Climate Change Scenarios for Pacific Northwest Water Planning Studies: Motivation, Methodologies, and a User's Guide to Applications

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Overview

This document describes the motivation for this project, the design goals for the streamflow scenarios, and the technical methods that have been used to produce the scenarios based on linked climate and hydrologic model simulations. Some notes on the use of the scenarios for water planning and some strategies for coping with climate uncertainty in the planning process are also included.

Motivation for the Project

During an upper level policy workshop on climate change (Skamania, 2001) a number of specific action items for facilitating appropriate water planning to cope with potential changes in climate were proposed. Two of these were:

- target existing water planning groups and planning studies at the river basin scale,
- and provide freely available climate change streamflow scenarios to help reduce the costs of including climate change information in planning.

This project was designed to respond to these recommendations.

Designing Appropriate Linkages Between Hydrologic Research and Water Planning Studies

Potentially significant changes in regional climate over the time horizon for water resources planning may create new challenges for risk assessment and the development of appropriate adaptation strategies. An important first step in assessing vulnerabilities to an altered climate (and ultimately creating viable response strategies) is understanding the implications of potential changes in hydrologic variability. In the Pacific Northwest (PNW), climate change is likely to produce reductions in snowpack which would reduce summer and fall streamflows, and increase flows in winter. Hydrologic models can be used to predict such changes, however planning functions at many water management agencies tend to be linked to specific periods of the historic streamflow record and internally developed water management models. Incorporation of climate change into water planning studies has therefore been somewhat hampered by the lack of freely available streamflow scenarios that produce appropriate perturbations to the specific historic record(s) of interest. Given a set of adjustments to the historic streamflow record that reflect alternative future climates, there is little additional cost associated with including this information in an existing water planning study. The streamflow scenarios are simply substituted for the historic flow record.

Another reason for creating climate change scenarios based on the historic record is that institutional memory regarding climate variability is frequently linked in water management agencies to case histories of the effects of particular water years on system performance. This suggests that simulating the effects of climate change on the historic record will tend to promote a better understanding of the potential changes than would a fully synthetic representation of the altered variability.

Climate Change Scenarios

The climate scenarios developed in this study are based upon monthly summaries of regional changes in mean precipitation and temperature simulated by several global climate models for two future decades (2020's and 2040's), following the methods developed in Hamlet and Lettenmaier (1999). Four global climate model scenarios were selected for this study based largely on the relatively high spatial resolution of the models and the use of sophisticated land surface schemes that simulate the effects of vegetation and runoff mechanisms. These scenarios are all based upon essentially the same greenhouse gas forcing scenario (IS92a or 1% increase in equivalent CO2 per year), which may be considered a "middle-of-the-road" scenario. Figure 1 shows the changes in temperature and precipitation for the PNW associated with these four models with respect to long control runs. Note that all the models predict significant future warming, but the seasonal patterns of warming, and the changes in precipitation are frequently significantly different between models. Climate models are generally acknowledged to be more successful at simulating regional temperature than they are at predicting regional precipitation, so the temperature changes predicted by the models are projected with higher confidence than the changes precipitation. It should be noted that these simple scenarios do not explore the issue of changing temporal of spatial variability of temperature and precipitation. Rather they explore the effects of regional scale shifts in monthly means overlain on the temporal and spatial variability of the historic record. Given the objective of this study, which is to "adjust" a given set of historic naturalized streamflows in a clearly defined manner, a simple perturbation of the observed climate record was felt to be appropriate. The goal is to allow water planners to explore, in quantitative terms, the question, "What would water year XX from the historic record look like under a global warming scenario?"

