EVALUATING POTENTIAL CLIMATE CHANGE IMPACTS ON WATER RESOURCE SYSTEMS OPERATIONS: CASE STUDIES OF PORTLAND, OREGON AND CENTRAL VALLEY, CALIFORNIA

Nathan T. VanRheenen and Richard N. Palmer
Department of Civil and Environmental Engineering, University of Washington
Margaret A. Hahn
Consulting Engineer, RW Beck, Seattle, Washington

INTRODUCTION

Since its initial report in 1990, the Intergovernmental Panel on Climate Change has consistently noted that climate is changing (IPCC, 1990; 1996; 2001). These reports, the studies upon which they are based, and other studies indicate that water resources are particularly susceptible to the impacts of climate change (Frederick and Major, 1997; Gleick et al., 2000). The most significant impacts of climate change on U.S. water resources are expected to occur in the midlatitudes of the West, where the runoff cycle is largely determined by snow accumulation and melt patterns (Cohen et al., 2000). It is well documented that the effects of warmer climates on the seasonality of runoff in these regions will likely shift a portion of spring and summer melt runoff earlier in the year (Smith and Tirpac, 1989; Piechota and Dracup, 1996; Piechota and Dracup, 1997; Lettenmaier et al., 1999; IPCC, 2001). Despite the high degree of regulation in many western U.S. water supply systems, the impact of these shifts on runoff seasonality is generally negative. This is due to the significant water storage in snowpack that, under normal climates, is relied upon to augement low streamflows during relatively dry summers (Hamlet and Lettenmaier, 1999; VanRheenen et al., in review).

Climate change may also impact water supplies on the watershed level. The extent to which this occurs is a function of several factors, including the magnitude of the change in climate, the physical setting of the watershed, and the degree to which the watershed has already reached its sustainable use. Watersheds located at high elevations may not be impacted by modest changes in temperature, as most precipitation will continue to fall as snow. Watersheds at low elevation will likewise likely be unaffected, as precipitation will continue to fall as rain. Changes in winter total precipitation may not impact water supply systems, as this water is not typically captured for later use. Changes in spring and summer precipitation, however, may have significant impacts. Furthermore, watersheds already at sustainable levels of use may be strongly impacted by shifts in climate that might not be sufficient to impact under-utilized watersheds.

Two types of watersheds are at greatest risk of being impacted by climate change in the U.S. The first is the transient watershed. A transient watershed receives precipitation as both rain and snow and has a “two peak” hydrograph: one peak occurring in the early winter from increased rainfall and a second peak in spring from snowmelt. In these watersheds even small changes in climate may influence the quantity and timing of runoff. Analyses of the impacts of climate change in municipal watersheds around the Pacific Northwest reveal that climate change-induced snow accumulation and melt may influence the timing of streamflow volumes due to climate change (Hahn et al., 2001).

The second type of watershed at greatest risk is the highly developed watershed commonly seen in the Southwest and West. These watersheds have large reservoirs that hold several years of annual streamflow, but are characterized by high annual demands relative to annual inflows. The timing of streamflow runoff in this type of watershed is less significant than for the transient watershed, as the storage capacities of the reservoirs can be used to moderate flow variability. Although a single year of low flows may not impact these systems, a multi-year drought caused, in part, by climate change could have significant impacts due to increased water demands, a decreasing percent of runoff associated with each precipitation event, and the longer periods during which demands exceed inflows. The multi-objective nature of many of these large systems, including those in the Central Valley of California, may preclude the use of adaptive management strategies used in the transient municipal watersheds to maintain current levels of performance in future climates (VanRheenen, in review).

This paper investigates the implementation of climate change studies performed in transient municipal

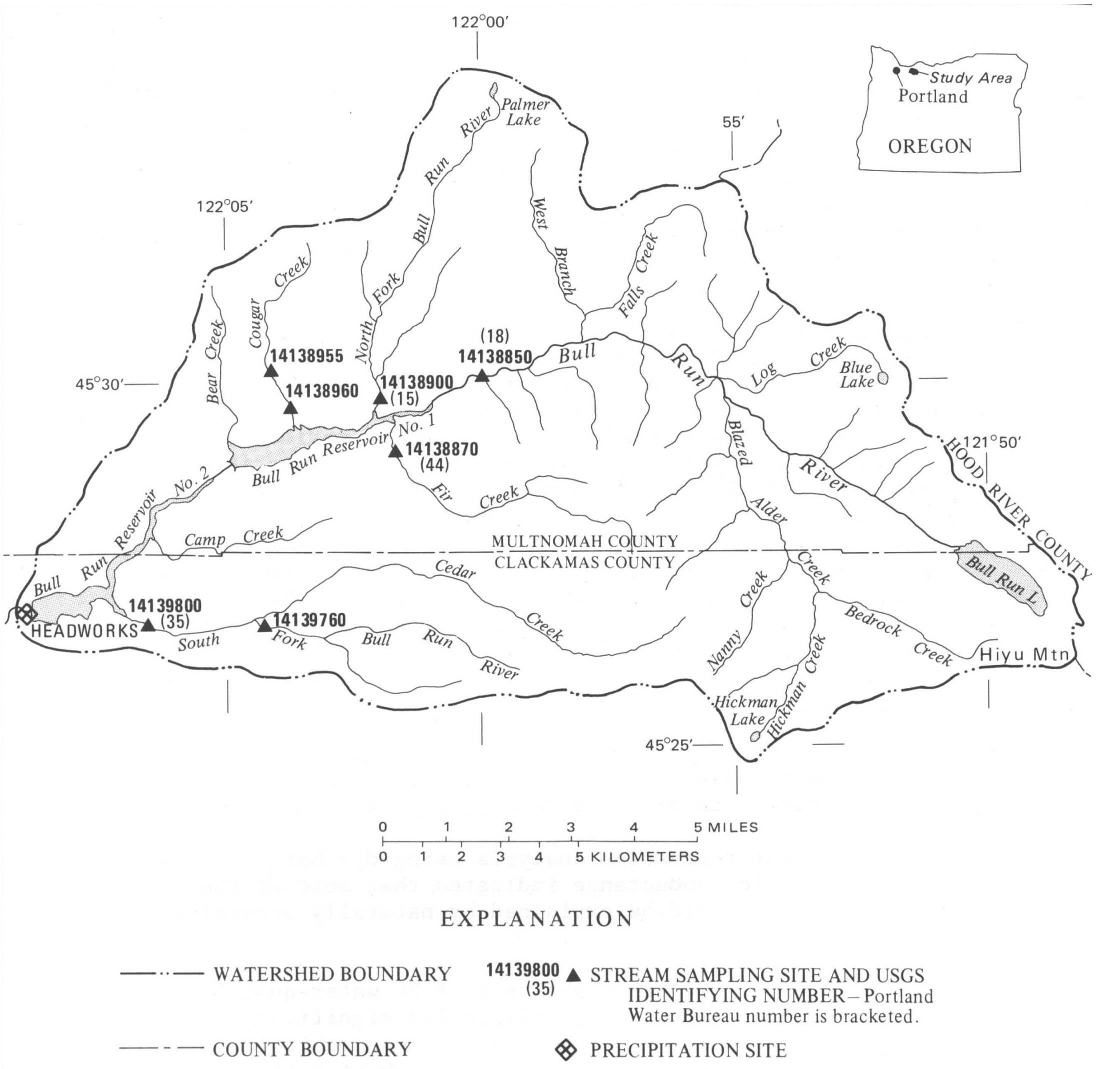

Figure 1. Map of the Bull Run watershed, Portland, Oregon

watersheds and those in larger, more highly developed watersheds. The Bull Run watershed in greater Portland, Oregon, and the Sacramento-San Joaquin River watershed in the Central Valley of California are used as case studies.

