The Potential Impacts of Climate Change on Portland, Oregon's Water Supply

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Abstract

This paper evaluates the impacts of climate change on municipal water supplies using the City of Portland, Oregon and its Bull Run River watershed as a case study. The impact of climate change on the basin's hydrology is evaluated, together with Portland Water Bureau's (PWB's) ability to provide water reliably from the Bull Run system in the future. Forecasted climate change from four general circulation models (GCMs) are used to translate past meteorological events into streamflow forecasts using a distributed watershed model. Hydrologic impacts from climate impacted forecasts suggest an increase in winter flows and a decrease in spring and summer flows associated with the timing of precipitation and the timing snowmelt runoff. Water demand is anticipated to increase by 8% due to climate change during the summer months, resulting in longer period of reservoir drawdown. The average loss in safe yield of one of the GCM's by the year 2040 is 21 mgd. Increases in water demand due to regional growth are expected to be twice that of climate change, making climate change a significant, but not the dominant, impact on the region's ability to supply water reliably.

1. Introduction

The initial reports of the Intergovernmental Panel on Climate Change (IPCC 1990 and 1996) and those that have followed (IPCC 2001) have consistently noted that our

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climate is changing. These reports indicate that one of the most important impacts of climate change is on the world's water supplies. In a review of over 1000 relevant peer-reviewed studies, Gleick et al. (2000) concluded that “in many cases and in many locations, there is compelling scientific evidence that climate changes will pose serious challenges to our water systems.” These reports have noted that not all regions will be impacted equally, with some regions experiencing particularly negative effects, while other areas may actually benefit from climate change. The impacts of climate change on U.S. water resources is expected to be most profound in the west, where the runoff cycle is largely determined by snowmelt (Cohen et al., 2000). Many previous studies indicate that the effects of warmer climates on the seasonality of runoff in such regions will likely shift a portion of spring and summer melt runoff earlier in the year (U.S. EPA, 1989; Piechota and Dracup, 1997; Lettenmaier et al., 1999; IPCC, 2001).

Water supply systems in the western U.S. are negatively impacted from such shifts in runoff seasonality, because, although streamflows are heavily regulated, snowpack represents significant water storage that helps to augment low streamflows during relatively dry summers (Hamlet and Lettenmaier, 1999; VanRheenen et al., 2003, in review). The impact of climate change on water supplies in the Pacific Northwest has been of interest for a number of years (Hahn et al., 2001; Lettenmaier et al., 1999; Wood et al., 1997). Pacific Northwest basins hold particular interest because of the interplay of two factors, precipitation and temperature. All of the major water resource systems in the Northwest rely on snowpack to provide a significant source of water in the late spring and early summer. Changes in temperature and precipitation alter the delicate interaction between the amount of precipitation that falls as rain and the amount that falls as snow.
Temperature directly influences the eventual accumulation of snow during the winter and the temporal variability with which this snow melts and is released in a watershed.

The extent to which climate change may impact a watershed and its use are a function of several factors including the magnitude of the change in climate, the degree to which the watershed has already reached its sustainable use, and the physical setting of the watershed. Small shifts in climate (precipitation and temperature) may or may not result in significant changes in a watershed. Generally, watersheds that are already at their sustainable level of use may be significantly impacted by even minor shifts in climate. Watersheds that are located at very high elevations may not be impacted by modest changes in temperature, as most of their precipitation will continue to fall as snow. Watersheds at low elevation will likewise 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 may have significant impacts on the drawdown and refill cycle of a reservoir.

Two different types of watersheds are at greatest risk to climate change in the US. The first include highly developed watersheds in the Southwest and West. These watersheds have large reservoirs that can hold several years of annual streamflow, but are characterized by high annual demands relative to annual inflows. The timing of streamflow runoff is not significant, as the storage capacities of the reservoirs can be used to moderate the 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 second watershed type that is at significant risk is transient watersheds. A transient watershed receives its precipitation as both rain and snow resulting in a “two peak” hydrograph, one peak in early winter from rain fall and another peak in the spring due to snow melt. Watersheds supplying municipal water in the Pacific Northwest in particular encounter the possibility that even small changes in climate may influence the quantity and timing of runoff. Analysis of the impacts of climate change in municipal watersheds for Puget Sound, Washington reveal a change in the timing of streamflow volumes, as a result of the climate change induced snow accumulation and melt (Hahn et al., 2001). The Bull Run watershed, similar in elevation and vegetation to other Western Cascade municipal watersheds, is examined here in detail to determine the range of potential impacts associated with climate change.