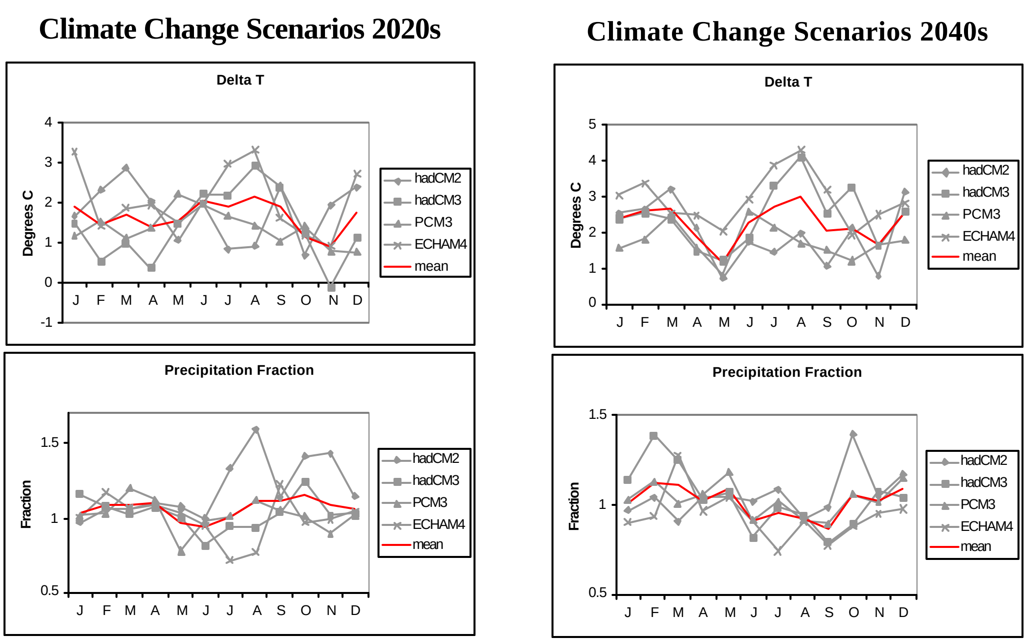

Figure 1 Changes in temperature and precipitation for four climate change scenarios for the Pacific Northwest for the 2020s and the 2040s. "Delta T" is the change in monthly temperature (future climate minus current climate). "Precipitation fraction" is the ratio of future precipitation to current climate precipitation (future precipitation/current precipitation).

Hydrologic Model

The Variable Infiltration Capacity (VIC) macro-scale hydrologic simulation model implemented over the Pacific Northwest (PNW) is used in this study to quantify the effects of changes in precipitation and temperature in the climate scenarios. The VIC model simulates the effects of various hydrologic processes at the surface and in the first several meters of the soil column, including the effects of vegetation on evapotranspiration, canopy interception of rain and snow, snow accumulation and melt, etc. The primary hydrologic outputs for generating streamflow are baseflow and runoff from each grid cell in the model. These data are post processed using a routing model to produce daily time step simulations of natural streamflow at a number of points in a simulated channel network. The daily time step numbers are aggregated to monthly mean values for this study. Figure 2 shows a schematic of the VIC model and the channel network for the 1/8 degree implementation over the Columbia River Basin.

Variable Infiltration Capacity (VIC) Model

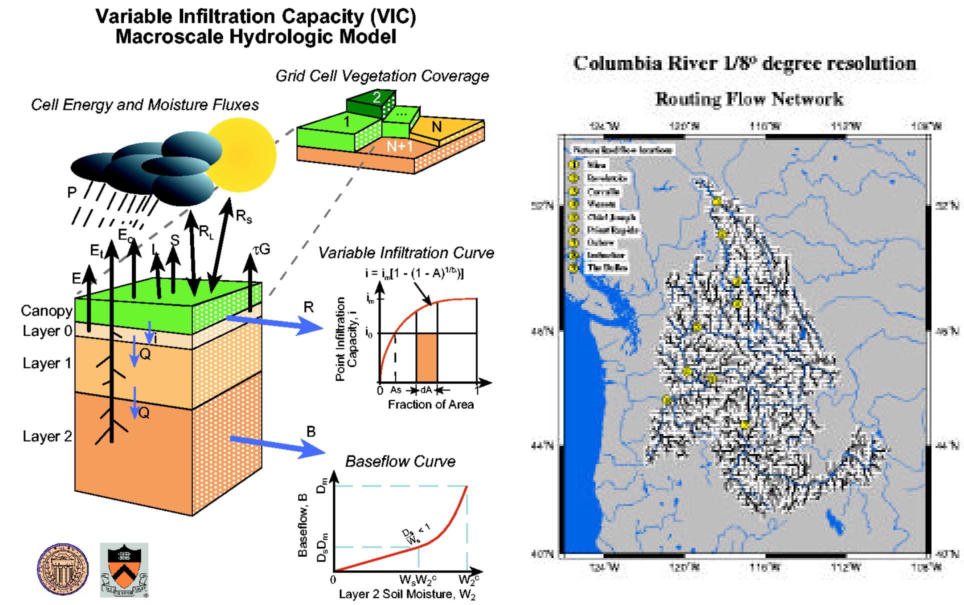

Figure 2 Schematic of the land surface scheme in the VIC hydrologic model and the simulated channel network for the Columbia River at 1/8th degree resolution

VIC does not simulate hydrologic processes associated with groundwater or groundwater/surface water interactions. Thus the changes simulated by the model are associated only with changes in surface water processes. In areas where significant interactions between ground water and surface water are present (and could potentially be altered by changes in climate), these scenarios should be used with a clear understanding of their limitations. The adjustments to the historic streamflow record we employ here assume that the groundwater component of the observed streamflows remains constant with time.