HYDROLOGY AND SYSTEM DESCRIPTION

Bull Run Watershed

The Bull Run watershed is located nearly thirty miles east of the City of Portland. The watershed contains three reservoirs: Bull Run Lake, a natural lake in the upper portion of the watershed; Reservoir 1, located fourteen miles downstream of Bull Run Lake; and Reservoir 2, located four miles downstream of Reservoir 1 (Figure 1). The watershed experiences an average annual precipitation of 80 inches in the lower elevations and up to 180 inches at higher elevations, resulting in an average annual runoff of 300,000 acre-ft (AF) at Bull Run Headworks.

The basin's precipitation falls as both rain and snow. There is a direct correlation between the average monthly precipitation and streamflow throughout the year, with the highest correlations in the summer and fall. Snowmelt contributes to streamflow in April and May. Low soil moisture in August dampens August streamflows even after precipitation increases after the typically dry summers.

Bull Run River and the dams serve as a primary source of water for the City of Portland and the surrounding suburban region. Reservoirs 1 and 2 have a combined capacity of 31,000 AF of active storage. Bull Run Lake, used intermittently during times of drought, has a capacity of 1841 AF. Approximately 10% of the average runoff is captured as usable storage. The system provides

Figure 2. Map of the Central Valley, California

drinking water to approximately 831,000 residents, nearly one-fourth of the population of Oregon. Over half of the customers receiving water are within the City of Portland (481,000), with the remainder of the customers served by wholesalers, including Rockwood Water PUD, Powell Valley Road Water District, the City of Gresham, the Tualatin Valley Water District, the City of Tualatin, and the Burlington Water District. Currently, the average annual water demand is 115 million gallons per day (mgd), with a fall/winter/spring average of 100 mgd and a summer average of 144 mgd. The drawdown of the reservoirs typically begins in June and refill typically begins in late September. In addition to surface water, Portland also has groundwater available for water supply. Groundwater is provided by more than 20 production wells, designed to produce as much as 90 mgd. In recent years, these wells have served as a backup to the surface sources, and have been used an average of only 20 days per year. Even so, the city has water rights to more than 300 mgd from the well field that could be used during a significant drought event.

Sacramento-San Joaquin Watershed

The Central Valley of California is one of the largest multi-purpose water storage and conveyance systems in the world. Four hundred miles in length, from Redding to Bakersfield, CA, it supplies more than one quarter of the food consumed in the United States (Umbauch, 1997). The Sacramento-San Joaquin watershed comprises the upper three-fourths of the Central Valley (Figure 2).

The Sacramento River basin experiences an average precipitation of 25 inches in the lower elevations and more than 60 inches in the upper elevations. Mean annual runoff is 11.8 million acre-feet (MAF). The San Joaquin River basin averages 9 inches in the lower elevations and 17 inches in the upper elevations and has a mean annual runoff of 10.7 MAF.

The State Water Project and the Central Valley Project coordinate operations of a system of 20 major dams and reservoirs in the Sacramento-San Joaquin River basin with a combined storage capacity of nearly 17 MAF, containing 13 major hydropower plants, over 630 miles of major canals and aqueducts, and various related facilities. Locally-owned reservoirs of significance provide an additional 4 MAF of storage, bringing the total Central Valley surface water storage to nearly 21 MAF.

MODELS

Three types of models were used in each of these studies: climate models (general circulation models - GCMs), a watershed model, and a water resources management model. The linked model process is common in the area of climate change impact assessment (Hamlet and Lettenmaier, 1999; Kirshen and Fennesey, 1995; Wood et al., 1997).

General Climate Models

Each of the GCMs used in these studies represents the evolution of climate and its dependence on greenhouse gas concentrations at some point in the future by incorporating a one percent increase in atmospheric carbon dioxide per year. The Parallel Climate model (PCM) (PCM, 2001) and Hadley Center models (HadCM2, HadCM3) (Hadley Center, 2001) are coupled land-ocean-atmosphere models with resolutions ranging from 2.8 x 2.8 degrees (PCM) to 2.5 x 3.75 degrees (HadCM2, HadCM3). The Max Plank Institute model (ECHAM4) (Max Plank Institute, 2001) is an atmosphere-only model, with a resolution of 2.8 x 2.8 degrees. The Portland study uses the PCM, HadCM2, HadCM3, and ECHAM4 scenarios. The Central Valley study uses an ensemble of three PCM “business as usual” (BAU) future climate scenarios and one current climate “control” scenario, as described in Washington et al. (2000).

In each of these studies, the coarse resolution of the GCM climate signals prevents the explicit consideration of many geographic, orographic, and maritime features (landscape and vegetation, mountains, bodies of water) that directly impact expected climate effects. Climate information is “downscaled” to a more useful resolution by translating it from a multi-degree scale to a finer scale by estimating the average monthly difference of temperature and precipitation of a control run (a run that simulates current climate) of the specified model and a future climate model prediction. These techniques have been commonly used in the water resources literature (Hamlet and Lettenmaier, 1999; Wood, et al., 2001).

Downscaling Climate Information – Portland Study

In the Portland case study, climate signals from GCMs are calculated by taking the average monthly difference of temperature and precipitation of the specific climate model control run (a run that simulates current climate) and a future climate model prediction. The temperature signal is reported as the difference of the control and future monthly temperature averages, and the precipitation signal is the percent difference of the control and future monthly precipitation averages (Hamlet and Lettenmaier, 1999). These shifts or "deltas" are then applied to the historic data and used as inputs into the watershed model. It is important to note that simple changes in temperature and precipitation can significantly alter the amount of precipitation, the proportion of rain to snow, and the timing when snowpack in a watershed melts.

Although this technique is relatively simple, it was concluded that this method provided a good representation of the changes in climate change. It is still well beyond the capabilities of GCMs to effectively model some of the most important climate teleconnections that impact the Pacific Northwest such as the El Nino/Southern Oscillation (ENSO). The basic structure between El Nino and La Nina events is maintained by using the historical climate record and modifying the precipitation and temperature record. Maintenance of this feature was felt to be essential in evaluating climate impacts.

Downscaling Climate Information – Central Valley Study

In the Central Valley study, as with the Portland study, climate signals are downscaled from a coarse resolution to one that is finer and more accurately represents climatic impacts on hydrology. In this case, the climate information is bias corrected, then spatially disaggregated, to create temperature and precipitation inputs for the hydrology model. To directly use PCM output, T_{avg} and P_{tot} forcings from each climate gridcell located within the study region are treated individually for purposes of bias correction. For bias removal, PCM model climatology is quantile-mapped to the observed monthly climatology for each variable (T_{avg} and P_{tot}). The observed climatology is re-gridded and averaged to the PCM grid resolution. This mapping is then applied to the PCM raw output and translated to a plausible range with respect to historical observations. Any adjustments made vary spatially at the PCM grid scale by month.

For the BAU scenarios, the PCM cell-specific temperature shifts (monthly averages relative to the historical run monthly averages) are removed from the uncorrected PCM output prior to the bias-correction step, then replaced following bias-correction. This step is required to better account for differences between the variability of the BAU temperature and the climate model historic run distributions. With the temperature shift removed, the spread of the BAU run temperature distribution is very close to the historical range, enabling the bias-correction step to be applied with little extrapolation. The basic assumption of this approach is that the variability of the BAU run temperature distributions remain similar to the retrospective run variability, despite the mean BAU shift.

Spatial disaggregation imposes sub-PCM grid scale spatial variability on the bias-corrected PCM-scale forcings. The monthly time step, bias-corrected PCM-scale BAU scenario time series are spatially interpolated to the hydrology model grid cell centers. Anomaly fields, developed from the observed climatological monthly means (for T_{avg} and P_{tot}), are applied to the resulting ⅛-degree monthly variable fields in two steps:

1) Observed monthly mean T_{avg} and P_{tot} 1975-95 averages are aggregated to the climate model scale (½-degree), and then interpolated back to the ⅛-degree scale, in the same way that climate scale model forcings were interpolated; and
2) Temperature differences and precipitation ratios between the ⅛-degree monthly mean T_{avg} and P_{tot} and the interpolated monthly mean fields are calculated to create the anomaly fields.

