Water Supply and Climate Change in the Upper Deschutes Basin, Oregon

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ABSTRACT

Climate change is expected to alter the time and space characteristics of the global hydrologic cycle and to impact regional water supplies. The Upper Deschutes Basin is in one of Oregon's fastest growing regions, and the increasing population is straining regional water resources. Surface water is fully allocated and increased groundwater use will require careful management to offset seasonal or long-term declines in aquifers or the depletion of stream flow. While altered temperature and precipitation accompanying global change are both concerns, the watershed is more sensitive to changes in precipitation than in temperature. Watershed climate simulation reveals a 25 percent increase in mean monthly runoff, and extremely high monthly runoff is four times more frequent. These changes indicate an increased risk of winter floods, greater spring and summer runoff, and a shift in the occurrence of the minimum runoff month to earlier in the year. Increased potential evapotranspiration, a decrease in the amount of precipitation stored as snow, and changes in the amount and timing of runoff will constrain water development options for humans, agriculture, and regional fisheries. Water restrictions will magnify water-use conflicts in the watershed and increase the risk of regional economic discord.

Experiments using general circulation models (GCMs) indicate an increasing potential for climate change during the next 50 years that will impact regional water resources throughout the world. In the arid and semiarid western United States, the impacts of global warming on water supplies may be evident within the time horizons of current planning because even modest changes in precipitation have proportionally large impacts on water supplies (Jones 1996). However, water managers are reluctant to consider the policy implications of climate change because there are substantial uncertainties in GCM simulations of future climates and even larger uncertainties in transferring these GCM predictions into water balance and rainfall-runoff models for specific watersheds. Consequently, even areas experiencing critical limitations on water supplies under the present climate regime are reluctant to consider the implications of climate change for most operational applications while the acknowledged prediction errors remain large (Jones 1996; Changnon and Kunkel 1999). Furthermore, Lins and Stakhiv (1998) suggest that climate variability is an inherent part of water project design and operation and potential changes in weather patterns and climate should be viewed in the broader context of growing population and shifting water demands.

Runoff is a sensitive indicator of climate variability and a useful measure of how climate change might affect water supplies and other water-related resource uses (Wolock and McCabe 1999). Changes in precipitation are usually amplified in runoff because runoff integrates much of the spatial variability within the watershed (Jones 1996). However, transforming climate change scenarios produced by GCMs into estimates of regional, and ultimately watershed-scale, water balances and runoff is a major challenge.

In the Upper Deschutes Basin in central Oregon, both temperature and precipitation changes associated with an atmospheric doubled carbon dioxide ($_{2xCO2}$) climate are a concern because climate change will affect the water demand as well as the water supply. Climate change might influence a wide range of water-system components, including reservoir operations, irrigation diversions, water quality, and aquatic ecosystems. The purpose of this paper is to assess the expected water supply changes related to a 2xCO$_2$ climate in the Upper Deschutes Basin. Knowledge of potential water supply changes is needed for developing water management strategies that can respond to changing water demands created by population growth and changes in economic, social, and legislative conditions occurring concurrently with climate change.

Upper Deschutes Basin

The Upper Deschutes Basin is the major headwater area for one of Oregon's fastest-growing regions, and it drains 4,580 km^2 of the south and southeastern portion of the Deschutes River Basin south of Bend (Figure 1). The western and eastern drainage divides are clearly defined by the Cascade Range and the Paulina Mountains, respectively. The northern and southern watershed boundaries are poorly delimited topographically.

Regional climate is strongly influenced by the seasonal frequency of Pacific storm systems and the presence of the Cascade Range along the entire western boundary of the watershed. A winter precipitation maximum, a continental temperature regime, and steep west-to-east temperature and precipitation gradients characterize the watershed. Average annual precipitation is 1,500 mm at the highest elevations near South Sister, and is less than 400 mm across the lowlands southeast of the Little Deschutes River. Over 80 percent of the Upper Deschutes Basin is forested, but numerous volcanic peaks and lava flows contribute to a landscape mosaic with significant spatial heterogeneity.

Groundwater storage and transfers in layered basalts mask the influence of the watershed's natural climatic, topographic, and edaphic variability and efficiently filter groundwater to produce conspicuously clear and consistent streamflow. Average annual runoff for the Upper Deschutes Basin is 277 mm or $1,550 \times 10^6$ m^3 (Shelton 1999). A fault zone near Benham Falls forces northward-moving groundwater to discharge into the stream system, thus increasing confidence that the flow at Benham Falls is a reliable indicator of the total runoff for the Upper Deschutes Basin. About 60 percent of the Upper Basin runoff is diverted below Benham Falls, mainly for agricultural purposes. These diversions are supported by 0.44×10^6 m^3 of seasonal irrigation storage and releases in Crescent Lake and Crane Prairie and Wickiup reservoirs. Water rights allow streamflow diversions to irrigate 15,500 hectares within the Upper Deschutes Basin.

