise guidance documents. More nationally applicable guidance, such as the USACE sea level rise guidance, refers back to an approach developed for the 1987 NRC report (NRC 1987). Since this report was published, models and approaches have improved. However, the "medium" and "high" sea level rise projection methods outlined in the USACE guidance result in sea level rise projections that are very similar to the CO-CAT guidance.

The CO-CAT guidance document provides sea level rise estimates that are applicable to the California coast for the years 2030, 2050, 2070 and 2100. However, planners may need to calculate projected rises for other time frames.

Data Needed

The Vermeer and Rahmstorf method requires globally averaged GCM temperature projections extending through the planning period. Local mean sea level in the years 1990 or 2000 are also needed. Using sea level rise estimates to project inundation also requires local elevation data for the coast.

Conducting the Analysis

The Vermeer and Rahmstorf method empirically relates global mean temperature to sea level rise. Because California's projected sea level rise is expected to be similar to the global average sea level rise, no regional adjustments needs to be made in the parameters used by Vermeer and Rahmstorf (CO-CAT 2010). Planners using the year 2000 as a baseline should subtract 3.4 cm from resulting sea level rise projections, however, because the reference year used in the Vermeer and Rahmstorf study is 1990. Projected sea level increases can be compared with digital elevation data to identify land at risk to either inundation due to sea level rise or potential coastal flooding.

Incorporating Uncertainty

Uncertainties in using the Vermeer and Rahmstorf method are associated with:

- Our understanding and characterization of climate and other variables in general and how sea levels will respond to changes in the future.
- Projections of future climate variables and other boundary conditions influenced by climate, such as streamflows and water quality.

Given the empirical nature of the Vermeer and Rahmstorf method, and the direct use of GCM temperature projections, a probabilistic framework might be appropriate for quantifying uncertainty associated with the climate projections. As discussed in Appendix C, results of this type of analyses should not be strictly viewed as likelihood of occurrence probabilities, but rather are more representative of levels of consensus of the best available projections.

Potential Performance Metrics

Possible performance metrics for sea level rise include differences in the amount of infrastructure at risk before and after considering sea level rise. This comparison could be quantified by the potential cost for repairs in a flood event, or it could be quantified by the critical nature of the vulnerable infrastructure (e.g., influencing regional ability to respond in an emergency).

5.3.5.2 Erosion

Erosion and sediment deposition rates will change as sea levels rise. The Pacific Institute completed a study of California Coastal Erosion in 2009 (http://www.pwa-ltd.com/about/news-CoastalErosion/PWA_OPC_Methods_final.pdf) that maps projected potential hazard zones along much of the California coast. The CO-CAT guidance document refers to parts 3 and 4 of the U. S.

Geological Survey National Assessment of Shoreline Change for additional guidance on future erosion and accretion rates:

- U.S. Geological Survey report on shoreline changes for California's beach habitat http://pubs.usgs.gov/of/2006/1219/, and
- U.S. Geological Survey report on shoreline changes for California's bluff habitat http://pubs.usgs.gov/of/2007/1133/.

5.3.5.3 The Sacramento-San Joaquin Delta

The Delta is the largest estuary on the west coast of North America. Sub-sea level Delta islands, protected by aging levees, are particularly vulnerable to sea level rise, levee collapse, and flooding. Analysis of the impacts of sea level rise in the Delta should rely on recent work by DWR as part of the Delta Risk Management Study (DRMS) (http://www.water.ca.gov/floodmgmt/dsmo/sab/drmsp/phase1_information.cfm). Phase 1 of DRMS was completed in 2009 and provides a comprehensive risk analysis that considers the potential effects of climate change including sea level rise. The DRMS also considers the likelihood of occurrence of earthquakes, island subsidence, and flooding resulting from the increased magnitude and frequency of storms due to climate change.

5.3.5.4 100-year Coastal Flood Plains

One method for quantifying climate change impacts is to superimpose projected sea level rise onto elevations for existing coastal floodplains. For example, the Pacific Institute conducted a study on potential impacts of 1.4 m of sea level rise on coastal floodplains. This rise in sea level corresponds to the high estimate for the year 2100 in the CO-CAT guidance mentioned above. The results from this study are available at http://www.pacinst.org/reports/sea_level_rise/ as GIS shapefiles delineating new floodplains. With new floodplains mapped, it is possible to compare existing infrastructure and resource locations with these flood plains. For example, the Santa Monica Bay Restoration Commission (SMBRC) State of the Bay 2010 report (SMBRC 2010) includes such a comparison for the LA area (using the Pacific Institute's shapefiles), as does the initial Pacific Institute report (Herberger et al 2009). The Pacific Institute analysis does not strictly follow the CO-CAT guidance, as it was developed before the guidance was released; however, the Pacific Institute provides coastal flooding and erosion projections based on a 1.4 m sea level rise "high" projection by 2100, which is consistent with the CO-CAT guidance. Figure 5-12 depicts the steps for a coastal flood plain impacts analysis.