Climate change is, of course, only one of many concerns faced by utilities when they plan for the future. Utilities must also cope with the uncertainties associated with water demand, conservation, changing user demographics, unanticipated treatment costs, maintenance of system infrastructure, changing water quality regulations, evolving requirements of aquatic populations and other environmental concerns, and their ability to develop and maintain new water supply options.

Explicit consideration of climate change is important, however, as it may significantly alter water supply sources that have been considered "certain" in the past. Climate change can not be controlled directly by an individual utility (this will be address with national and global policies), but it should be considered when evaluating source
reliability. Studies identifying the impacts of climate change on water are becoming more numerous and our ability to understand and model such impacts is improving (IPCC 2001). It is a primary purpose of this report to place potential climate change in its proper perspective relative to other planning concerns, most explicitly that of growing future water demands.

This study employs a series of loosely linked models to address potential impacts of climate change. These models simulate three aspects of process: the climate, the hydrologic cycle, and water supply system management. Outputs from climate models are used to alter past meteorological data to capture the potential impacts of future climate. These data then serve as inputs into a hydrologic model of the Bull Run watershed, which in turn, provides inputs to the water supply systems model.

This report describes the models that are used, the analysis process, and the results that were generated for the Bull Run system. Section 2 describes the hydrology of the Bull Run watershed and the interaction between the basin’s hydrology and the PWB's system of reservoirs. Section 3 discusses the models and model assumptions used in the analysis. Section 4 presents the climate change impacts that come from the GCMs. Section 5 describes how climate change is modeled within the watershed. Section 6 describes the impacts of climate change on the water supply system performance. The final section summarizes the major conclusions and provides recommendations for planning and management strategies for the Bull Run system.
2. Bull Run Watershed Hydrology

The Bull Run watershed is located approximately 30 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 rainfall 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 (97 billion gallons, 13 billion cubic feet) at Bull Run Headworks.

Reservoirs 1 and 2 have a combined capacity of 51,384 acre-ft (16.7 billion gallons) of which 31,384 acre-ft (10.2 billion gallons) is active storage and 20,000 acre-ft (6.5 billion gallons) is considered dead storage due to natural sediments in the lower portions of the reservoirs. Bull Run Lake, used intermittently during times of drought, has a capacity of 1841 acre-ft (0.6 billion gallons). The total annual flow at the point of diversion on the Bull Run is 600,000 acre-ft (195.5 billion gallons). The vast majority of this flow occurs during winter months.

The basin's precipitation falls as both rain and snow and there is a direct correlation between the average monthly precipitation and streamflow throughout the year, with the highest correlations in the summer and fall. Snow melt does contribute to streamflow in April and May, and low soil moisture in August reduces August's streamflows even after precipitation increases after the typically dry summers.

3. Models

Three types of models were used in this study: GCMs, a precipitation/runoff watershed model, and a water supply system management model. The linked model
process is common in the area of climate change impact assessment (Hamlet and Lettenmaier, 1999; Wood et al., 1997; Kirshen and Fennesey, 1995). Each of these models is described in detail in the following subsections.

3.1. General Circulation Models

Four GCMs were used in this study: the Department of Energy’s Parallel Climate Model (PCM), the Max Planck Institute’s ECHAM model and the Hadley Centre’s HadCM2 and HadCM3 models. These models incorporated a one percent increase in atmospheric carbon dioxide per year. They report climate information for the years 2025 and 2045, which approximate the average conditions for the 2020 and the 2040 decades.

The Parallel Climate model was developed in 1996 by the National Center for Atmospheric Research with support from the US Army Corps of Engineer's Cold Regions Research and Engineering Lab and Los Alamos National Laboratory with funding from the US Department of Energy. It is a coupled atmosphere-ocean model with a 2.8 by 2.8 degree resolution. The PCM is currently used for climate change studies throughout the western US (PCM 2001).

The Hadley Center models and the Max Plank models are included in the most recent IPCC report (IPCC 2001) and in IPCC reports of the past (IPCC 1990, 1996). The Hadley Center models, HadCM2 and HadCM3, were developed in 1994 and 1998, respectively. These models are also coupled atmospheric/ocean models with resolutions of 2.5 x 3.75 degrees. Although the HadCM3 is the successor model, the Center uses both models to estimate climate change. The difference between the two models is primarily in the modeling of ocean layer interactions and ocean decadal variability (Hadley Center 2001).
The Max Planck Institute of Meteorology model, ECHAM4, does not model the ocean. ECHAM4 models the atmosphere with a resolution of 2.8 by 2.8 degrees. ECHAM was developed in 1995, based on the weather forecast model of the European Centre for Medium Range Weather Forecasts (ECMWF) (Max Plank Institute 2001).