When applied to timeseries of interpolated climate model-derived fields, the mean monthly sets of anomaly fields add spatial variability to the smooth ⅛-degree field created in the interpolation step. This method of spatial disaggregation creates VIC-scale monthly forcing time series that correspond to the PCM scale time series, yet still reflect VIC-scale spatial structure.

Finally, a temporal disaggregation step is used to form daily time step inputs for the VIC model. The monthly forcing time series are replicated using scaled or shifted daily patterns sampled from the historic record at the hydrology model resolution. Month-long daily patterns of precipitation and temperature are sampled for each monthly timeseries by picking a single year from the 50-year climatology period at random. Each sampling year is used for the entire Central Valley domain to preserve a degree of synchronization in the weather components driving hydrologic response. The daily patterns are then scaled (for precipitation) and shifted (for temperature) to match the monthly timeseries (in T_{avg} and P_{tot}) created by applying the interpolated, bias-corrected PCM anomalies to the VIC cell climatological means. Various screening methods are applied to the precipitation patterns to ensure that rescaling did not result in unrealistic values.

Hydrology Models

The GCM signals for temperature and precipitation are used to drive physically-based hydrology models that represent each watershed as a multi-layered grid. Each pixel in the grid is characterized by several physically-based data layers that may include the soil and vegetation type, soil depth, vegetation height, and surface elevation and slope. The model simulates hydrologic processes with meteorologic data (temperature and precipitation) and the physical data layers that are unique to the watershed. The runoff in each simulation is transferred from cell to cell to generate streamflow networks.

The case studies described in this paper employ different hydrology models. The Portland study uses the Distributed Hydrology, Soil-Vegetation Model (DHSVM), in which the grid size of the model element is 150m by 150m. The small grid size of DHSVM enables the model to effectively simulate small-scale catchments with complex topography. The model has been used most extensively and successfully in the tree lined watersheds of the Pacific Northwest (Wigmosta, 1994; Storck, 2000). Each DHSVM application is based on a series of data sets and model parameters that are unique to a watershed. The data sets represent the general physical nature of the basin (elevation, soil type, precipitation, vegetation) and the parameters represent more detailed characteristics of interactions (roughness of snow, leaf area index, and other features) among the physical components of the basin. The application of the DHSVM to the Bull Run watershed included gathering spatial datasets that describe the basin's physical nature, collecting meteorological datasets that describe the precipitation and temperature of the basin for an extended time period, and calibrating the model so that the simulated streamflows represent the observed streamflows.

The Central Valley study uses the Variable Infiltration Capacity (VIC) model. VIC is implemented at ⅛-degree latitude/longitude resolution over a hydrologically-defined domain that covers the State of California and drainage areas extending into the State of Oregon (2,906 grid cells in all, each about 150 km^2). Within the study domain, runoff in smaller subbasins is routed (using the routing model of Lohmann et al., 1998a, 1998b) to produce streamflow estimates at points collected with USGS river gauging stations and/or water resources system inflows. VIC has been used extensively in the simulation of large continental river basins and is well documented (Liang et al., 1994; Liang et al., 1996; Nijssen et al., 1997; Maurer et al., 2001).

Water Resources Models

Portland Supply and Transmission Model (STM)

The streamflows generated by DHSVM are used as input to the Portland Water Bureau's Supply and Transmission Model (STM), developed by the University of Washington and PWB staff. The STM operates at a daily time step, simulating the flow of water throughout the water transmission system. It contains seasonally-varying rule curves that control the amount of water stored in the reservoirs. It also estimates releases made for instream flows and hydropower production. Groundwater operations are coordinated with reservoir operations with a variety of operating alternatives that either encourage or discourage groundwater use. The model was constructed in the STELLA® programming environment. The model contains approximately 1,500 variables, each solved at a daily time step. The model was typically run for a 50-year period to evaluate a climate change scenario, generating 27×10^6 state variables.

The model can evaluate a large number of system expansion alternatives, together with different conservation policies. Drought management alternatives and impacts are modeled in detail. Variables, such as the length of the draw-down period, the amount of groundwater pumped during drawdown, the minimum storage during drawdown, and the water used during the drawdown provide useful metrics to compare system alternatives.

Central Valley Model (CVmod)

The Central Valley Model (CVmod) is a monthly timestep water resources simulation model that incorporates the major projects and operational features of the Sacramento-San Joaquin basin and simulates the movement and storage of water within the basin given current operational policies.

The model was constructed in the STELLA® programming environment. Modeled facilities include 12 reservoirs having a combined storage capacity of over 16 MAF, 10 power plants, the San Francisco Bay Delta, and the California Aqueduct and Delta-Mendota Canals. Also included are major operational rules for fish, water quality, flood control, power production, and navigation.

The primary hydrologic input to CVmod is monthly streamflow, either from observed natural or unregulated flows (for studies of past climate) or from the VIC-generated hydrology. CVmod is used to explore system performance and reliability given various operating policies and alternative climate and operating scenarios. The model's outputs are reservoir levels and releases. From these, the predicted performance of the system is calculated with respect to such operating criteria as water quality, flood control, hydropower production, agricultural and municipal diversions, navigation, and instream flows for fish. As with the STM, CVmod can evaluate a large number of system expansion alternatives and conservation policies.