Data Needed

The data necessary for this exercise includes the floodplain model results that are available from the Pacific Institute, along with digital information on the location of various pieces of infrastructure in coastal areas for comparison. Assembling this data is represented by step 2 in Figure 5-12.

Conducting the Analysis

Comparing the Pacific Institute model results with existing infrastructure could be done by overlaying the infrastructure and floodplains from the Pacific Institute and taking an inventory of at-risk infrastructure. Conducting a "what-if" analysis of how vulnerable each facility would be in a flooding event may also be useful. This exercise is represented by steps 3 and 4 in Figure 5-12.

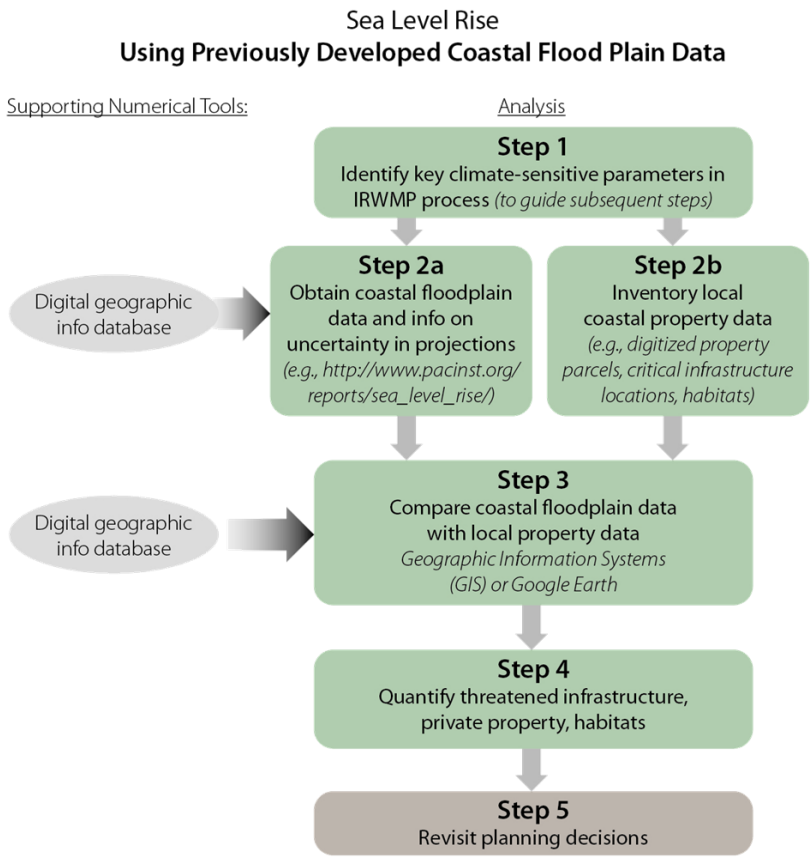


Figure 5-12: Coastal Flooding from Sea Level Rise Process Flow-chart.

Incorporating Uncertainty

The dominant source of uncertainty in this type of analysis is that associated with the sea level rise estimates used to make the floodplain maps. For documentation of uncertainties associated with the Pacific Institute study, see the original report developed by the Pacific Institute (Herberger et al 2009).

Other uncertainties are associated with assumptions made regarding what coastal infrastructure will be present in the planning horizon. Step 4 in Figure 5-12 includes incorporating uncertainty.

The use of multiple projections of sea level rise and shoreline changes from multiple expert sources might be an appropriate technique for addressing uncertainty in this type of planning analysis.

Potential Performance Metrics

Possible performance metrics for sea level rise include differences in the amount of infrastructure contained in the present 100-year floodplain and the 100-year floodplain with sea level rise. This comparison could be quantified by the potential cost for repairs in a flood event; or it could be quantified by the critical nature of the vulnerable infrastructure

(influencing regional ability to respond in an emergency). Step 6 of Figure 5-12 represents quantifying performance metrics.