In this study, the climate signals are “downscaled,” because the spatial resolution of the GCM models is relatively coarse. This coarseness prevents the explicit consideration of many geographic, orographic, and maritime features (landscape and vegetation, mountains, bodies of water) that directly impact expected climate effects. To "downscale" the climate information, it was translated from a multi-degree to a one-degree scale with the Symap algorithm (Shepard, 1984).

In addition, the climate signals from GCMs are defined 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. This technique has been commonly used in the water resources literature (Hamlet and Lettenmaier, 1999). The temperature signal is 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. This approach addresses the natural biases that are inherent to the coarse resolution of the models and their inability to capture many of the physical features that impact climate. Unfortunately, this approach does not account for more systemic changes in weather patterns.

Average monthly differences between temperature and precipitation in the GCMs at the year 2000 and the GCMs at future years (2020 and 2040) are used to determine average monthly shifts due to climate change. These shifts are then applied to the
historic data and used as inputs for the watershed model. In any given year the impacts of climate change are created by using the basic historic temperature and precipitation data shifted by the appropriate value. Changes in temperature and precipitation can significantly alter the amount of rainfall, the proportion of rain to snow, and the temporal release of snowpack to the watershed. These changes form the foundation of the impacts that will be investigated in this report.

3.2. Distributed Hydrology, Soil-Vegetation Model

The hydrology model used in this analysis, the Distributed Hydrology, Soil-Vegetation Model (DHSVM) produces daily streamflow values that reflect the climate change signal. DHSVM is a physically based hydrology model that characterizes a watershed as a multi-layered grid. Each pixel in the grid is characterized by several physically-based data layers, including 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 grid size of the model element is 150 meters by 150 meters. The runoff in the simulation is transferred from cell to cell and forms streamflow networks.

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; Bowling, 1997; Van Shaar, 2000; Storck, 2000). It is currently being used at the University of Washington to generate short-term streamflow and snowpack forecasts for basins along the western slopes of the Cascade Mountain range (Hydromet, 2003)
Inputs into the DHSVM model include general basin characteristics (elevation, soil
type, precipitation, vegetation) and parameters estimates of detailed system interactions
(roughness of snow, leaf area index, etc.). The application of the DHSVM to the Bull
Run watershed required gathering spatial data sets that describe the basin’s physical
nature, collecting meteorological data sets 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 DHSVM model of Bull Run was calibrated in three stages: 1) an Initial
Calibration, 2) a Data Set Driven Calibration and 3) Parameter Driven Calibration. This
three-stage process is typical in calibrating physical models. It is important to first
establish that the basic model is appropriate, apply specific data for a basin, and then
modify parameter values to obtain a best fit.

Figure 2 compares the annual cumulative flows of the observed record and the
simulated flows of DHSVM, Current Climate. The average annual flows generated by
DHSVM are equivalent to the historical average. The calibrated model does an excellent
job of estimating the streamflows. It should be noted that there is a paucity of weather
stations within the basin. This lack of observed precipitation data makes estimating the
spatial distribution and quantity of precipitation throughout the basin difficult. The
results of the calibration process were considered excellent given the precipitation data
available.

3.3. Supply and Transmission Model

The streamflows generated by DHSVM are used as input to the Portland Water
Bureau’s Supply and Transmission Model (STM). The model was developed by the
University of Washington and PWB staff over several years. The model is used by PWB staff to analyze terminal storage and groundwater operations. The model evaluates future planning scenarios, such as conservation and expansion alternatives. In this study the model examined the impacts of climate change on the existing system as well as two planning scenarios. The development and application of the STM has been described previously (Palmer and Hahn, 2001; Palmer et al., 2000).

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 hydropower production, as well as for instream flows. Groundwater operations are coordinated with reservoir operations with a variety of operating alternatives that regulates groundwater use. The model also 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.

