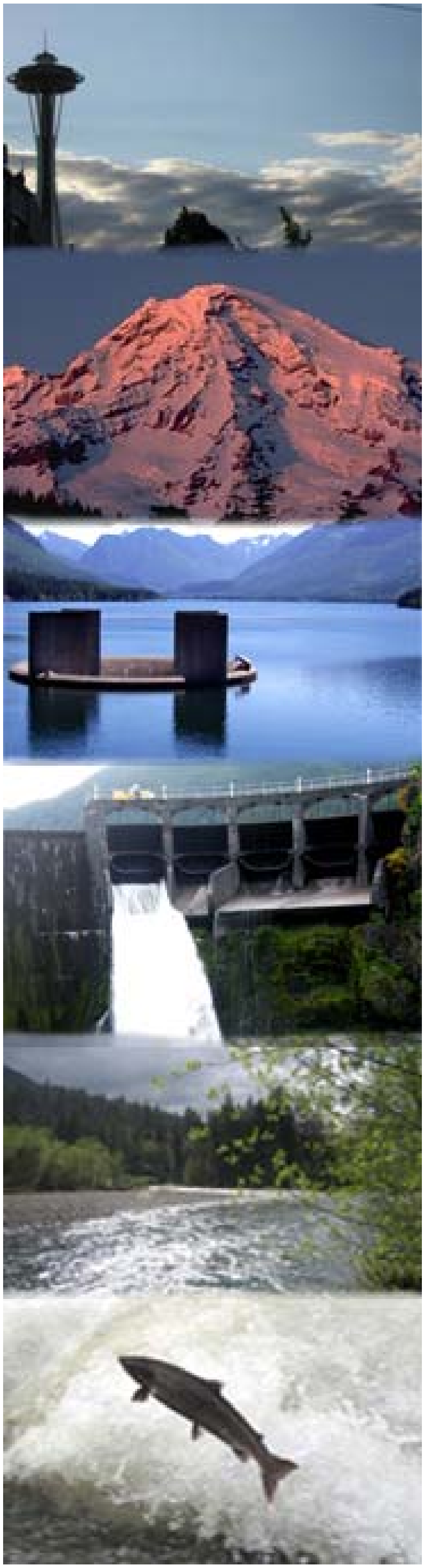

Technical Memorandum #1: Literature Review of Research Incorporating Climate Change into Water Resources Planning

Prepared for:

Climate Change Technical Committee

12/13/2007

Acknowledgments

Funding for the research conducted by the University of Washington for the Climate Change Technical Committee (CCTC) came from Washington State's Department of Ecology, Seattle Public Utilities, Cascade Water Alliance, and King County Department of Natural Resources and Parks. In addition, the members of the committee acknowledge all of the agencies that generously provided staff members and their time to participate in the committee's activities. Funding for the CCTC's facilitator was provided by King County Department of Natural Resources and Parks.

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We would particularly like to acknowledge the efforts of Joan Kersnar of Seattle Public Utilities for her help with editing all of the products of the CCTC.

This document should be cited as: *Alexander, D., R.N. Palmer, and A. Polebitski. 2007. "Technical Memorandum #1: Literature Review of Research Incorporating Climate Change into Water Resources Planning." A report prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process, Seattle, WA.*

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Technical Memorandum #1
Incorporating Climate Change into Regional Water Supply Evaluations

Regional Interest in Climate Change

The Fourth Assessment Report (2007) from the Intergovernmental Panel on Climate Change (IPCC) concludes climate change is a real and pressing issue. To date, four IPCC reports have been published and contain the most extensively peer reviewed critique available on the topic. Beyond the IPCC reports, numerous studies on the causes and impacts of climate change have appeared in the peer-reviewed literature, with a number of these studies being conducted on the Pacific Northwest. Studies suggest that the consequences of projected climate change scenarios are higher winter and spring flows and lower summer and fall flows. These results indicate that the topic of climate change is no less important in the Pacific Northwest, where much of the region has experienced declining snowpack in recent decades (Mote et al. 2000). With expected changes in peak streamflow timing, municipal water supplies throughout the West are facing the potential grim reality of water shortages during peak water demand seasons. Moreover, the projected impacts to salmon and other fish listed under the Endagered Species Act (ESA), indicate that lower summer flows, higher summer water temperatures and increased winter flows will all have negative impacts on fish populations throughout the West and specifically in the Pacific Northwest (Battin et al., 2007).

Many agencies and organizations in the Puget Sound Region are voluntarily participating in a regional water supply planning process for the purpose of identifying, compiling information on, and discussing many of the key issues that relate to or may affect water resources of the region. The goal is to develop the best available data, information, and pragmatic tools that the participants may use, at their discretion, to assist in the management of their respective water systems and resources, and in their water supply planning activities.

To address the issue of climate change and other key issues that relate to or may affect water resources in the region, a regional water supply planning process resulting from the efforts of multiple agencies and organizations is working together in an effort to develop substantive technical information regarding current and emerging water resource management issues in and around Puget Sound. The purpose of the regional water supply planning process is to identify, compile information on, and discuss many of the key issues that relate to or may affect water resources in the region. As part of the regional water supply planning process, a Climate Change Technical Committee was formed and has agreed that climate change should be explicitly considered in evaluating regional water supply, related instream flows, and forecasting water demands.