5.3.6 Flooding

The current suite of GCMs are not designed to project future extreme weather events and may not be the appropriate tools for evaluating these impacts. While the current suite of GCMs provides the best available information on long-term global climate trends at a monthly time step, extreme precipitation events that cause flooding occur at hourly and daily time steps. In addition, precipitation patterns are strongly influenced by regional and subregional geography, especially in mountainous areas. GCMs are not designed to provide information at these scales or time steps, and downscaling methods may not provide adequate accuracy or precision for making flood planning decisions. Therefore, the tools and strategies described for other planning activities that rely on GCM data are likely not appropriate for incorporating climate change into flood planning decisions.

Unfortunately, there are few examples of alternative tools and methods specifically tailored to incorporating climate change considerations into flood planning (DWR 2010c). Despite a lack of analysis methods, assessment of climate change impacts on future flooding is still an important aspect of regional water planning.

Given the difficulty in quantitatively assessing the frequency and severity of future storms, regional planners may need to take more qualitative approaches to assessing future flood risks, such as a threshold analysis, sensitivity analysis, or relative change analysis. An example threshold analysis method (described below) has been used by DWR as part of the Central Valley Flood Protection Plan (CVFPP). Other possible methods for planning for increased flood severity include applying a large uncertainty buffer to existing floodplain analyses. For example, one CWP recommendation is to refrain from placing critical infrastructure within 200-year floodplains (DWR 2009). DWR maintains the best available floodplain mapping throughout the state at: http://www.water.ca.gov/floodmgmt/lrafmo/fmb/fes/best_available_maps/. This data is a useful starting point for any flood planning exercise.

DWR's FloodSAFE is an integrated system-wide approach for sustainable flood risk management (http://www.water.ca.gov/floodsafe/). FloodSAFE manages several projects, including the Central Valley Flood Protection Plan (CVFPP), which is scheduled to be adopted by July, 2012 by the Central Valley Flood Protection Board. The FloodSAFE web site contains resources for many flooding topics, including progress on the CVFPP.

5.3.6.1 Threshold Analysis

A threshold analysis approach is being developed by DWR. The CVFPP will describe a system-wide approach for implementing possible future flood management improvements in the Central Valley, with a focus on lands currently protected by the State Plan of Flood Control. Planners may choose to tailor the threshold analysis approach described in the CVFPP Threshold Analysis Work Plan (DWR 2010d) (Work Plan) to their region. This subsection's methodology is based closely on the CVFPP Work Plan.