The hydrologic scenarios are produced by perturbing the historical meteorological driving data for the hydrologic model (based on the changes in precipitation and temperature predicted for each climate change scenario) and then running the hydrologic model for this altered climate. Thus an altered version of the historic streamflow record is produced, which may be compared with the historic streamflow record for the current climate in a planning context.

Although the VIC hydrologic model successfully captures many important features of PNW hydrologic variability, like all hydrologic models, the model output is sometimes biased in comparison with naturalized observations, and also contains random errors associated with errors in the driving data, uncertainties in parameter estimation during calibration, etc. Although these kinds of systematic errors are often secondary to the problem at hand, in practice hydrologic model bias can create difficulties when using simulated streamflow data in a water planning study, because a direct comparison of results derived from the historic streamflow record may yield "apples and oranges" comparisons that are difficult to interpret. Bias correction techniques can largely eliminate these kinds of problems without significantly distorting the important physically-based signals produced by the hydrologic model.

Bias Correction Techniques

The simplest kind of bias correction corrects for a systematic discrepancy in the mean by "rescaling" the mean of the simulations to match the observations. Similarly, a discrepancy between the variance of the simulations and the observations can be corrected by assuming a probability distribution (such as the normal distribution) and mapping normalized anomalies (i.e. standard deviations from the mean) between the simulated and observed populations. In many cases, however, the true form of the probability distributions of the simulated and observed data are not known with any certainty and the two probability distributions are not necessarily of the same form or statistically well behaved. In these cases a "quantile-based" bias correction scheme can be used to "translate" between the simulated and observed populations (see Wood *et al*., 2002). In this technique, simulated and observed data covering the same period of record are used to create a "quantile map" of each population using an unbiased quantile estimator (e.g. after Cunane in Maidment *et al*., 1993) applied to ranked data. Figure 3 shows the sequence of steps in extracting a bias corrected value from a simulated value using a quantile-based bias correction scheme. A simulated value is the input to the process and is associated with a particular quantile in the simulated distribution (i.e. the simulated value to be bias corrected is associated with the Xth percentile in the simulated distribution). This same percentile is extracted from observed distribution (i.e. the Xth percentile in the observed distribution is identified) and this quantile in the observed distribution becomes the bias corrected value.

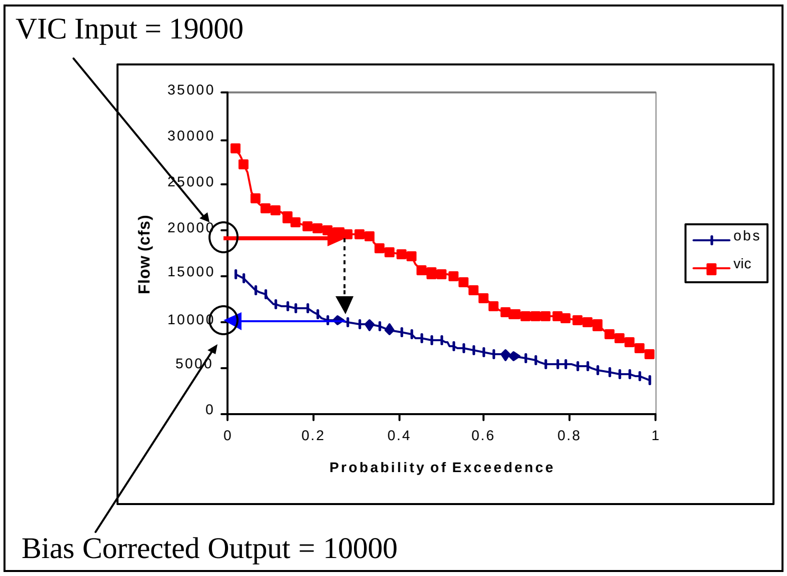

Figure 3 Illustration of quantile-based bias correction scheme (after Wood *et al*. 2001)

If the simulated values to be bias corrected come from the same population as the simulated training data, it is expected that this bias correction scheme will tend to translate the simulated data so that the probability distribution of the bias corrected values closely resembles that of the observed training data. If a group of simulated values have a particular "signal" contained within them, the translation process will tend to reproduce in the output the signals present in the input. An extremely wet hydrologic simulation, for example, will always map to an extremely wet observed value. As long as the fundamental physical processes that define the quantile map for the simulations are not significantly altered over time and the simulations capture the essential signals accounting for variability, the bias correction scheme should produce a reasonably undistorted "image" of the raw simulated data in the observed space. Figure 4, for example, shows bias corrected streamflows for the Columbia River at The Dalles, OR for WY 1991-1996, using quantile maps created using data from WY 1950-1989. Note that the training data for the bias correction process and the test data are independent in this example.