Goal of Climate Change Investigations for Water Resources

The primary focus of evaluating the impacts of climate change on regional water resources has been to determine the degree to which climate change will impact a system's ability to reliably provide the purposes for which the systems are placed and to determine the degree to which demands for water resources may change. It has been determined that climate change in the Pacific Northwest is likely to result in lower snowpack, change the timing of spring runoff and stream hydrology, and extend the duration and severity of summer low flows. In addition, climate change is expected to increase summer temperatures and evapotranspiration, resulting in increased outdoor water demands during the summer.

The goal of the research that is addressed in this study is limited to evaluating the impacts of climate change on the availability of water. This is accomplished by primarily investigating the impacts on streamflows, specifically focusing on spring and summer streamflows that serve as the major sources of water supply for the Puget Sound area. Potential changes in fall and winter flood flows will also be investigated to help aid in flood management. Further, an equally important goal is to inform regional decision makers on the likely impacts these changes will have on the region's ability to provide water in the future.

Early Climate Change Studies

Evaluations of the impact of climate change in water resources began in the late 1970s. Simple statistical models were first used to forecast the impacts of temperature and precipitation. In the late 1980's, physically-based models, capable of evaluating climatic conditions beyond the range of statistically based models, were introduced. Then, in the late 1990's, in addition to investigating hydrologic responses to climate change, researchers began evaluating the sensitivity of the performance of water resources systems.

Initial interest in the impacts of climate change on water resources were focused on the Colorado River Basin. In the late seventies Dracup (1977) used historical analogies and regression approaches to evaluate the impacts of hypothetical temperature and precipitation changes (Dracup 1977). Then in 1990, using a simple water balance model, Shaake (1990) evaluated the percent change in runoff in watersheds for a specified change in precipitation in the Animas River, a tributary of the Colorado River. Shaake found that changes in temperature would have significant seasonal effects on snowmelt. These results were emulated by a study conducted by the U.S. Army Corps of Engineers on another tributary of the Colorado, the Gunnison Basin, which found that a temperature increase of 2 to 4° C would result in advanced spring snowmelt of close to a month (Dennis 1991; Gleick and Chalecki 1999).

Gleick Studies

Nash and Gleick (1991) used physically-based conceptual hydrologic models to analyze the impacts of climate change scenarios on the Colorado River basin and many of its subbasins. In this study, they incorporated hypothetical temperature and precipitation scenarios and general circulation models (GCMs) available at the time. They also used one of the first GCM models that utilized transient greenhouse gas inputs (as opposed to the CO_2 doubling scenarios typically used).

As with earlier regression studies, flows in the Colorado River basin were found to be sensitive to both precipitation and temperature, resulting in earlier snowmelt and altered runoff; however, less than had previously been suggested. Further results indicated that the variables most sensitive to early runoff included hydroelectric generation, reservoir level, and salinity. While increased flows led to increased reservoir volume and hydroelectricity power and decreased salinity, small decreases in flows result in proportionally greater decreases in reservoir volume and hydroelectricity power and increased salinity, resulting in poor water quality. In fact, a 20% decrease in average natural flow would result in a 60% decrease in reservoir volume and hydropower generation. This study noted the non-linear response to climate change. The authors highlighted the non-linear response of the frequency of uncontrolled spills for various changes in natural flows in the Upper Colorado River Basin. All analysis completed in this study assumed no changes in the operating policies in the basin (Nash and Gleick 1991; Nash and Gleick 1993).

Some of the first studies to identify the effects of climate change on the impacts of snow conditions in snow-melt dominated basins were completed in the 1980’s (Gleick 1986; Gleick 1987). In these studies, Gleick developed a water balance model for the Sacramento River Basin and evaluated the effects of GCM scenarios of climate change on annual and monthly runoff and soil moisture. Gleick identified six major temperature driven effects:

1. Increased ratio of rain to snow,
2. Increased winter runoff as a fraction of total annual runoff,
3. Earlier start and faster spring snowmelt,
4. Shorter snowmelt season,
5. Decreased late spring and summer runoff as a fraction of total annual runoff, and
6. Earlier drying of summer soil moisture.

Chalecki and Gleick (1999) published a comprehensive review of almost 900 bibliographic references analyzing and evaluating the impacts of climate change and variability of water resources in the United States. The authors stated that, “Considerable progress has been made in the modeling of climate change effects on first-order systems such as regional hydrology, but significant work remains to be done understanding subsequent effects on the second-, third-, and fourth-order economic and social systems (e.g. agriculture, trade balance, and national economic development) that water affects.” The authors suggested that scientists should collaborate with social scientists in order to make known the effects of climate change on systems that affect how people live.

Lettenmaier Studies

Other researchers investigated the effects of climate change on the Sacramento-San Joaquin systems. Lettenmaier and Gan (1990) evaluated the hydrologic sensitivities of four medium-sized snow-melt dominated catchments of varying elevations in the Sacramento and San Joaquin River basins by applying CO_2 doubling scenarios simulated from three GCMs to each basin. The hydrologic response of these catchments were simulated by the coupling of the snowmelt and soil moisture accounting models of the U.S. National Weather Service River Forecast System available at the time. The responses from these studies concurred with those of Gleick; more precipitation fell as rain instead of snow, spring snowmelt runoff decreased, winter flood frequencies rose, and summer soil moisture declined.

Lettenmaier and Sheer (1991) used a three-stage approach that investigated the climate impacts of the combined Central Valley Project-California State Water Project (CVP/SWP). The three stages to the study were as follows:

1. Climate input was taken from CO_2 doubling scenarios from three GCMs and used in the simulation of rainfall/snowmelt-runoff models.
2. Using a stochastic disaggregation model, long-term inflows to the CVP/SWP reservoir system were simulated, based on the study catchment flows.
3. Using a reservoir system simulation model, the performance of the reservoir system was evaluated.