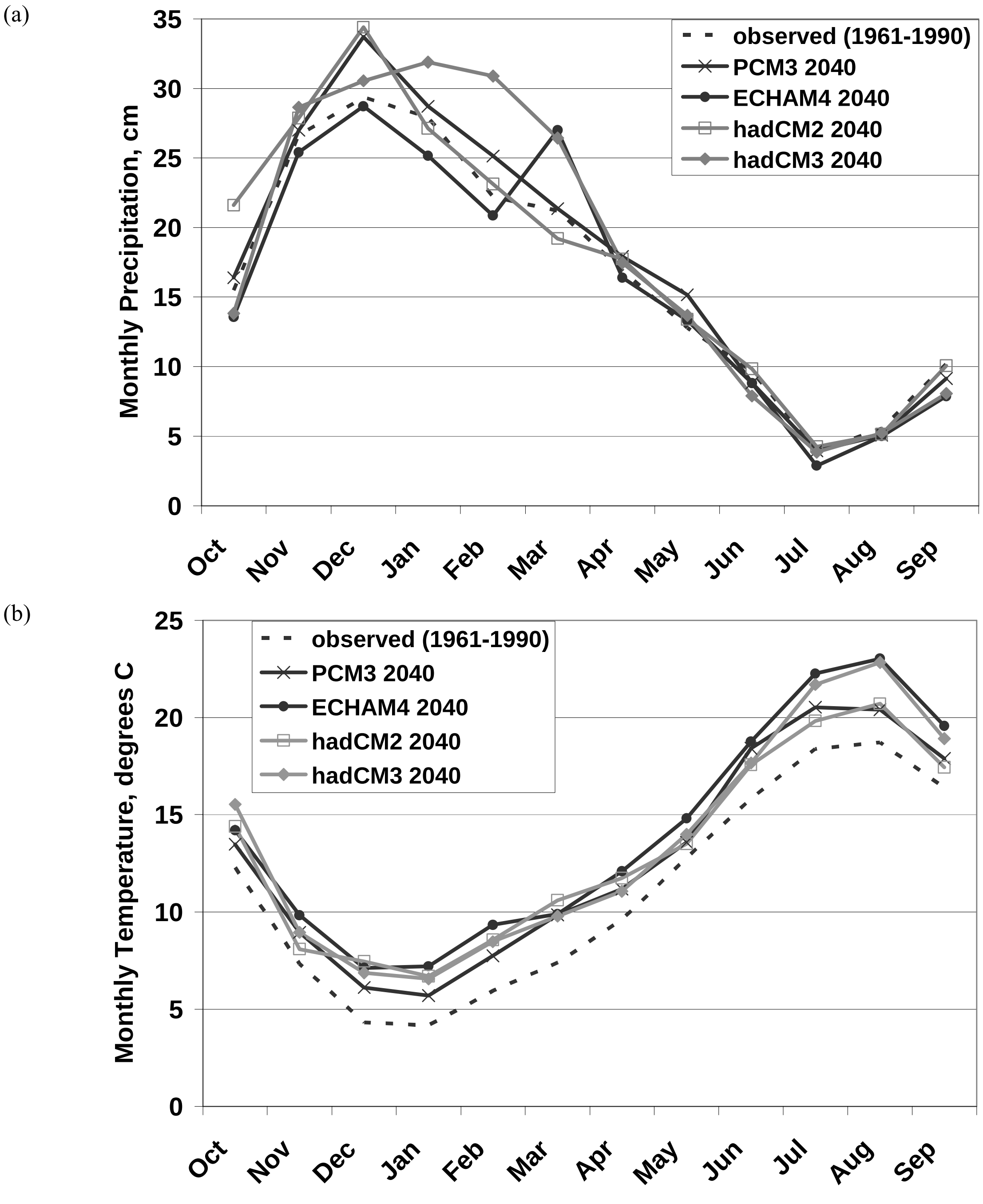

Figure 3. Observed and 2040 mean monthly precipitation (a) and temperature (b) at Bull Run Headworks

RESULTS - PORTLAND

Climate Change and Hydrology

Figure 3 demonstrates that by 2040, four of the climate change models predict warmer and wetter climates on an annual basis. The 2020 decade (not presented) shows similar characteristics. The only exception to these general trends is ECHAM4, that produces a significant variation in the forecasted average shift in precipitation in 2040. Precipitation is slightly greater than the historic average in October and May and lower in June through September.

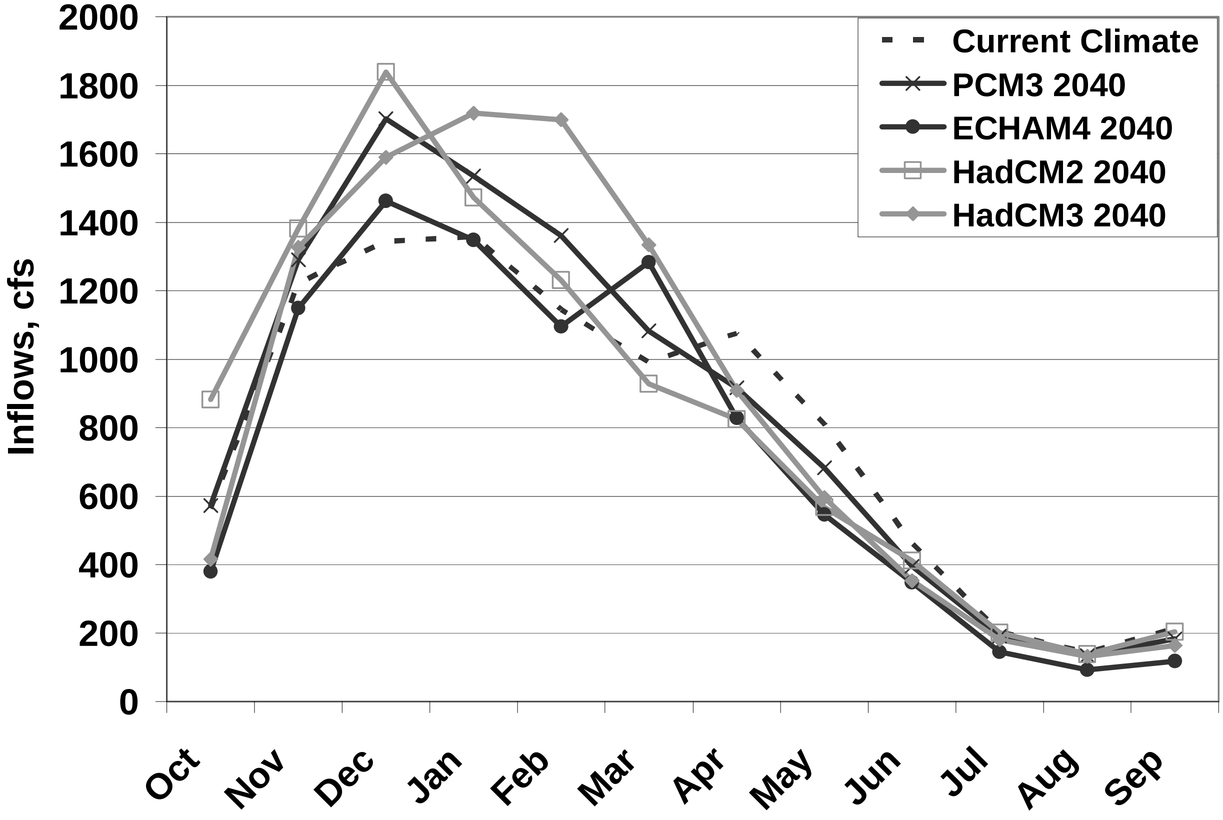

Figure 4. Mean annual hydrograph of cumulative Bull Run inflows for current climate and 2040 scenarios

The change in the temperature signal also varies among the four climate models, however, the signal is more consistent, always indicating warmer weather in future scenarios. The temperature signal for 2040 predicts higher temperatures on average in the summer and an overall average annual increase of 2.0 °C. These higher temperatures in the winter months will reduce the amount of snow in the basin. The higher temperatures in the summer will likely create an increase in the summer water demand.

Figure 4 shows the mean monthly hydrograph of the basin for the four 2040 climate change scenarios and current conditions. The range of values for fall and winter flows is indicative of the variability of the climate change precipitation signal of the four models. Increased winter precipitation and the warmer temperatures create higher winter streamflows and lower spring-time flows. This lagged effect of warmer winter temperature is similar in the four climate change signals. HadCM3 2040 predicts less precipitation in the months of October, November, December, and January. The four GCM flows are the extremes, with higher flows in the mid-winter (January and February). The remaining three signals are similar to one another and create higher flows in the early winter, a decrease in the spring peak and an earlier declining hydrograph in the spring.

<u>Water Resources Impacts</u>

A primary measure of the water resource system performance is annual minimum storage. If storage decreases below established thresholds, water reliability can be compromised and management actions must be taken. For the Portland system, if surface storage decreases earlier in the drawdown cycle than normal, then more groundwater must be pumped. In extreme cases, voluntary and mandatory water use restrictions must be implemented. In strategic terms, if surface storage in the Bull Run system decreases sufficiently, consideration must be given to significant changes in management. Increased emphasis on conservation might be warranted, new infrastructure might be considered (such as the expansion of existing reservoirs or the construction of a new reservoir) or changes in groundwater operation might be required.

Although the water management model used in this study could evaluate the impacts of new infrastructure investments, the results presented in this paper focus on the impacts of climate change to the existing system. The measure of system performance presented here is the minimum annual storage less system shortfalls. In extreme events, these shortfalls might include missed instream flow targets for fish flows or municipal and industrial water demands not being met.

Figure 5 presents the cumulative distribution of minimum storage less shortfall for combinations of demand year and climate change year. The figure indicates that for a given probability, the storage values for the current climate with a 2000 demand curve are greater, generally, than those of the changed climate. In Figure 5a, differences in the storage values for the 2040s are consistent and range between zero and one billion gallons in minimum storage less shortfall for both the 50% and 90% probability. For some probability levels, the differences are as large as 2 billion gallons.