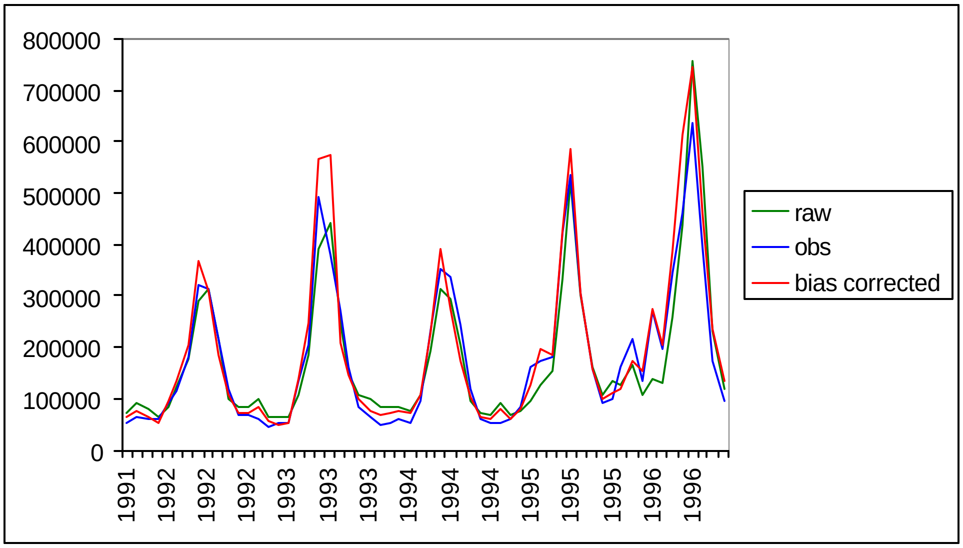

Figure 4 Bias corrected simulated streamflows for WY 1991-1996 compared to naturalized observations for the (Columbia River at The Dalles, OR).

Note also that there are errors in the hydrologic simulations that are not associated with systematic model bias. The discrepancy in observed and simulated peak flows for WY 1993, for example, are probably attributable to spatial errors in precipitation data. These kinds of errors in individual months of particular water years are largely removed by the final step of the data processing sequence described below.

In the context of simulating climate change streamflow scenarios, several other potentially important problems emerge that are not present in bias correcting simulations of the "current climate" described in the preceding paragraphs. Firstly, the simulated value may be outside the range of the simulated quantile map. It is straight-forward to extend the simulated and observed quantile maps with a fitted distribution, and this theoretical distribution can be used if the simulated values are not too far outside the range of "current climate" simulations. For values far outside the range of simulations for the current climate (which can occur because of shifts in streamflow timing), the "observed" quantile maps for the climate change scenario are not known, and a very simple rescaling procedure based on the long term mean is probably as effective as any other technique (and is used here). Figure 5 shows the decision tree used in this study for selecting the primary bias correction technique.

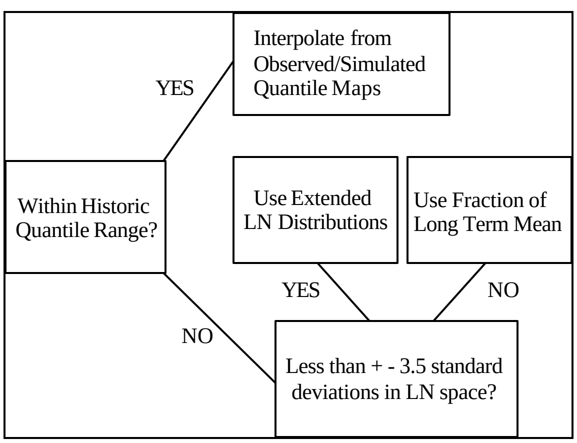

Figure 5 Decision tree for selecting the primary bias correction scheme for the hydrologic model output