Results indicated that significant changes to the annual hydrograph would occur, shifting runoff from the spring to the winter. They also noted increased winter spills due to this shift, and if operational changes were not made, reduced reliability could lead to challenges in meeting system demands.

In 1999, Hamlet and Lettenmaier evaluated the effects of climate change on hydrology and water resources in the Columbia River Basin. The study used two GCM simulations, from the Hadley Centre (HC) and Max Plank Institute (MPI) made available via the National Assessment for climate change, to create inferred conditions for 2025, 2045, and 2095. Monthly temperature and precipitation changes from the GCMs simulations for each time-period were then input into a macro-scale hydrology model. The resulting streamflow simulations for each scenario were then used to drive a reservoir model, ColSim to determine if the current system could meet water resources objectives under an altered climate.

Results from the two GCM simulations illustrated different seasonal patterns of temperature change; however, in general there was good correlation between the two models. Each showed consistent basin average increases in temperature of about 1.8 2.1°C for 2025, and about 2.3-2.9°C for 2045. Only the Hadley model was run for 2095; simulations predicted an annual average temperature increase of about 4.5°C for 2095. Changes in winter precipitation ranged from a -1 percent to +20 percent for the Hadley model and MPI scenarios, respectively. Reductions in future snowpack were significant in the simulations regardless of precipitation changes. Average March 1st basin average snow water equivalents were 75 to 85 percent of normal for 2025, and 55 to 65 percent of normal for 2045. By 2045, runoff volumes from April-September were reduced from 75 to 90 percent of normal, resulting increased competition for water during the spring, summer and early fall between irrigation, instream flow, non-firm energy production and recreation.

In 1999, Lettenmaier et al. studied six water resources systems – the Green River (Tacoma, WA, water supply system), the Boston water supply system, the Savannah River system, the Columbia River system, the Missouri River system and the Apalachicola-Chattahoochee-Flint River (ACF) system – representing a range of geographic, hydrologic, social and institutional settings. The objective of the study was to evaluate and generalize the potential effects of climate change on the performance of multiple use water resources systems. Relative effects of both climate change and long-term demand growth were also studied.

In this study, a series of climate change scenarios were chosen (based on the 1995 IPCC assessment), a series of transient scenarios and a CO_2 doubling scenario; from which, a sequence of models were used to infer the water resources effects for each scenario. Temperature, precipitation and solar radiation were downscaled from the various GCM scenarios and used as forcing sequences for the hydrologic models of each river basin. The hydrologic models generated times series of streamflow, which were then used as inputs to the water resource management models for each of the reservoir systems. Results were significant for each of the climate scenarios and water resource system; however, some general patterns did persist throughout, and some general statements can be made.

- Climate Change
  - Temperature increases for the transient scenarios tended to be smaller than the temperature increase for the CO_2 scenario used in this study and many earlier studies.
  - The transient scenario temperature increases grew progressively (although not always in an evenly distributed manner) throughout the projected time period.
  - Precipitation changes were less consistent than temperature changes. Some scenarios projected increases in precipitation, while others projected decreases.
- Hydrology
  - River basins where snow plays an important role in the hydrology (Tacoma, Columbia, Missouri, and Boston, to a much lesser degree), changes in temperature resulted in changes in streamflow hydrographs.
  - In the Savannah and ACF systems, changes are more directly linked to precipitation and evapotranspiration related to changes in temperature.
- Water Resources Management
  - Changes in runoff and the effectiveness of the system's storage capacity were the most important determinants of system sensitivity to climate change.
  - The vulnerability of system performance to runoff varied from system to system, GCM to GCM, and operating objective.
  - For most sites, the effects of demand growth and other non-climatic effect on future system performance was equal to or exceeded the effects of climate change for the system planning period.

Using a case study approach, Wood et al. (1997) assessed how climate change information could or should be used in water resources systems planning. The authors attempted to determine the extent to which adaptive mechanisms (if any) could be used to protect a system from climate change effects. Specifically, the authors addressed whether planning based on climate change information would be justified.

The paper assessed the possible reallocation of flood storage to municipal water supply storage on the Green River, WA, which supplies water to the city of Tacoma; however the authors used an approach to determine whether climate change information should be used in a planning decision that can be used for any water resource system. The procedure is as follows:

- First, a water resource management decision is made assuming a stationary climate. The decision is evaluated by assessing system performance under current climate conditions and then altered climate conditions.
- Second, the water resource management decision is made based on an altered climate. The decision is evaluated by assessing system performance under current climate condition and then altered climate conditions.
- Third, comparisons of system performance for both the current and altered climate conditions for both decisions are made. From this, the benefit of planning for climate change in the event that it occurs or does not occur can be shown.
- Fourth, this process is repeated multiple times for different climate change scenarios.

For the Green River storage system, it was found that the prospect of climate change did not play an important role in making reallocation decisions for the following reasons:

1. Meeting instream flow at high reliabilities resulted in rule curves that preserved conservation storage.
2. Low autumn flows results in selection of a two-week earlier reservoir drawdown alternative, but did not alter refill timing.
3. Finally, even the most notable difference between the system's simulated historical performance and altered performance due to climate change did not produce large enough differences in M&I benefits to warrant large increases in conservation storage.

The authors, however, suggested that, using the same methodology, there were likely other water resources systems for which the outcome would be opposite.

Kirshen Studies

Kirshen (2002) evaluated the potential impacts of climate change on a highly permeable, unconfined aquifer in Eastern Massachusetts. Using the groundwater model, MODFLOW, calibrated and verified for the area, he analyzed the impacts of several mean and drought climate change scenarios for the years 2030 and 2100. The study assumed there would be no increases in water demands from the aquifer.