4. Climate Change Impacts on the Meteorological Record

As discussed previously, the climate change signal is downscaled as a shift in temperature and a percent change in precipitation. The monthly climate change signals for precipitation and temperature downscaled from the four GCMs are used in this study. Figures 3 and 4 demonstrate that by 2040, four of the climate change models predict warmer and wetter climates on an annual basis. Data for the 2020 decade (not presented)
show similar characteristics. The one exception to these general trends is ECHAM4, which predicts less precipitation in months of October, November, December, and January. The four GCMs produced significant variation in the forecasted average shift in precipitation in 2040. Precipitation was slightly more than average in October and May and less than the historic average in June through September.

The change in the temperature signal also varies among the four models, but the shift is more consistent, always indicating warmer weather. The temperature signal for 2040 predicts higher temperatures on average in the summer with 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.

5. Hydrologic Impacts

Having established the impacts of potential climate change on temperature and precipitation, the impacts of climate change on the hydrology of the Bull Run watershed was determined. A number of issues arise. First, will changes in temperature and precipitation in the future influence the basic hydrology of the basin? More precisely, will the volume and timing of streamflow change? Second, if there is a shift, which factors are the most important in this change--precipitation, temperature, or their joint influences on snowpack accumulation and melt? Finally, how will these changes be manifested in the basin relative to water supply issues? Will climate change most likely influence annual water availability, seasonal water availability, or late summer availability?
Climate Change Signals

Figure 5 presents the average monthly hydrograph of the basin for the four 2040 climate change scenarios. The range of values for fall and winter flows is indicative of the variability of the climate change precipitation signal of the four models. The temperature portion of the signal has a relatively consistent impact, as spring flows are lower for each of model runs. The spring flows (April) are significantly less in the 2040 scenarios than in the current climate scenarios. This demonstrates the impact of the warmer 2040 temperatures on spring runoff.

The increased winter precipitation and the warmer temperatures create higher winter streamflows and the lower spring time flows. This lagged effect of warmer winter temperature is similar in the four climate change signals. HadCM3 2040 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.

The impacts of climate change on the basin hydrology is quantified by the season cumulative flow and presented in exceedance probability curves, Figure 6 and Figure 7. The climate change signals create greater winter flows and smaller summer flows. The ECHAM4 2040 cumulative winter flows are similar to the current climate, whereas the ECHAM4 2040 cumulative summer flows are the lowest of the four climate models and the current climate cumulative flows.

A plot of cumulative annual summer flows (Figure 8) indicates that the response to climate change is not uniform. Climate change can have a relatively small impact on annual cumulative summer flows, or a very large impact. Further investigation lead to
the conclusion that for this setting, the impacts of temperature were greater than those of precipitation. Figure 9 indicates the change in streamflows related solely to changes in temperature. Rather than investigating a specific model (in which the temperature signal varied from month to month), this figure presents the impacts of climate change on average monthly flows if the temperature in all months were 1° and 2° C warmer. As the figure indicates, the temperature change alone can produce hydrographs similar to those predicted for climate change.

6. Supply and Transmission Results

After calculating the impacts of climate change on streamflows, these climate-altered streamflows are used to evaluate their impacts on water supply performance with the STM. Several combinations of current and future conditions are evaluated. Special care has been taken to separate the impacts of climate change from those of population growth.

The STM is used to examine water supply and water demand under climate conditions and to compare the impacts of climate change with other key components. The results are presented in two evaluations. The first evaluation compares the climate impacts on streamflow volumes and timing and the impacts of regional water demand on system performance. This evaluation uses the current infrastructure and a 49-year record to generate exceedance probability curves with which to quantify impacts of climate change on streamflow volumes and timing and the impact of regional growth on demand.

The second evaluation also uses the current system, but investigates the seven featured years in greater detail. The evaluation presents the different impacts (climate impact on hydrology, climate impact on demand, and growth impact on demand)
separately and then jointly. The ECHAM4 climate scenario is chosen for the detailed analysis in the second because it has a relatively consistent signal between the 2020 and 2040 decade and has the greatest impact on hydrology.

6.1 Impacts on System Performance for all years

A primary measure of a system’s performance is the minimum storage during the year. If storage decreases below established thresholds, water reliability is compromised and management actions must be taken. Figures 10 and 11 present the ranked minimum storage minus any shortfalls for combinations of demand year and climate change year.

The figures indicate that for a given probability, the storage values for the current climate / 2000 demand curve are greater generally than those of the changed climate. Differences in the storage values for the 2040s are consistent and range between 0 and one billion gallon difference 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 also developed for the minimum storages less shortfalls for the system if only the impact of regional growth on demand is considered (Figure 11). 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 reduction in storage for 2020 regional growth and an additional 1.5 billion 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.