The second problem that can occur is that in the process of bias correcting individual months, annual streamflows (which hydrologic models usually simulate quite well) may be distorted. For example, in a climate change simulation, the bias corrected annual mean flow may be 75% of the current climate values for the same year, but the sum of all the monthly bias corrected values may be 80% of the current climate values. To remove this artifact of the monthly bias correction process, each month of the bias corrected simulation ("bc_climate_change" in the equation below) is multiplied by rescaling factor F defined by:

$$(\text{bc\_annual\_mean\_flow})*12 = (\Sigma\ \text{bc\_monthly\_flow}) * F$$

Thus the bias corrected annual streamflow is exactly reproduced by the rescaled monthly values, but the relative "shape" of the monthly values is defined by the monthly quantile mapping procedure. The correction factor F is usually close to 1.0, so the monthly values are not greatly distorted by this procedure.

A similar problem to that described above can create discrepancies in spatial mass balance at an annual time scale as well. This can occur because each streamflow location is bias corrected independently. To deal with this issue, mass balance is checked starting from the most downstream location and working upstream, and the sum of the upstream sites are then adjusted to exactly equal the downstream flows on an annual basis. Figure 6 shows the four components of the mass balance adjustment for The Dalles (1), Priest Rapids (2), and Ice Harbor (3) in the Columbia River basin. Note the addition of the incremental inflow (which is also bias corrected) to close the water balance equation.

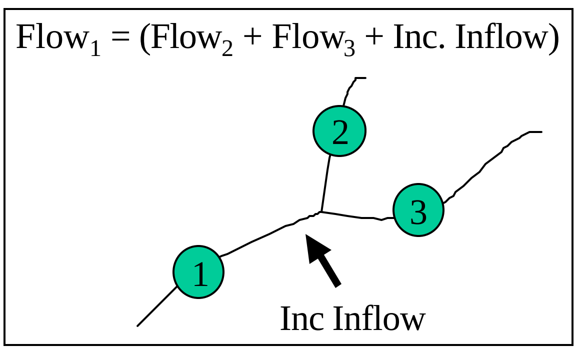

Figure 6 Schematic for mass balance correction in the bias correction scheme

Final Adjustment of Historic Streamflow Record
After hydrologic simulations for both the current climate and the climate change scenario are bias corrected, a time series adjustment to the historic streamflow record is calculated as the difference between the climate change simulation and current climate simulation (i.e. climate change minus currrent climate for each month). This adjustment is simply added to the historic record for each month, which is aligned in time with the simulations. This final step tends to minimize the importance of errors in the hydrologic model simulations for particular months due to errors in driving data, etc. The final product covers only the overlapping period between the historic record and the hydrologic simulations, and consists of an observed naturalized streamflow sequence, and an adjusted record for the same period representing the altered climate. For the pilot project this overlapping period is WY 1950-1989.

Thus the bias correction process has five steps:
1) Quantile mapping between simulated and observed space for each month in the water year
2) Quantile mapping between simulated and observed space for annual mean flow
3) Adjustment of monthly flows to match bias corrected annual values
4) Adjustment of flows at different locations in the channel network to preserve mass balance, moving from the downstream most site to the upstream sites.
5) Application of changes in the bias corrected simulated streamflows to an overlapping period of the historic record.

Figure 7 shows a monthly summary of the VIC simulations before and after bias correction. Note that despite considerable differences between the raw and bias corrected simulations, the climate change signals present in the raw simulations are preserved.

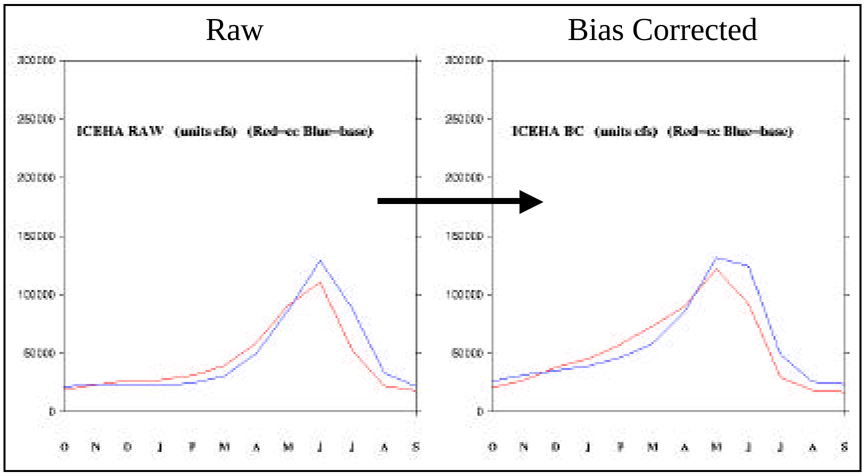

Figure 7 Comparison of monthly mean simulated flows before and after bias correction at Ice Harbor Dam on the Snake River. "CC" refers to the climate change scenario, "base" refers to the simulation of the historic record.