In this study, two 2030 mean scenarios were chosen, one which assumed a 1°C increase in annual average temperature, and one which assumed a 1°C increase in annual average temperature (S1) and 10% increase in annual average precipitation (S2). The temperature and precipitation changes were selected for their similarity to several GCM scenarios.
Based on the U.S. National Assessment recommendations, results were taken from the Canadian Climate Center (CCC) and used as the basis for the mean and drought conditions for year 2100. For the 2030 extreme conditions event, a 20-year drought condition (annual precipitation at a non-exceedance probability at the 5 percentile level) was used.

Results indicated that for 2030 mean climate conditions, impacts on groundwater elevation and recharge may not be significant or may even be beneficial. Under 2100 mean climate conditions, the impacts were sensitive to actual evapotranspiration estimates and could be positive or negative. Drought scenarios for 2030 and 2100 resulted in neutral or harmful effects on groundwater elevation and recharge, respectively. Each of the climate scenarios had differing impacts on water supply potential.

Key Issues in Evaluating the Impacts of Climate Change

General Circulation Models

The most common method for including the impacts of climate change in the evaluation of water supplies is through the use of a climate model. The Intergovernmental Panel on Climate Change (IPCC) defines a climate model as a,

> *"…numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity, i.e. for any one component or combination of components a hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parameterizations are involved. Coupled atmosphere/ocean/sea-ice General Circulation Models (AOGCMs, or GCMs for short) provide a comprehensive representation of the climate system. There is an evolution towards more complex models with active chemistry and biology. Climate models are applied, as a research tool, to study and simulate the climate, but also for operational purposes, including monthly, seasonal and interannual climate predictions"* (IPCC 2001a).

The Pacific Institute has compiled an on-line bibliography of over 920 studies of climate change and impacts in the U.S. alone (Chalecki and Gleick 1999). The majority of these studies use GCMs to simulate the state of future climate variables. The effectiveness of GCMs in studying climate change depends on the level of complexity and ability to simulate the main physical processes that effect climate. The IPCC's Third Assessment Report identifies more than 30 GCMs that have been used to study climate change (IPCC 2001a).

General Circulation Models (GCMs) share a number of characteristics that are common to all models that attempt to simulate natural processes. These characteristics include the model's spatial resolution, the type of processes included, and their approach to flux adjustments. All GCMs represent the land, air and water of the earth as a series of three dimensional cells. Each cell is analyzed individually, and the flux of energy and mass across each of the cell's surfaces serve as inputs to the adjacent cells. The physical phenomenon influencing atmospheric and ocean processes are calculated at a resolution defined by the cell size. Cells are described by their two dimensional projection on the earth, (as area), and by their depth (as height). The resolution of a GCM typically refers to the size of the cells associated with the most important physical process. Different GCMs have different resolutions; additionally the resolution of the various physical components that comprise a GCM can also vary within a specific model.

The resolution at which a model simulates phenomenon affects both the computational requirements and the complexity of the modeling details. The resolution of available GCMs ranges from 2.0 to 5.6 degrees (latitude or longitude) with between 9 and 30 layers for the atmosphere, and 0.67 to 5.6 degrees with 12 to 45 layers for the ocean. Greater resolution may increase the potential for accurate projections at a given point. GCMs contain several components. Less sophisticated models have been used to successfully simulate the dynamics of the individual components of the earth system. GCMs typically are comprised of multiple models, each representing a different portion of the greater climatic system. Climate models which contain several linked models are referred to as coupled models. The principal components of coupled models are the: Atmosphere, Ocean, Sea Ice model, Land Surface (including river flows and terrestrial cryosphere).

In coupled models, multiple components act individually to model different aspects of the total global climate. Each component is generally developed separately and operates with its own set of input and output parameters. A coupled model connects disparate components via a coupler. The coupler interprets the inputs and outputs from the individual components and integrates the flow of data between different components. This arrangement makes possible the use of model components using different resolution scales.

In their earliest versions, most GCMs required the use of flux adjustments to accurately simulate the present day climate (IPCC 1996). Flux adjustments are empirically derived constants for the heat, water, and momentum exchanges between the atmospheric and oceanic components of the models. These adjustments are not based on physically observed phenomenon. Flux adjustments were necessary to prevent drift in model results. Flux adjusted models are able to reproduce the current climate accurately. However, the uncertainty added by the necessity of flux adjustments has encouraged model builders to improve models so that flux adjustment is not needed (IPCC 2001).

Large supercomputing facilities are required to operate climate models. The computational time required is typically on the scale of several hours per year of modeled time. For this reason, the most accepted, reliable, and verifiable GCMs have been developed, maintained and operated by large research institutions, often associated with national laboratories. Results from GCM scenarios are frequently made available to the scientific community through data archives accessible over the internet. The IPCC and the institutions at which the models are developed maintain databases of output from the many different models over several different forcing scenarios. Model output consists of climatic data such as temperature, precipitation, air pressure, humidity, and wind speed, given for a network of grid points which cover the Earth's surface. Although GCMs operate at a time step on the scale of hours, due to the volume of data generated, the output is typically aggregated and stored as monthly means and totals.

Because GCMs are highly complex models, incorporate different assumptions, use different inputs, and operate at different levels of resolution, the output of the models vary. Indeed, the same GCM can generate different versions of the future, depending upon the input used in the model. The fact that slight variations in input can result in different outputs is a function of the level of complexity of the models and the fact that the models include many non-linear relationships between variables. These models can provide ranges of future scenarios that can be used to estimate future climate conditions.