Exceedance probability curves are developed for the minimum storages less shortfalls for the system when only considering the impact of regional growth on demand (Figure 5b). The difference between the storage values is greater for regional growth than for climate change. At the 50% probability level there is a 4 billion gallon reduction in storage for 2040 regional growth and an additional 1.5 billion gallon reduction in the annual minimum storage for 2040, indicating that climate change will exacerbate the challenge of growing demand.

These results place the impact of climate change into perspective, and this result will be seen again in the following section. Climate change has a significant impact on the hydrology of the basin and results in changes in the pattern of storage in the reservoirs. Although the climate change impacts are significant, they are not as large as those that can be associated with the continued growth in population in the region and the corresponding increase in water demand. Providing water to a growing service area is the primary factor for consideration of increasing supply. However, the impacts of climate change on both water supply and demand will exacerbate this need.

RESULTS – CENTRAL VALLEY

Climate Change and Hydrology

Figure 6 shows the downscaled, basin-averaged mean monthly temperature and precipitation from the control run and averaged simulations from the BAU ensembles. The control run average temperature in both basins is slightly warmer than the observed average (reflecting warming that has occurred in the last 50 years), while the observed and control run averages for precipitation are nearly equivalent (Figure 6a). In Periods 1-3, the BAU ensemble averages are warmer than the control by 0.5, 1.2 and 1.9 ºC, respectively, and the increases are slightly greater in summer than in winter. BAU precipitation is moderately lower than control run precipitation (Figure 6b). In Period 2 (2040-2069), spring precipitation is closer to the historic and control than in Periods 1 and 3. BAU ensemble precipitation is, on average, reduced (with changes of 10 to 25 percent in the basin average) in winter and spring for all periods relative to the control run.

Figure 7 shows control run and BAU ensemble-average naturalized total mean monthly streamflow for the Sacramento River basin (Figure 7a) and the San Joaquin basin (Figure 7b). The primary change in streamflow in both the north (Sacramento basin) and south (San Joaquin basin) for the BAU ensembles is a reduction of streamflow volume, larger in Periods 1 and 3 than in Period 2. In the north, there does not appear to be a significant change in seasonality (a shift in runoff toward earlier in the year, due to earlier melt), although the volume reductions are greater in the spring (the melt period) than the winter. In the south, the greater severity of the summer streamflow reduction indicates a slight seasonality shift, although for Period 1 monthly variations in precipitation and temperature complicate this general seasonal response. Overall, the volume reductions are more severe in the southern portion than in the northern part of the basin.

Water Resources Impacts

Figure 8 presents the ranked distributions of minimum annual cumulative storage for the Sacramento (8a) and San Joaquin (8b) systems. The figures indicate that for a given probability, the storage values for the control climate are greater than the predicted climate during all periods. In the Sacramento system, differences in the storage values across all periods are generally consistent and range between 700 and 850 TAF difference in minimum storage for the 50% and 90% probability. For the San Joaquin system, differences range between 300 and 400 TAF for the 50% probability and 200 and 300 TAF for the 90% probability. For some probability levels during Period 3 (2070-2098), the differences are as large as 1.5 MAF in the Sacramento system and 850 TAF in the San Joaquin system. Reservoir releases follow patterns of reduction consistent with future storage.

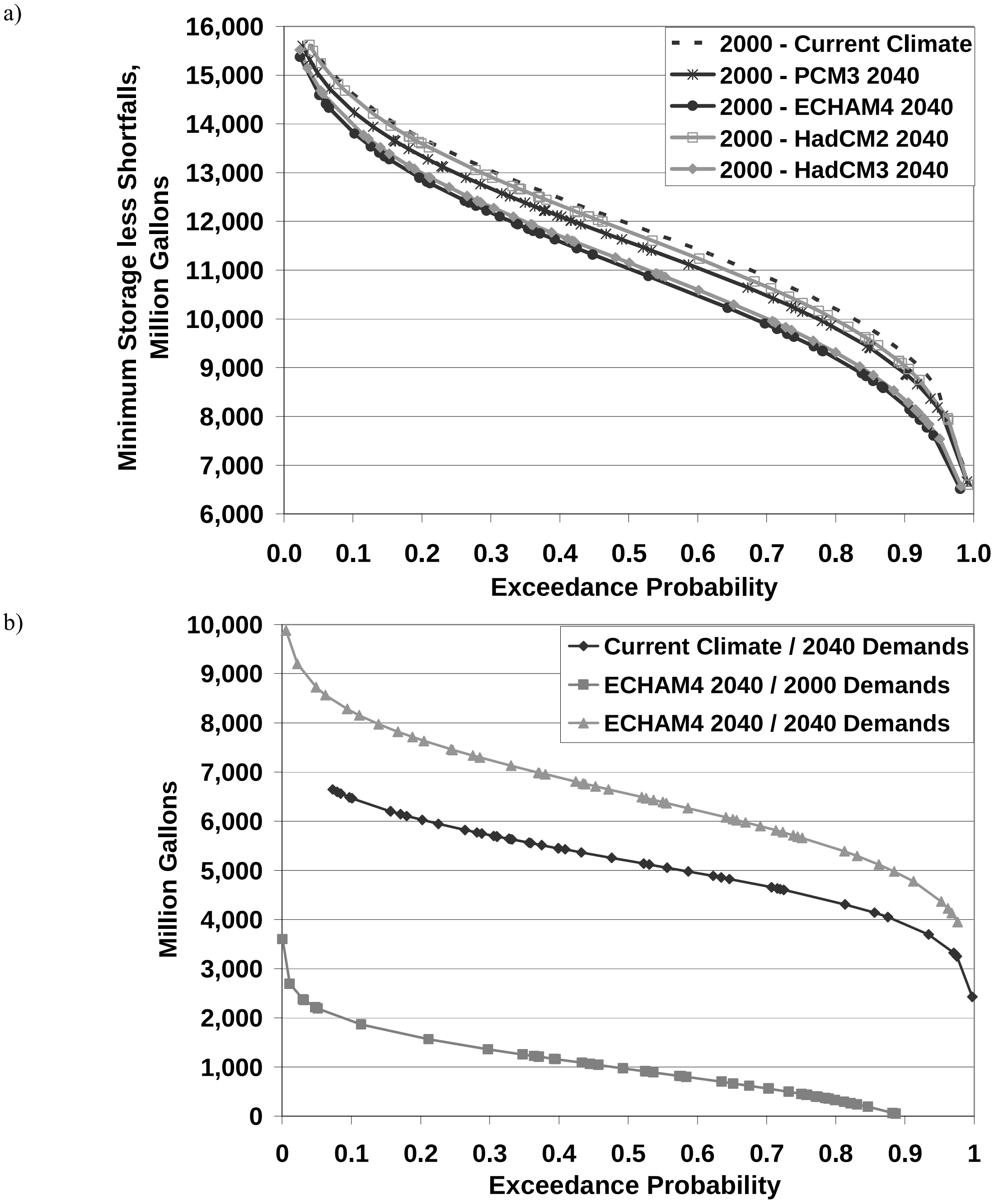

Figure 5. a) Exceedance probability of minimum storage of combined Bull Run system for current and 2040 climate change scenarios with 2000 demands. b) Difference between minimum Bull Run storage of scenarios using 2000 demands and scenarios using 2040 demands

A key measure of water resources system performance is functional reliability, defined by Hashimoto et al. (1982) as the probability that a primary function of a system is met. While a decrease in annual reliabilities for various rules in the system is expected, given results described earlier, seasonal impacts have not been demonstrated. Figure 9 illustrates the impact of climate change on the seasonal reliability of meeting environmental flow objectives below the largest reservoir in the Central Valley system, Lake Shasta. January-June reliability is within 10 percent of control reliability levels, with the greatest variance during Period 3, of 9 percent. June-December reductions in reliability are much greater, with reliability reductions of 25, 19, and 40 percent during Periods 1, 2 and 3.