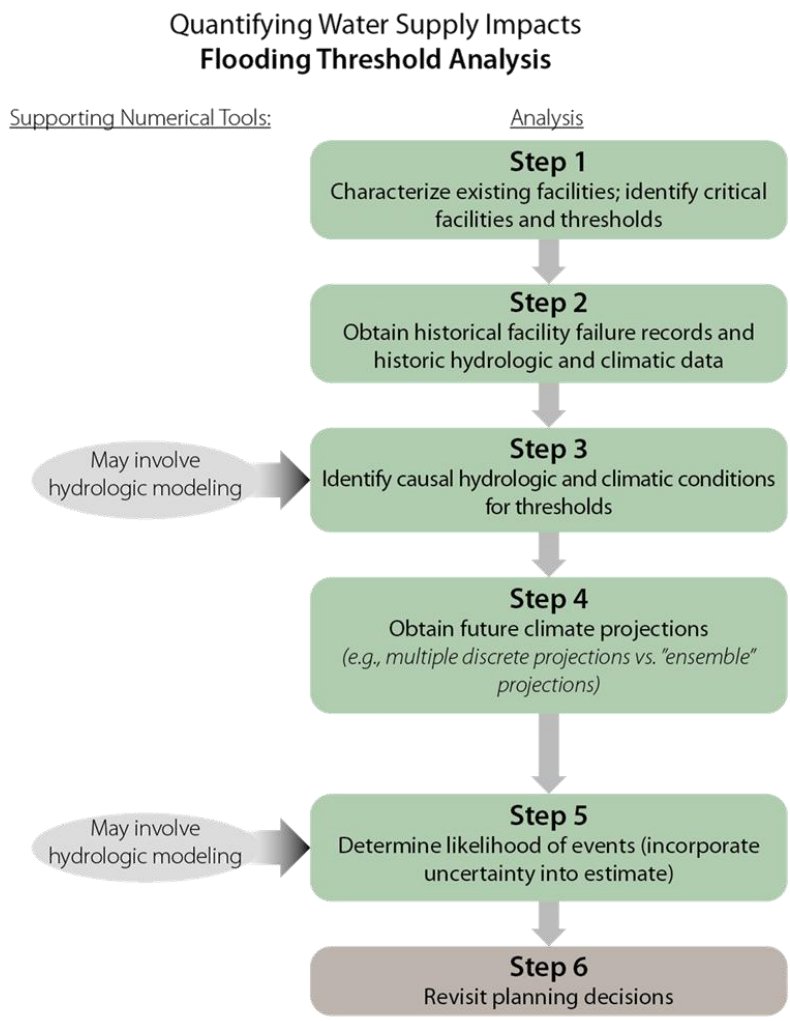


Figure 5-13: Flooding Threshold Analysis Process Flow-chart.

Data Needed

This analysis requires knowledge of current water systems in the region, including existing floodplains and flood control infrastructure. If an existing regional hydrologic model exists, the process of obtaining data and assessing the current regional flood control systems may be facilitated. Historical data relating past flooding events to hydrologic and atmospheric conditions is also needed.

Conducting the Analysis

The threshold analysis approach developed by DWR follows the following components:

- Identify critical components (e.g., levees), thresholds (e.g., conditions for levee failure), and consequences (e.g., flooding, resulting in property damage and economic losses);
- Identify climatic and hydrologic conditions that will result in crossing thresholds; and
- Characterize likelihood of conditions that result in undesirable consequences.

Thresholds

Characterizing and describing the regional flood management system and operations is an important first step to assessing thresholds. Of the many critical components and thresholds identified in the Central Valley system, examples include levee failure, objective reservoir release exceedence, and uncontrolled releases from major flood control reservoirs. This process of identifying particularly vulnerable facilities is similar to the vulnerability assessment

described in Section 4 of this handbook. Thresholds can be framed in terms of performance metrics identified in an IRWMP.

Causal conditions

Once key thresholds have been identified, the hydrologic and climatic conditions that could lead to approaching thresholds are identified. The CVFPP Work Plan Identifies hydrologic and atmospheric metrics that help characterize causal conditions. Hydrologic metrics discussed in the Work Plan include:

- 3-day and instantaneous peak flow,
- Flow volumes over several-day increments (1-day through 30-day),
- Flow duration,
- Inundation duration,
- Seasonal flow timing, and
- Time to peak flow.

Atmospheric metrics discussed in the Work Plan include:

- Atmospheric river index,
- Freezing elevation, and
- Rain-on-snow events.

Likelihood

Estimating the likelihood of specific atmospheric metrics may be difficult to do using GCM results, though it is possible to follow extreme event sampling (the CVFPP Work Plan describes a methodology for extreme event GCM sampling). However, because the GCMs are not designed to represent extreme events, qualitative methods may also be used to develop scenarios or assumptions about future extreme weather events. Qualitative assumptions and expert opinions may be used to develop likelihood brackets. Sensitivity analyses can also be used to assess the climatic conditions that would result in thresholds being crossed.

Incorporating Uncertainty

Uncertainty in threshold flooding analyses has several sources:

- Our limited understanding of existing facilities. A threshold analysis relies on an accurate assessment of thresholds that would result in undesirable consequences. It also relies on a solid understanding of the consequences that would result from a critical facility failure.
- Hydrologic and climate variability. Fluctuations in climate and hydrology at annual or sub-annual time scales are not predictable and often are viewed as effectively "random" for planning purposes.

- Our estimates of how likely certain events are. While it is likely that severe storm events will become more frequent as the climate warms (CCSP 2009), assessing likelihood of specific precipitation events and resulting hydrologic responses is difficult to do using available science.

Potential Performance Metrics

The various consequences identified with threshold exceedences may include undesirable events, such as casualties and economic damage. The risk associated with these events may be a metric used to evaluate potential flooding impacts under various project alternatives. Exceedance thresholds such as 100-year protection might be an appropriate performance metric; however, such metrics may be moving targets if climate change alters the recurrence interval for extreme flooding events.