Because GCMs do not provide a single version of the future, it is common to make use of ensemble runs of a GCM or several GCMs in single climate impacts study. Using several GCMs provides a range of potential results and permits the calculation of a central tendency from the models. Both the central tendency and range of results can be useful in decision making.

Downscaling

Why do it?

General Circulation Models (GCMs) simulate climatic variables at a coarse scale relative to regional scale processes. Even the latest versions of GCMs, such as those used in IPCC A4 simulations, use a grid-scale of approximately two-degrees latitude by two-degrees longitude for efficient computation. This coarse spatial resolution prevents many individual and sub-grid scale processes from being resolved properly, particularly those in which the hydrologic cycle depends (Wilby et al. 1999). Essentially, the GCMs represent the earth as a smooth surface, thus the topographic features that cause spatial variation in weather are not represented. To improve or account for these sub-grid processes, such as topographic and spatial variation in climatic variables, a method that appropriately scales the coarse output to a finer resolution is needed. Downscaling processes transfer a spatially coarse dataset to a finer resolution, while preserving the climate signals from the GCM, whether it is simulation of historic or future climate periods. Many studies have found that downscaling methods are capable of representing mesoscale spatial patterns that are not accounted for by the GCMs (Schmidli et al. 2006; Wilby et al. 1998; Wilby et al. 1999). Though some uncertainty is added to climate impact analyses when downscaling is introduced, there is an overall reduction in uncertainty and an increase in climate projection accuracy (Wilby et al. 1999). The downscaling method used for evaluating local impacts as part of the Regional Water Supply Planning Process is the quantile mapping method. This method is fully described in Salathé et al. (2006), but originates from research first performed by Wood et al. (2002) for long range forecasting.

What are the approaches?

There are many approaches to downscaling (Wilby 1998 et al.; Murphy 1997 et al.; Salathé 2004; Salathé 2006 et al.; Wiley 2006 et al.; Wood et al. 2002) and these approaches can be placed into two major categories: dynamical and statistical downscaling. Each downscaling method has certain advantageous properties relative to others, as well as biases, though in general they all improve mesoscale features of the climate projections generated by GCMs.

Dynamical Downscaling

There are several methods used in dynamical downscaling; however, the most common method utilizes a higher-resolution regional climate model (RCMs) nested within a GCM to generate regional climatic and weather patterns. These higher resolution regional models are capable of simulating fine-scale physical processes that GCMs commonly parameterize. RCMs can be as complicated and computationally intensive as GCMs because they contain the same and typically more physical equations, but operate at a smaller scale, finer resolution, and involve more non-parameterized variables. To better represent regional scale weather patterns, RCMs incorporate detailed topography as part of the model. This adds another degree of complexity compared to GCMs.

Dynamical downscaling methods, especially use of RCMs, have an advantage over statistical methods in that weather patterns can change dynamically with the GCM forcing. Extreme events, such as high winds or heavy precipitation are typically resolved better in mesoscale models than in statistical downscaling methods. This is also true for cloud cover. Although dynamical downscaling offers an arguably more accurate representation of climatic variables, it comes at the price of high computational needs, use of an additional complex model in the climate impact assessment process, and long run times to generate a single trace of data.

It is important to emphasize the current computational limitations associated with downscaling. For evaluating water resources reliability, typically 50 to 100 years of data are used. Dynamical downscaling may be able to produce a climate impacted record of this length given considerable time, but only for one GCM and scenario. At this point in time, there are no such examples of dynamical downscaling in the literature.

Statistical Downscaling

A variety of statistical methods exist for relating macro-scale processes within a GCM to sub-grid resolution. These include use of stochastic weather generators, multivariate regression, empirical orthogonal function (EOF) analysis, neural networks, and quantile mapping. All statistical methods provide varying degrees of resolution and accuracy of sub-grid scale processes. Statistical downscaling has been applied to many water resources studies for mid range forecasting and climatic change studies. (Hamlet et al. 1999; Lettenmaier et al. 1999; Van Rheenan et al. 2004; Wood et al. 2002; Wood et al. 2004; Wiley et al. 2006) Statistical downscaling is commonly applied in one of two ways, a dynamic fashion or as a perturbation of historic climate records. The dynamic statistical method utilizes GCM output on a daily, weekly, or monthly time-step and generates a future time series that is purely dictated by the GCMs climate output.

Stochastic weather generators and multivariate regression are common approaches used in this statistical downscaling process. The second statistical downscaling method relies on historic climatology to which GCM output is mapped. This mapping is used to transform the historic climatology to match the GCM's future climatology while retaining many of the statistical parameters contained in the historic record. This mapping of a simulated future climate on historic climate is referred to here as the quantile mapping process.

Statistical downscaling offers an arguably more flexible, computationally efficient, and less complex approach than dynamical downscaling. Coupled with a GCM, statistical downscaling can provide reasonably accurate projections of current climate and aids immensely in translating GCM output for future climate scenarios. The use of historic climatology in statistical downscaling can provide water resources utilities with an altered climate record that is familiar, yet contains projected climate patterns to provide a glimpse of what a changed climate may bring.

A drawback to statistical downscaling methods, specifically the quantile mapping process, is that unforeseen changes in weather patterns that might arise due to a warmed climate are not fully evaluated. There are two main reasons for this: 1) the topography is not well resolved in the GCMs, and 2) small scale effects such as convergence zones are only represented by the historical observations. The quantile mapping method partly overcomes this by relying heavily on long historic records at specific locations that represent regional climate well, thus retaining historical variability in the future output. By coupling a hydrology model that distributes temperature and precipitation variables spatially, a reasonably accurate representation of projected climate impacts to variable, such as streamflow, can be created.