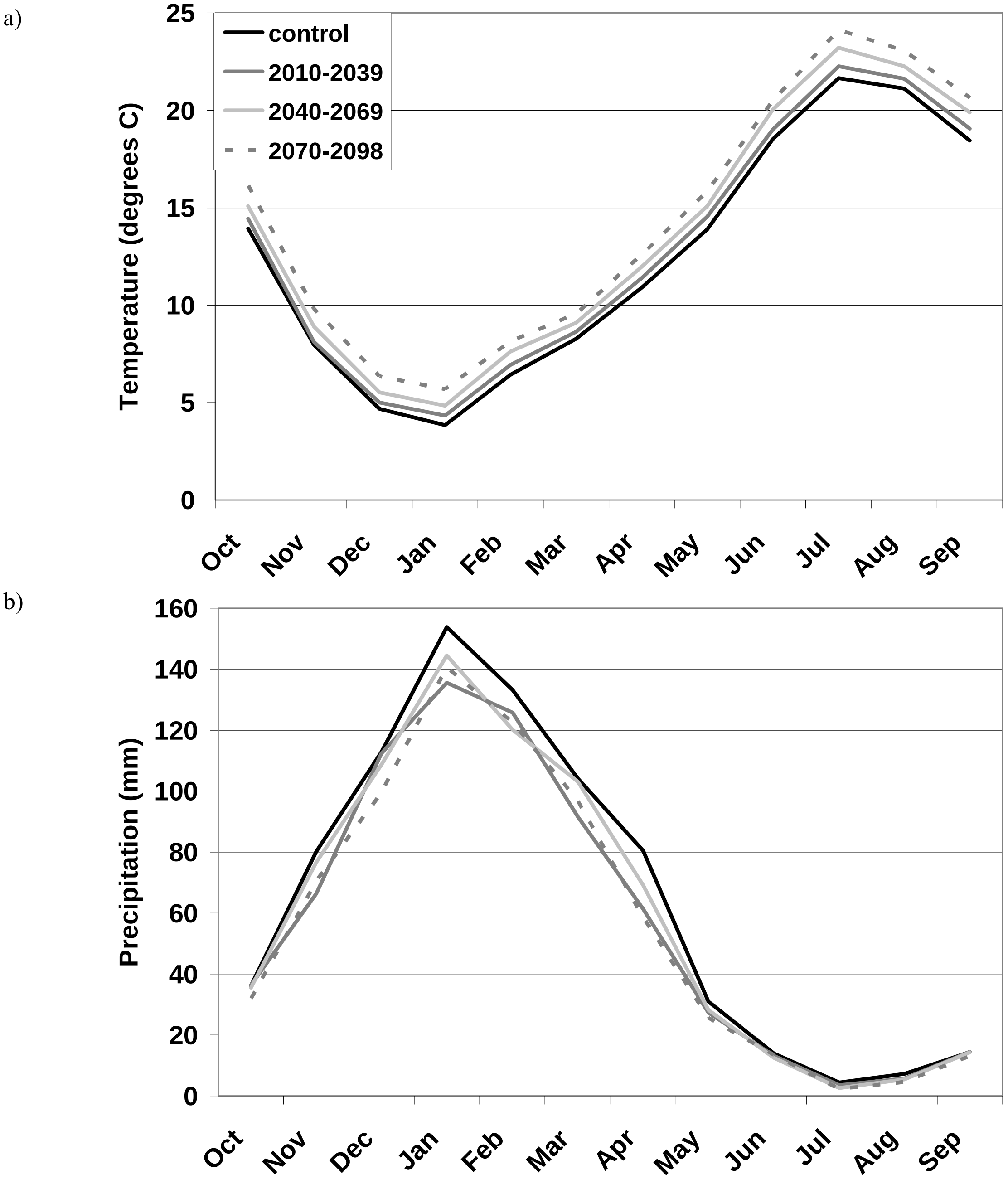

Figure 6. Observed and mean monthly Central Valley precipitation (a) and temperature (b) for control and Periods 1-3 (2010-2039, 2040-2069, 2070-2098)

In general, the climate and hydrology changes associated with the PCM BAU ensembles would significantly degrade the performance of the CV water resources system. Most impacted is the ability to reliably provide water needed to meet fisheries, environmental, and hydropower objectives. Efforts to mitigate these potential impacts using various management strategies have been largely unsuccessful in simulations (VanRheenen et al., in review).

It is becoming increasingly clear that the joint impacts of climate change and future demand growth in the Central Valley will create a system impossible to return its past performance. The obvious implication is that adaptive management techniques in Central Valley operations are

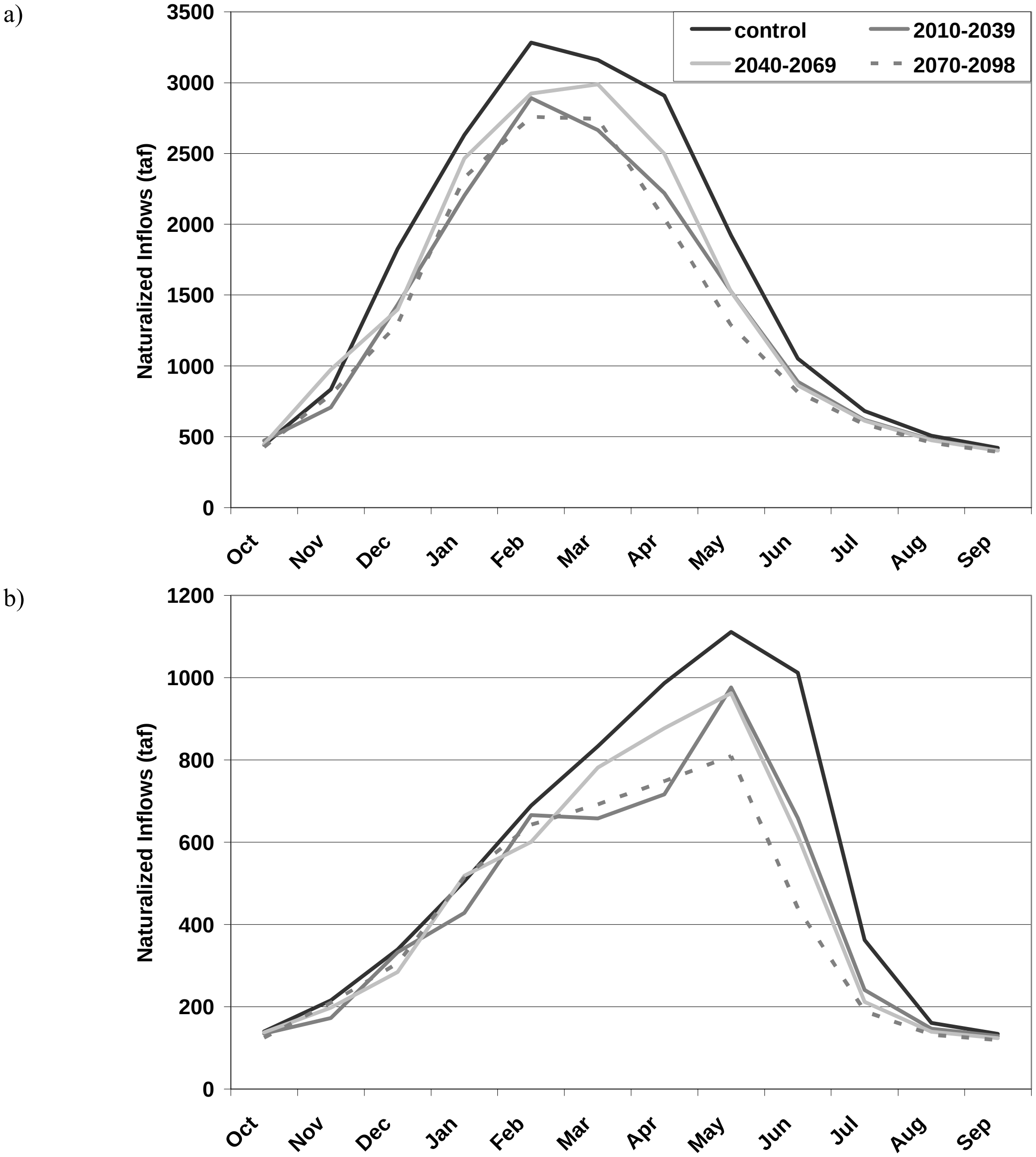

Figure 7. Naturalized control and climate change inflows for the (a) Sacramento and (b) San Joaquin River basins.

not enough. It is very likely that infrastructual changes and expansion projects will be necessary to reliably and responsibly prepare for a changing future.