### 6.2 Impacts on System Performance for Selected Drought Years

The second evaluation includes the impacts of climate change on water demand, which is calculated with data provided by Dr. Hossein Parandvash of PWB. The impact on demand is calculated based on a change in average temperature and precipitation using an econometric water demand model. The peak season demand is increased approximately 8% and the average annual increase in demand is 4%. The impacts of climate change on demand are not available for all 49 years; however, the seven years chosen provide insight into the response of the system for average years and for the hydrologic and weather extremes.

The years chosen in this analysis for particular scrutiny include: 1952, 1966, 1968, 1982, 1987, 1992 and 1994. Four of the years commonly are used to describe hydrologic events with particular return periods: the 1 in 30 year event (1987), the 1 in 20 year event (1992) and 1 in 10 year event (1994) and the average year (1982). Other years, 1952 and 1966, were chosen because they are significantly impacted by climate change. One other year, 1968, was chosen to represent a relatively wet year.

Figure 12 presents the impacts on the seven years using the ECHAM4 climate change scenario. The impact of climate change on hydrology and demand vary between years. The sensitivity of hydrology to weather is greater than that of demand. The climate change impact on both demand and hydrology is calculated to be between 5.366 billion gallons (1966) and 1.188 billion gallons (1968).
The results of Figure 12 can be summarized as the following: for the case of the seven hydrologic years, average minimum storage will decrease by about 4 billion gallons by 2020 and 5.5 billion gallons by 2040 due to growth in demand alone. This stress on the system is exacerbated by the impacts of climate change on hydrology and demand in the future, decreasing the average storage by 8 billion in 2020 and 9 billion in 2040.

Table 1 presents the average of the seven years, the number of days of drawdown and the loss in remaining yield. Remaining yield is the annual minimum storage value divided by the number of days of drawdown, and it represents the volumetric rate of water that could have been used or that is still remaining. Loss in remaining yield is based on the comparison of the base case (current climate/current demand) and an alternative (changed climate/current demand). The loss of remaining yield is therefore the difference between the remaining yield of the alternative (2040 climate change impacts on hydrology and demand and regional growth impact on demand) and the base case (current climate/2000 demands).

The average loss of remaining yield for the seven years is 21 mgd during drawdown. For years (such as 1968) rainfall and snowpack is plentiful and the yield of the system is much larger than demand. During such years, losing twenty mgd in yield does not compromise system reliability. For drought years, however, this is a significant problem. For those years whose ranking changes due to significant climate impacts on hydrology, the loss of remaining yield is an emerging and potentially significant problem. Figure 16 compares the loss in remaining yield to the actual remaining yield.

The evaluation of the seven featured years highlights several conclusions about the impacts of climate change. First, the average impact of climate change on hydrology
is a 1 billion gallon reduction in storage, but can be as great as 3.6 billion gallon (1966 hydrology). Second, the impact of climate change on demand results in an 8% demand increase during the peak season which results in an average 1.5 billion gallon reduction in storage and as much as 2.3 billion gallons (1992). The average combined impact of climate (on both demand and hydrology) is 2.8 billion gallon reduction in storage with the largest impact from 1966 hydrology of a 5.4 billion gallon storage reduction. The impacts on the system of climate change exacerbate the impacts of regional growth, creating an average of 9.6 billion gallons of reduction in storage and can be as great as a 12.2 billion gallon reduction for the 1966 hydrology.

7. Conclusions

The results of this study suggest that many US water supply systems may be negatively impacted by climate change, particularly those that use snowmelt as a source of water. This includes the majority of the large population centers in the western US. Although annual precipitation in watersheds may increase in some regions, the timing of the precipitation may not correspond to those periods during high water demand. Runoff will likely occur earlier in the spring time, due to temperature increases, and summer flows will be lower due to the combination of smaller spring runoff and lower summer precipitation. These impacts will not be limited to municipal water supplies, as other studies by the author have indicated (Lettenmaier et. al, 1999; Wood et al., 1997), but will have significant impacts on power production and the ability to meet environmental flows.

In addition, climate change will also increase water demands for municipal water supplies. In many US systems, even modest increases in municipal water demands will
accelerate the need to develop new water supplies or increase conservation efforts. These increases in demands will come during the portion of the year when the system is least capable of meeting them.