Emphasis on statistical – bias correction and quantile mapping

Wood et al. (2002) first proposed bias correction through quantile mapping methods for use in long range forecasting in the eastern US. This method relates cumulative distribution functions of GCM output to historic climate data. The relationships, or transfer functions developed, are used to bias correct the poor agreement between the GCM grid, which does not account for land surface heterogeneities such as orography, and historical values aggregated to the same grid size. The transfer functions are applied to GCM output simulating future climate, making the projected climate output from the GCM more usable for water resources studies.

The bias correction method was modified by Wiley et al. (2006) to investigate climate change impacts specific to water resources management. The modified method uses a two-step transformation. One transformation bias corrects the GCM grid-level output to a regional grid of 1/8 degree resolution. A second transformation function bias corrects regional grid level data to specific stations. These relationships are applied to output from GCM simulations of future climate, resulting in projected monthly temperature and precipitation values.

To utilize the full range of historic variability in the historic record, a time-series expansion approach is developed. The time-series expansion approach uses a thirty-one year slice of the projected future climate data and applies the differences from the historic climate onto the daily meteorological dataset. This generates a quasi-steady-state dataset (i.e. climate indicative of a specific period) for a decadal era of interest in the future, such as 2025, 2050, or 2075.

Limitations

The quantile mapping method uses projected future climate data to alter historic records, yielding a dataset that incorporates the entirety of observed natural variability within a region. The downscaling method does not explicitly account for changes in climate that may occur from shifting weather patterns on a meso- or micro scale. Sub GCM grid shifts in circulation due to warming may not be fully accounted for by this technique due to lack of topography resolution and missing land surface – atmosphere feedbacks in the GCM.

Alternatives

Dynamical downscaling is an alternative to statistical downscaling that purportedly captures climate change in a physical model, i.e. circulation changes, surface-atmosphere interaction, and other interactions are physically specified. Dynamical downscaling through use of an RCM provides output at a high resolution grid in which any point of interest will contain a full time-series of climate variables. The statistical method is limited by either station level or a regional grid level resolution. In addition, this approach has not been used for ensemble evaluations, and extensive runs of such models have not yet appeared in the literature.

Due to the computational limits, time constraints, and the speculative nature of dynamical downscaling used in climate assessments, the quantile mapping as described in Wiley et al. (2006) is used as the primary downscaling tool. The quantile mapping method preserves historic variability while also adding projected future climate signals. The long record length developed for climatic variables provides water resources managers a complete view of the past and many possible outcomes for future conditions.

Hydrologic Modeling

Hydrologic models attempt to represent the physical movement of water within a region of interest by replicating patterns of the water cycle. The most commonly used output from hydrology models are streamflow, but all of the physical features represented by the model (snow-pack, evapotranspiration, etc.) are typically also available. The hydrology model used to generate streamflows as part of the Regional Water Supply Planning Process is the Distributed Hydrology Soil Vegetation Model (DHSVM). The robustness of features within DHSVM provides an appropriate platform for research-oriented hydrological characterization.

DHSVM has been applied successfully in many realms of research, including: sediment transport modeling, watershed characterization, climate impact studies, land use and land cover change, and streamflow forecasting. The model has been applied to several basins in the USA (Battin et al. 2006; Bowling et al. 2000; Bowling and Lettenmaier 2001; Palmer and Hahn 2002; Storck 2000; VanShaar et al. 2002; Wiley et al. 2006) and in British Columbia (Schnorbus and Alila 2004), and in Southeast Asia (Rattanaviwatpong et al. in review; Giambelluca 2002; 2003; Zieglar et al. 2000; 2004). DHSVM uses model grids ranging from 30 to 300 square meters to represent variations in landscape. The model is intended for small to moderate drainage areas (typically less than about 10,000 km^2), over which digital topographic data allows explicit representation of surface and subsurface flows. For each grid-cell, and time-step, energy and water mass balance equations are solved with flow being routed accordingly to neighboring grid-cells. A detailed discussion of the model physics is presented (Wigmosta et al. 1994). A brief description of the streamflow generation process is presented here.

Translating meteorology into streamflows

Before streamflows can be calculated, unique characteristics of a basin must be represented as physical processes or parameterizations. There are a wide variety of hydrologic models used for different purposes with varying degrees of complexity. In general, as model complexity increases, more complete and finer resolution data are required to create and force the model. For instance, a simple hydrology model based on regression may use only two variables to determine streamflow, whereas a distributed, physically-based model may require input for tens or hundreds of variables. With advancements in computing power, geographic information systems, and remote sensing, data requirements for more complex models are readily satisfied, as is the computing power needed to run them. This allows for complex distributed models or detailed lumped models to be readily used. It is common for basin specific studies to use models that require inputs of topography, land cover, soil types, geologic structures, vegetation, and the precise location of the watershed. An additional input for more detailed models is a stream network, which is commonly built outside of the hydrologic model in geographic systems software. A stream network contains information that is used to route streamflow from upstream segments to downstream river segments.

To calculate streamflows, a hydrology model uses meteorological data, typically consisting of temperature and precipitation. The observed meteorological data provides the essential forcing, with other important processes that contribute to runoff calculated within the model. A common example of this is evapotranspiration, where temperature, precipitation, wind speeds, and incoming radiation are used to calculate values of evapotranspiration rather than evapotranspiration values being used as an input.