Application of the Streamflow Scenarios to Planning Studies

Figure 8 shows a simple schematic diagram of two key inputs to a water planning study directly affected by climate. Hamlet and Lettenmaier (1999) describe an approach for using climate change streamflow scenarios with a reservoir operations model to assess the sensitivity of a set of reservoir operating policies to altered climate. In practical terms, investigating of the impacts of altered hydrologic variability is a straight-forward process of substituting a simulated streamflow scenario for the historic record of streamflows for a particular period of record. Hamlet and Lettenmaier, for example, used the period from 1961-1997 for the Columbia River basin, and compared four streamflow scenarios to a base case simulation representing the current climate to investigate the sensitivity of the status quo reservoir operating policies.

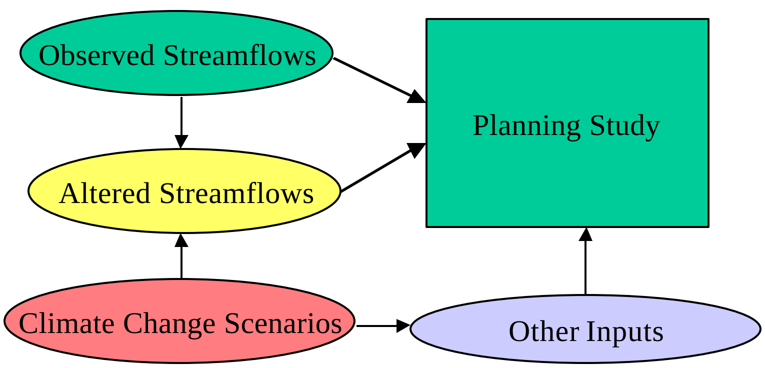

Figure 8 Important inputs to water planning studies affected by climate and linkages to climate change scenarios

In a planning study the process is very much the same, except the process is repeated for a set of projected future conditions (e.g. population growth, demographic changes, etc.), alternative management policies, and infrastructure changes. In some instances, changes in the demand for water, energy, or other externalities that are affected by climate may also need to be considered (e.g. irrigation or urban water demand may be higher in a warmer climate). Thus one or more degrees of freedom are added to a conventional planning study by explicitly considering the implications of altered climate variability.

Coping with Uncertainties

Many kinds of uncertain data and information are typically used in a long-range water planning studies. Considering the implications of potential changes in climate adds more degrees of freedom to such investigations that may make the results of the study more difficult to interpret, but there are no fundamental differences between climate uncertainties and other uncertainties that affect planning outcomes. There are several broad approaches to assessing the results of a water planning study in the context of uncertain climate information.

1) Identify the components of the planning process that are sensitive or insensitive to climate uncertainties
2) Identify planning alternatives that are acceptable and robust to different climate scenarios, even if they are perhaps not optimal under all climate scenarios
3) If no one plan is best under all climate scenarios, then identifying which plan is best for each scenario may be helpful in assessing the ability to respond to evolving conditions.
4) Identify alternatives that are more flexible than others in the sense that they can be substantially altered as uncertain conditions evolve. Such plans may be preferable if the water system is very sensitive to altered climate (and particularly uncertain projections of precipitation variability).
5) Identify plans that have "irreversible" components (e.g. because of investment in infrastructure or other capital expenditures). Such plans may in some cases increase future risks and reduce response capability.
6) Identify "no regrets" strategies that create desirable outcomes regardless of uncertainties.

Long-Term Project Strategy
In the first year of the project, the list of streamflow locations supported by the project and the length of these data records will be expanded to support several ongoing planning studies in the Columbia basin, one at the Northwest Power Planning Council, and the second at Idaho Department of Natural Resources. Among other benefits, we are hopeful that these highly visible planning efforts will help produce a useful "road map" for other water management agencies in the region that may be considering the incorporation of climate information into long range water planning studies. Other regional planning efforts may be supported by the project as time and resources permit. Secondly, additional GCM scenarios representing the range of potential responses of the climate system will be produced.

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