Specifically, this study evaluates the potential impact of climate change on the Bull Run watershed and the performance of the PWB's water supply system. The study examines these impacts using a series of linked models that evaluate the climate change signal from four GCMs, the impacts of these climate signals on streamflows, and the impacts of these climate-altered streamflows on water supply performance.

The primary conclusion of this study is that climate change will have a significant impact on the hydrology of the Bull Run watershed and will impact the safe yield of Portland's water system. For seven typical dry years, climate change will reduce the amount of water that can be used to meet water demands by an average of 1.5 billion gallons and increase demand during the drawdown period by 2.8 billion gallons, resulting in 4.3 billion gallons of reduced minimum storage. These climate impacts exacerbate the need that exists to provide some 9.6 billion gallons of increased demands due to regional growth. This primary conclusion is based upon the following:

• The streamflows in the Bull Run watershed are controlled predominantly by rainfall rather than snowpack. Snowpack does provide additional flows in the early spring, but these are typically exhausted before the supply system begins it drawdown in late June.

• The average climate change signal from the four general circulation models result in increased temperatures (1.5 - 2.0 C) and slightly increased precipitation.
• The trend in the decade 2020 and decade 2040 is for wetter and warmer winters and drier and warmer summers. The Bull Run watershed responds to the climate change signals as higher flows in the winter, lower spring-time flows and an earlier spring recession.

• The impacts of climate change are not uniform from year to year. The years for which climate change will have the greatest impacts are those that had high winter precipitation, cool winter and spring temperatures, and/or warm summer temperatures.

• The shift in the timing and volume of spring runoff in the Bull Run basin associated with climate change, particularly by 2040, will decrease the average maximum winter snowpack. This will result in an increase in the frequency of low flow in early summer. This shift will result in a number of droughts as extreme as 1992.

• In approximately 50% of the years, climate change impacts by the year 2040 would decrease minimum system storage by more than 1 billion gallons each year. This decrease results from earlier spring runoff that cannot be captured in the reservoirs and lower summer flows due to the earlier streamflow recessions.

• An analysis of the 6 dry years (within the lowest 30%) reveals an average loss in annual minimum storage of 2.8 billion gallons due to the impacts of climate change on hydrology and demand. Although continued growth in the M&I demand will have a more crucial impact on minimum annual reservoir storage than climate change (5.5 billion gallon reduction), the addition of climate change to growth results in a significant impact of an average reduction of 9.6 billion gallons reduction by 2040.

• The average loss in the annual safe yield for the ECHAM4 2040 climate scenario and the seven drought years is 21 mgd.
Studies at the University of Washington are underway to determine the impacts of climate change on a number of municipal water supplies, in addition to the impacts of major river basins in the US such as the Columbia, (in Washington, Oregon, Idaho, and Montana), the Colorado River (which spans many of the western states), the Rio Grande (Rio Bravo) River in the US and Mexico, and the Sacramento-San Joaquin in California. Preliminary results indicate that climate change will have significant impacts on regional hydrology, and mitigation efforts will be required to limit the economic impacts of such changes.

8. References


River Basin Hydrology and Water Resources,” submitted to *Journal of Climate Change*.


Figure 1 - Map of the Bull Run Watershed, Oregon
Annual Cumulative Flow
Combined Bull Run River Flows

Figure 2 - Comparison of Annual Cumulative Flow between Observed flows and DHSVM simulated (Current Climate)

Observed and 2040 Climate Change
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Figure 11 – Minimum Storage less Shortfalls 2000 Demands/2040 Climate
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Comparação da produção anual e perda em relação ao uso atual devido a mudanças climáticas e demanda.

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Figura 13 – Comparação da Produção Anual e Perda em Produção Anual devido a Mudanças Climáticas em Hidrologia e Demanda
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<table>
<thead>
<tr>
<th>Year</th>
<th>Climate impact on hydrology</th>
<th>Climate impact on demand</th>
<th>Climate impact on demand and hydrology</th>
<th>Impact of growth on demand 2040</th>
<th>Impact of climate change on 2040 demand and hydrology</th>
<th>Number of days of drawdown</th>
<th>Loss in Remaining Yield - Impact of climate change on 2040 demand and hydrology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1952</td>
<td>629</td>
<td>1,200</td>
<td>1,859</td>
<td>5,562</td>
<td>8,657</td>
<td>149</td>
<td>12</td>
</tr>
<tr>
<td>1966</td>
<td>3,598</td>
<td>1,232</td>
<td>5,366</td>
<td>5,633</td>
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