Hydrology models incorporating meteorological data respond by transporting water within the system to achieve mass and energy balance. The equations that govern water and energy balance vary in form and complexity across models. For hydrologic modelers, an important term in these equations is runoff. In all hydrology models, runoff is the excess water in the system, i.e., water that is either not leaving the system via a form of export (evapotranspiration, groundwater transport, or streamflow exiting the modeling domain), or water that is stored (soil moisture or snow).

DHSVM uses the Cressman interpolation and PRISM maps to distribute precipitation measured at a weather station across a basin[1]. After solving mass and energy balance equations for each grid-cell in the model domain, DHSVM routes excess water to neighboring grid-cells for each time-step. Water flows to low points in the model topography where it coalesces into streams, is stored within a grid-cell for as many time-steps required by the model physics, or leaves the model by stream export, deep groundwater percolation, or evapotranspiration. Water that collects and forms streams is routed through a pre-determined stream network using a modified "Muskingum equation" approach.

Types of Models

Most hydrology models represent spatial characteristics in one of two ways, in a distributed approach or as lumped parameters. Lumped parameter models aggregate spatial characteristics of a basin into categories or percentages of space, ignoring where the defining characteristics occur in space. Distributed models attempt to incorporate the heterogeneity of a landscape into model processes by assigning specific spatial characteristics to individual grid-cells. Both types of hydrology models are capable of adequately simulating movement of water within a basin, depending on the purpose of the modeling exercise.

The major advantage of a distributed model over a statistical or lumped approach is the retained spatial heterogeneity. For regions with complex topography, such as the mountainous portions of the Pacific Northwest, runoff is dominated by small-scale variability in the landscape. Two adjacent sub-basins may have different runoff regimes due to rain-shadow effects, orography, or

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[1] The PRISM maps DHSVM uses are monthly totals of precipitation, i.e. a total of 12 maps are used in the forcing process to distribute precipitation across a basin. More information on Cressman interpolation and PRISM maps can be found in Cressman (1959), Zheng and Basher (1995), and Daly (1994).

aspect, slope, or elevation differences. In a statistical or lumped model, these differences are muted due to spatial information loss. Runoff may be modeled correctly in one sub-basin but poorly in the next. Distributed models explicitly account for these differences within the model physics, preserving the heterogeneity of the landscape and physical processes which may dominate water movement.

Concerns and Limitations

Distributed models require large data inputs. Model development is greatly facilitated by the availability of data from large governmental agencies (NRCS, NOAA, USGS, and USFS). Preparing these data for use in a model can require substantial time and complete datasets are not always available. The required computer processing time needed represent a heterogeneous landscape in model space can be large. A model developed in Hydrologic Simulation Program FORTRAN might take minutes to run on a modern desktop computer, a distributed type model such as DHSVM may take up to a month to complete. This makes calibrating the many parameters associated with accurately reflecting a heterogeneous environment challenging.

Distributed models typically require extensive and fine resolution landscape data to construct. Each pixel requires an input of vegetation, soil, geology, and elevation characteristics. A detailed network of meteorological stations is required to represent precipitation properly for complex topography, even with the enhancements provided through use of PRISM maps. A dense meteorological network is not always available, especially in smaller basins where effects of orography are more pronounced. To ensure the physics representing snow accumulation and ablation are modeled correctly within the model, a network of SNOTEL sites is commonly used for comparison. SNOTEL and snow-course sites are less dense then meteorological stations, and typically have limited periods of record with which to calibrate.

Distributed hydrology models typically use interpolation schemes to distribute precipitation over model regions. They often do not represent actual characteristics or timing of storms because they do not account for the physics driving the weather. Unless precipitation inputs have fine temporal resolution, it is difficult to capture the most extreme low or high flows. DHSVM, as with the majority of hydrology models, does not explicitly account for groundwater below the three layer soil column modeled. Independent groundwater models are typically too complex to couple to a hydrology model and may result in extended runtimes with little additional information gained for surface streamflows.

Alternatives

A hydrology model is essential in evaluating the impacts of climate change on water resources. There are alternatives to the model used here, DHSVM. Two commonly used models are HSPF (Hydrological Simulation Program – FORTRAN - or variations on this model), and the MIKE Basin model (produced by the Danish Hydraulic Institute). Of the hydrology models available, DHSVM is the best suited for this study area because of its ability to accurately incorporate the topographic character of the region and its ability to perform accurate energy balances on the snowpack.

Evaluating Uncertainty

In a report to the United States Geologic Survey and the Department of Interior detailing potential impacts of climate change to national water resources, Peter Gleick outlined a four-step process to quantify climate impacts and uncertainties. This process serves as a commonly used foundation for climate impacts studies. The four step process is summarized as follows: selection of GCMs and scenarios, downscaling of GCM projections to local river basins, processing the downscaled meteorological data through a hydrology model, and evaluation of climate impacted streamflows, which could involve ecological models, operations models, or economic models. Uncertainties occur in each step of the climate impact analysis process. The largest contributors of uncertainty when performing a water resources system analysis are the different GCMs and the emissions scenarios used to force the GCMs. Other sources of uncertainty are introduced in the downscaling process and within hydrology models.

Sources of Uncertainty and approaches to quantifying uncertainties

Uncertainty in climate projections stems from internal climate variability and the earth system processes modeled. Internal climate variability can be quantified through many runs of the same climate model using different initial conditions. A range of climate is generated as output, and either averages or the ensemble as a whole can be used as the bounding conditions as long as the modeled variability matches observed conditions. Accounting for uncertainty arising from earth system processes is more challenging; one approach is to use ensembles of models to generate a range of projected climates. This range is used to describe impacts to local systems as opposed to one average value. This is an active area of research.