CONCLUSIONS

Climate change is only one of many concerns faced by municipal water supply agencies and state-wide water supply projects when planning for the future. Also important are the uncertainties associated with water demands, changes in crop irrigation practices, costs of producing crops, national and international food preferences, hydropower operation values, energy and water demand conservation effectiveness, changing user demographics, unanticipated treatment costs, maintenance of system infrastructure, changing water quality regulations, evolving requirements of aquatic populations, and numerous other environmental concerns. In all analyses, the ability to develop and maintain new water supply options must be weighted against their respective costs and benefits. Dealing with each of these areas, whether in the context of climate change or not, will likely necessitate the need for robust mitigation and adaptive management techniques.

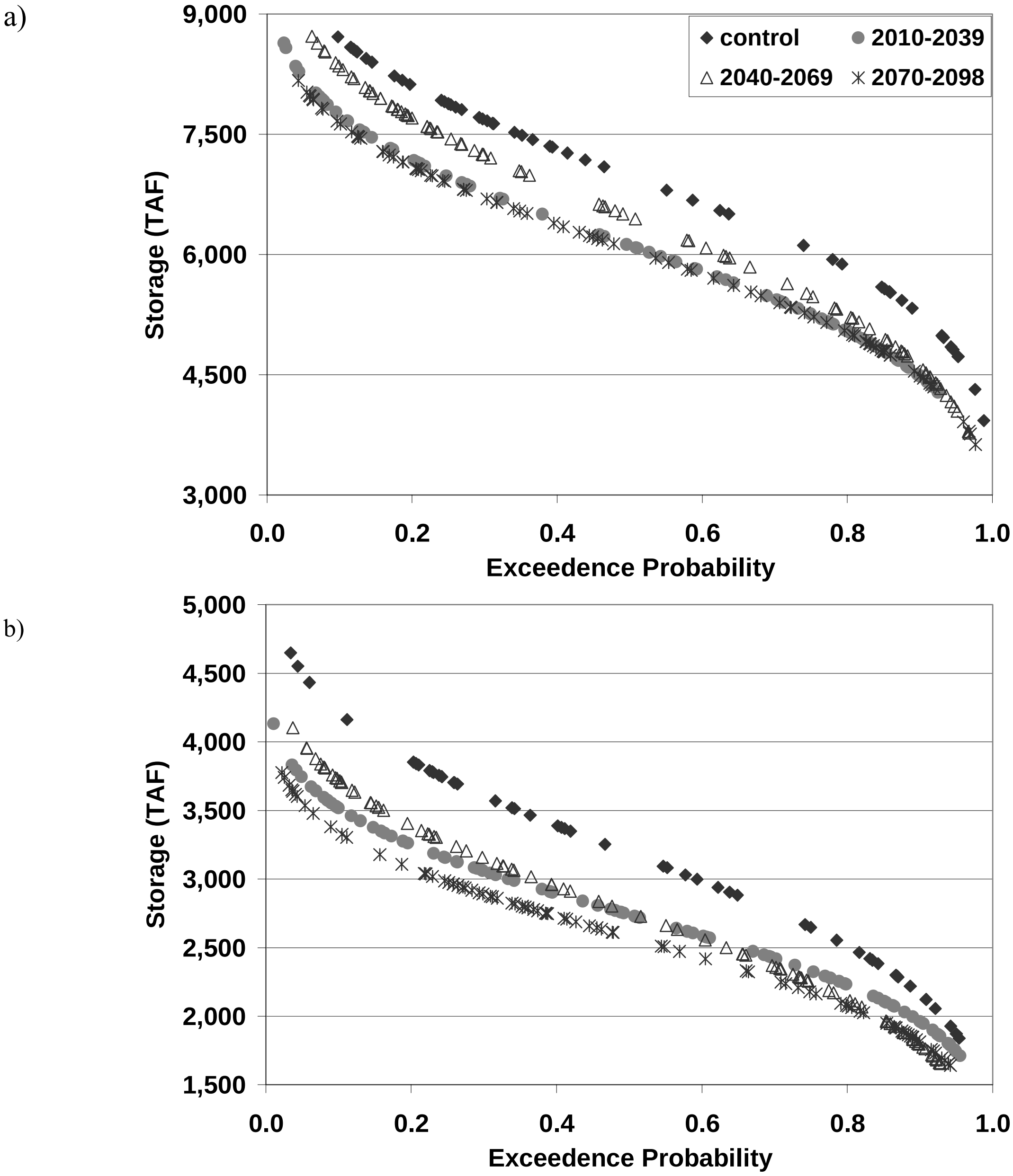

Figure 8. Cumulative frequency distribution of minimum annual cumulative storage for the (a) Sacramento and (b) San Joaquin systems

Explicit consideration of climate change is important, however, as it may significantly alter water supply sources that have been considered "certain" in the past. With respect to the agencies and utilities involved with the Portland and Central Valley case studies discussed in this paper, a great many strategies to mitigate the impacts of climate change are currently under review. These strategies include both management and build-based techniques.

A closing comment is appropriate relative to the uncertainties associated with the results of any current climate change evaluation. There is considerable and well- intentioned concern related to the "certainty" of the results from climate change models. An appropriate question is the degree of confidence that can be associated with such studies, given the relative infancy of the tools used to generate climate change scenarios. The approach taken in this paper is to generate results based upon the most widely accepted climate change models and two different downscaling techniques that appear to be appropriate in their respective applications. While none of the GCMs purport to model the exact climate that will occur in the decades ahead, they do attempt to

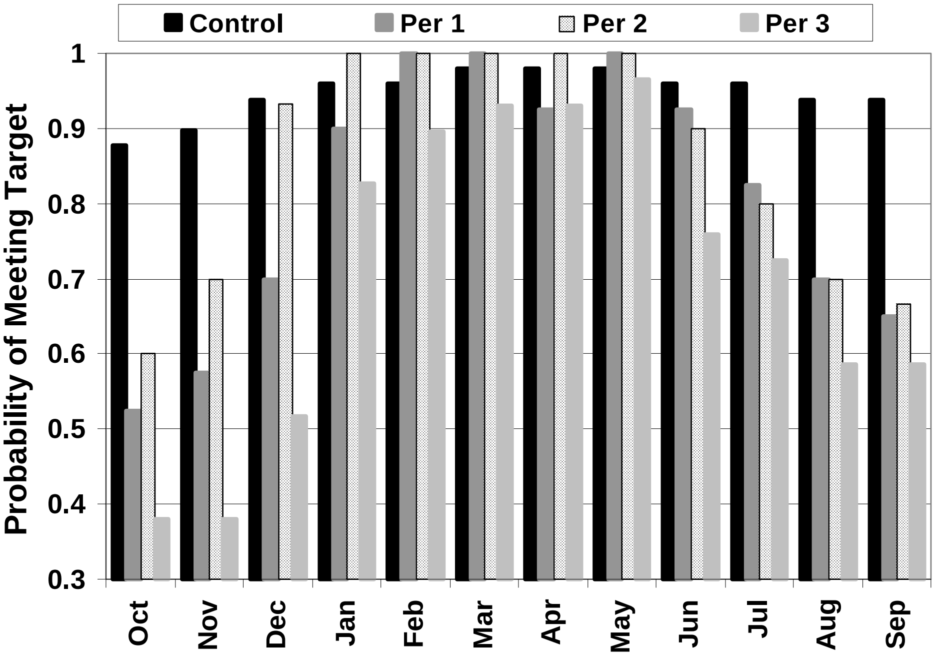

Figure 9. Mean monthly reliabilities of meeting Lake Shasta environmental targets for control and climate change scenarios, given current operating rules and year 2001 demands

generate global conditions that are likely to occur given the assumptions incorporated into the models.