5.3.6.2 Flood Assessment in the Central Valley

Within the Central Valley, the 200-year floodplain is the standard for planning purposes. These maps are available from the DWR database. The CVFPP has completed a draft scope report that identifies methods for taking climate change into account in future work (DWR 2009). Following recommendations in the scoping report, the Climate Change Threshold Analysis Workgroup developed the Work Plan (DWR 2010d) discussed above. The results from the Flood Protection Plan will require cities and counties in the Central Valley to modify their general plans and zoning accordingly, and comply with the required level of flood protection.

Regions within the Central Valley will be able to make use of CVFPP results and materials for planning purposes. FloodSAFE is an excellent resource for up to date information (http://www.water.ca.gov/floodsafe/).

5.3.7 Hydropower

Hydropower production could be impacted by shifts in streamflow timing that result from climate change. To quantify this loss in power production, it is possible to incorporate climate change into a power production model (Vicuña et al 2009, Chung et al 2009). The steps for this type of analysis are similar to the steps for a watershed model created for water supply analysis (see Section 5.3.2, Figure 5-7).

Data Needed

The information required to calibrate a dam operation model to an existing system includes:

- Historical streamflows entering the reservoir;
- Historical precipitation and evaporation rates for the reservoir;
- Historical and anticipated future dam operations rules , including:
  - Environmental flow release requirements,
  - Downstream water demand requirements,

- Power production objective,
- Any other flow-related constraint or objective,
- Weighting of flow requirements and objectives, and
- Flood protection rule curves (required flood storage space),

- Future streamflows impacted by climate change.

Future streamflows under climate change conditions may be obtained from a hydrologic model (see Section 5.3.2), or by adjusting historical flows, according to general trends projected in the literature for streamflow, as climate change becomes more evident (i.e., earlier snowmelt).

Conducting the Analysis

A model that has been calibrated to accurately represent historical dam operations can be used to assess impacts of climate change by using the model to analyze potential future streamflow scenarios that incorporate the likely impacts of climate change.

Incorporating Uncertainty

Uncertainties associated with future hydropower projections include:

- Our limited understanding of how the physical system responds to climate and other variables (i.e., gaps in the science of the hydraulic and hydroclimate system).
- Numerical accuracy of the hydrologic models. This uncertainty is associated with limitations of the underlying mathematical equations and the way the model solves these equations. There is also uncertainty associated with the assumption that the historical calibration dataset is comprehensive enough to provide a representative calibration for use in projecting the future.
- Hydrologic and climate variability. Fluctuations in climate and hydrology at annual or sub-annual time scales are not predictable and are often viewed as effectively "random" for planning purposes.
- Operational changes that may take place in the future.
- Water use changes in the future with diversions from, and return flows to, streams.
- Future changes in regulations and instream flow requirements.
- Projections of future conditions, including future land use and land cover, infrastructure development, and climate variables (step 3 in Figure 5-7).

As above, a suite of model simulations might be developed based on different assumed future climate conditions. These climate scenarios might be combined with a range of operational assumptions to arrive at a set of model projections that capture a degree of the uncertainty inherent in the analysis.

Potential Performance Metrics

Potential performance metrics include loss in power production or shifts in timing of power production.

Using the information and resources provided in this section, the reader should now be able to:

- Select an analytical approach for measuring the impacts associated with each of the vulnerabilities identified in the Vulnerability Assessment step,
- Gather the necessary data required as input for the analysis,
- Decide on a set of assumptions or scenarios that will represent how the region characterizes future climate, and
- Conduct the analysis.

  The result of these activities will be: 1) a set of projected future conditions that assume some level of climate change occurring over the planning period, and 2) a performance metric for each sector or resource identifying how well that sector is projected to perform. The performance metrics should directly reflect a project's contribution toward meeting the objectives of an IRWMP.

5.4 Summary

This section provides information on:

- Determining the level of sophistication appropriate for a region's highly prioritized climate vulnerabilities,
- Resources available for defining future climate variables to use to conduct many types of quantitative and/or qualitative analyses of many types of water resource vulnerabilities, and
- Resources available for conducting various types of quantitative and qualitative analyses for many types of water resource vulnerabilities.

While this section discusses many analysis tools and methods, it is not comprehensive. Planners are encouraged to ensure that the analysis methods they use for planning purposes are both appropriate to their needs and current to scientific advances. The data sources and tools in Appendix D may also be a useful resource for this exercise.

Results from the analyses conducted in this section are useful in quantifying performance metrics to help planners evaluate projects and identify the need for additional projects in a planning portfolio. This process is discussed in Section 6.