GCMs

Upper and lower bounds might be used as impact scenarios for future climates. One bracketing might involve choosing the driest and wettest GCM-scenario combinations, and coupling these with varying degrees of warming. Another approach is to average many GCMs climate projection together to create an average scenario. Climate scientists have begun describing uncertainty in a probabilistic framework as their ability to generate multiple sequences of climate future improves. In a probabilistic analysis, multiple runs from many GCMs are used, and where GCMs agree on projected future conditions, higher likelihoods of occurring are assigned. This provides a picture of what physical processes GCMs capture well, and the locations of where climate scientists have high certainty in these projections. In quantifying uncertainty for the Regional Water Supply Planning Process, three GCMs were selected based on their appropriateness for regional climate and the range of future climates they provide. A range of warming is used as a means to quantify the inherent uncertainties of the GCMs and provides a broad view of potential impacts. These differences in future projections provide decision makers a range for evaluating water resources and future challenges.

Downscaling

Downscaling has been called “among the least quantifiable” steps in the process of using climate models to assess climate change impacts to water resources (Wood et al. 1997); however, it is important to determine the relative uncertainty in this process. While it is reasonable to compare downscaling results with observed records for a given period, it would be unreasonable to expect an exact match. Observed records give only what actually happened in a given year, where the downscaling methods being examined attempt to produce the range of what could have happened in that given year. Confidence is gained when the observed data lies within the range of projections. The full quantile mapping process preserves natural variability by more completely addressing the entire range of possible states than other statistical downscaling techniques.

One method for ensuring that uncertainty added from the downscaling process and GCMs is within acceptable bounds is to examine how well they replicate a recent or historic period. It is important that means, variances, and extremes match well with the observed. For the quantile mapping method, it is possible to compare months or days of the projected record to the historic due to the nature of the relationship between the two. Very hot days in the past should be similarly hot in the future, but may be slightly shifted in temperature, thus possibly increasing the number of days above a certain threshold, i.e. more days with maximum temperatures above 90 degrees Fahrenheit.

Hydrology Models

Lastly, uncertainties arise in hydrology models due to how earth system processes are physically described. Uncertainties associated with hydrology models are among the most quantifiable. A common method for quantification is comparing how well the hydrology model simulates observed streamflows and energy fluxes. The stream gage network available from the USGS provides easily accessible historic flows for points within many watersheds. Most basins have records available that can be compared to modeled flow. Also available are SNOTEL and snow course sites for ensuring proper accuracy of the snow physics within the model. It is important to accurately account for both water mass and seasonality when comparing historic flows to modeled flows. Once the annual flows are properly modeled, the majority of the uncertainties associated with streamflow output will stem from the GCMs.

Limits to the Reduction of Uncertainty

When performing climate impact analyses, it is important to identify the cause of the greatest uncertainties and how to bound those uncertainties in a constructive and informative way. A first step in accounting for uncertainty is to reduce the errors in the stages that are readily controlled, such as ensuring the hydrology models adequately represent historic flows through proper physics. Once these uncertainties are reduced and quantified, sources of uncertainty that have greater range and complexity can be either quantified through aggregate means, i.e. ensemble approaches, bounding scenarios, or in a probabilistic framework.

For the Regional Water Supply Planning Process, uncertainty is being addressed in each stage of the climate impacts analysis process. Uncertainty associated with GCMs and scenarios is bracketed through a GCM selection approach. Three GCM-scenario couples that represent regional climatic patterns well are selected based on the range of temperature and precipitation changes in the projected futures. The three GCM-scenario couples consist of: (1) significant increase in precipitation and temperature, (2) ‘middle of the road’ increases in precipitation temperature, and (3) a slightly drier and warmer future. All scenarios have increases in temperature, which is representative of the GCMs employed in the IPCC Fourth Assessment Report. Because the three scenarios are considered equally likely, it is important to examine climate impacts and associated risks within the entire range. Within this range, there are certainties, such as all models show increases in regional temperature that are useful for decision makers when developing long-term plans.

Uncertainty in the downscaling process and hydrological modeling are accounted for through comparison of historic records to the modeled output. For quantile mapping, uncertainty is challenging to quantify because it relies heavily on the observed record for replication of natural variability. A comparison can be made between the simulated 2000 period and the recent observed record. If the distribution of temperature and precipitation are represented adequately and the downscaling process improves upon the raw GCM projection, we can assume that the net benefit outweighs the uncertainty added through small-scale processes that might not be accounted for or truncation of variability. If the hydrology model provides reasonable representation of historic flows and we assume the physical processes that dictate runoff as described in the model stay the same in the future, (i.e. same land use patterns in upper watersheds, physical routing processes, etc.) then the uncertainty due to the hydrology model is the difference in mass or seasonal biases. If the model validates the historic record adequately, this uncertainty should be minimal when compared to the uncertainty associated with the GCM-scenario couples.

Uncertainties will always exist in climate science. Many advances have been made in GCMs, downscaling methods, and hydrologic models over the past two decades. Though GCMs represent atmospheric, oceanic, and land surface processes more accurately now than in any time in the past, further improvements in cloud physics and land surface interactions and feedbacks are needed to alleviate large areas of uncertainty. Though uncertainties exist, it is important to move forward in policy and decision making with what is known about future climate. Use of projected trends and model agreement in a risk based management approach provides robustness to all long-term planning efforts.

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