Despite the variability of results between GCMs, the message in each of these case studies is consistent: climate change will make managing our existing water resources more challenging. Ignoring the potential impacts of climate change because of limitations in current modeling methods is an option that may result in significant unplanned economic and social costs in the future. A far wiser path is to acknowledge the range of impacts that could occur and develop adaptive management policies that deal with climate change. Our studies indicate that the sooner this path is followed, the better.

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AUTHOR INFORMATION

Nathan VanRheenen is a Ph.D. candidate in water resources systems engineering in the Department of Civil and Environmental Engineering at the University of Washington. Richard N. Palmer (Ph.D., Johns Hopkins University, 1978) is a professor in the same department. Margaret Hahn is a consulting engineer with RW Beck, Seattle, Washington.

REFERENCES

Cohen, S.J., K.A. Miller, A.F. Hamlet and W. Avis, 2000. Climate Change and Resource Management in the Columbia River Basin, *Water International.* 25(2): 253-272.

Frederick, K.D. and D.C. Major, 1997. Climate Change and Water Resources, *Climatic Change* 37: 7-23.

Gleick, P.H., 2000. *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States*, National Water Assessment Group for the U.S. Global Change Research Program.

Hadley Centre, 2001. Hadley Centre for Climate Prediction and Research Web Page. Available: http://www.meto.govt.uk/research/hadleycentre/index.html.

Hahn, M.A., R.N. Palmer, A.F. Hamlet and P. Storck, 2001. A Preliminary Analysis of the Impacts of Climate Change on the Reliability of the Seattle Water Supply. *Proceedings of World Water and Environmental Resources Congress.* Orlando, Florida, May 2001.

Hamlet, A.F and D.P. Lettenmaier, 1999. Effects of Climate Change on Hydrology and Water Resources in the Columbia River Basin, *Journal of American Water Research Association* 35(6): 1597-1623.

Hashimoto, T., J.R. Stedinger, and D.P. Loucks, 1982. Reliabilty, Resiliency, and Vulnerability Criteria for Water Resource System Performance Evaluation, *Water Resource Research* 18 (1): 14-20.

Intergovernmental Panel on Climate Change (IPCC), 1990. *Climate Change: The IPCC Scientific Assessment: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* J.T. Houghton, G.J. Jenkins, and J.J. Ephraums, eds., Cambridge University Press.

Intergovernmental Panel on Climate Change, 1996. *Climate Change 1995: The Science of Climate Change: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell, eds., WMO/UNEP, Cambridge University Press.

Intergovernmental Panel on Climate Change, 2001. *Climate Change 2001. The Science of Climate Change: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Technical Summary.* F. Joos, A. Rojas-Ramirez, J.M.R. Stone, J. Zillman, eds., WMO/UNEP, Cambridge University Press.

Kirshen, P.H. and N.M. Fennessey, 1995. Possible Climate-Change Impacts on Water Supply of Metropolitan Boston, *Journal of Water Resource Planning Management* 121(1): 61-70.

Lettenmaier, D.P., A.W. Wood, R.N. Palmer, R.N., E.F. Wood and E.Z. Stakhiv, 1999. Water Resources Implications of Global Warming: A U.S. Regional Perspective, *Climatic Change* 43: 537-579.

Liang, X., D.P. Lettenmaier, E.F. Wood, and S.J. Burges, 1994. A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for General Circulation Models, *J. Geophys. Res.* 99(D7): 14415-28.

Liang, X., E.F. Wood and D.P. Lettenmaier, 1996. Surface soil moisture parameterization of the VIC-2L model: Evaluation and modifications, *Journal of Global and Planetary Change* 13: 195-206.

Lohmann, D., E. Raschke, B. Nijssen and D.P. Lettenmaier, 1998a. Regional Scale Hydrology: II. Application of the VIC-2L model to the Weser River, Germany, *Hydrological Sciences-Journal des Sciences Hydrologiques* 43: 143-158.

Lohmann, D., X. Liang, E.F. Wood, D.P. Lettenmaier and others, 1998b. The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) Phase-2c Red-Arkansas River Basin Experiment: 3. Spatial and Temporal Analysis of Water Balance Fluxes, *Journal of Global and Planetary Change* 19: 161-179.

Maurer, E.P., G.M. O'Donnell, D.P. Lettenmaier, and J.O. Roads, 2001. Evaluation of the Land Surface Water Budget in NCEP/NCAR and NCEP/DOE Reanalyses using an Off-line Hydrologic Model, *J. Geophys. Res.* 106(D16), 17, 841-17, 862.

Max Planck Institute, 2001. ECHAM4 webpage: http://www.mpimet.mpg.de/Depts/Modell/ECHAM/Description/ECHAM4_description.html.

Nijssen, B., D.P. Lettenmaier, X. Liang, S.W. Wetzel and E.F. Wood, 1997. Streamflow simulation for continental-scale river basins, *Water Resources Research* 33: 711-724.

Parallel Climate Model (PCM) webpage, 2001. http://www.cgd.ucar.edu/pcm.

Piechota, T. and J.A. Dracup, 1996. Drought and Regional Hydrologic Variation in the United States: Associations with El Nino/Southern Oscillation, *Water Resources Research* 32(5): 1359-1373.

Piechota, T. and J.A. Dracup, 1997. Western U.S. Streamflow and Atmospheric Circulation Patterns during El Nino/Southern Oscillation, *Journal of Hydrology* 201(14): 249-271.

Storck, P., 2000. Trees, Snow and Flooding: An Investigation of Forest Canopy Effects on Snow Accumulation and Melt at the Plot and Watershed Scales in the Pacific Northwest. *Water Resources Series Technical Report 161*, University of Washington.

Umbauch, K.W., 1997. A Statistical Tour of California's Great Central Valley. C*alifornia Research Bureau* CRB-97-009. http://www.library.ca.gov/CRB/97/09/index.html.

VanRheenen, N.T., A.W. Wood, R.N. Palmer and D.P. Lettenmaier, in review. Potential Implications of PCM Climate Change Scenarios for Sacramento - San Joaquin River Basin Hydrology and Water Resources. *Climate Change*.

Washington, W.M., J.W. Weatherly, G.A. Meehl, A.J. Semtner, T.W. Bettge, A.P. Craig, W.G. Strand, J. Arblaster, V.B. Wayland, R. James and Y. Zhang, 2000. Parallel climate model (PCM) control and transient simulations, *Climate Dynamics* 16: 755-774.
Wigmosta, M.S., L.W. Vail and D.P. Lettenmaier, 1994. A Distributed Hydrology-Vegetation Model for Complex Terrain, *Water Resource Research* 30(6): 1665-1678.

Wood, A.W., D.P. Lettenmaier and R.N. Palmer, 1997. Assessing Climate Change Implications for Water Resources Planning, *Journal of Climate Change* 37(1): 203-222.

Wood, A.W., E.P. Maurer, A. Kumar and D.P. Lettenmaier, 2001. Long Range Experimental Hydrologic Forecasting for the Eastern U.S., *Journal of Geophysical Research* 107(D20): 4429.