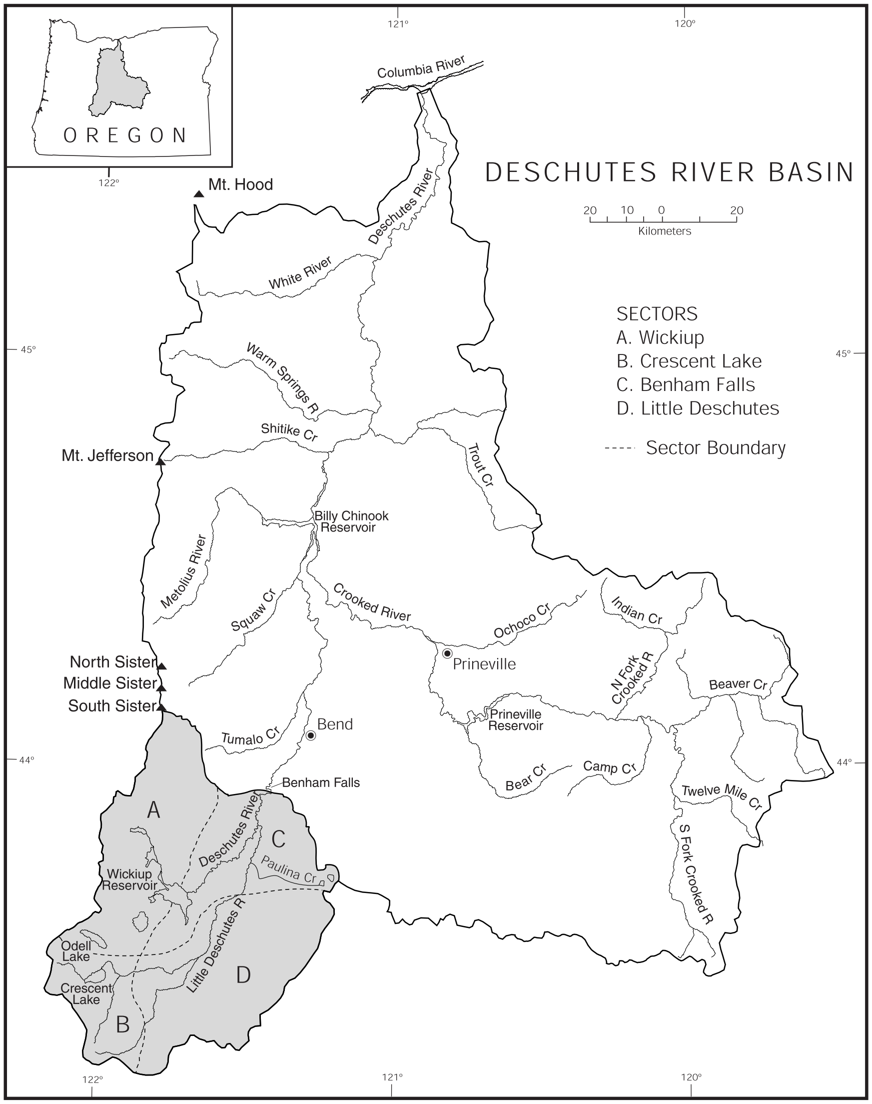

Figure 1. Upper Deschutes Basin and the Deschutes River Basin. Source: Figure 1, p. 70, APCG *Yearbook*, Volume 61, 1999. Reprinted with Permission.

Major recreation developments at the Sunriver resort and the Mount Bachelor ski area compete for water with other recreation and tourism activities and instream water uses within the basin. Historically, surface water has been the primary water supply in the Upper Deschutes Basin, but surface water is now fully allocated. Considerable investment is required to drill deep wells to develop groundwater in basalts, although groundwater may be relatively shallow in riparian areas. Population growth, agricultural water uses, and expanding water-based recreation and tourism industries are constrained by a lack of water, and recent legislative mandates for water to maintain streamflow and water quality have introduced additional regional water requirements.

Modeling Present Hydroclimate

Estimating the watershed response to a future climate requires successful modeling of the present hydroclimate and runoff process. Available data and the purpose of the study largely determine the watershed model selected to portray the transformation of precipitation into runoff in most climate change studies (Frakes and Yu 1999). A spatially disaggregated and semi-distributed moisture budget (SDMB) model requiring limited climatic and hydrologic data is employed to simulate hydroclimate in the Upper Deschutes Basin. The nonlinear and time-varying structure of the SDMB model, its previous application in the Upper Deschutes Basin, and the adaptation of the model to simulate a 2xCO_2 climate are described elsewhere (Shelton 1985, 1989, 1999, 2001). Only an overview of the model and the simulation of a 2xCO_2 climate are presented here.

The SDMB model allocates precipitation as a priority function determined by a series of regulators that operate on threshold principles (Shelton 1985, 1999). Two discrete groundwater storages simulate the hydrologic characteristics of stratified basalts. Mesoscale heterogeneity is included in the model by subdividing the watershed into four sectors identified using prominent physical features (Figure 1). The sectors are delimited to maximize internal homogeneity of precipitation, elevation, slope, vegetation, soil rooting depth, soil capillary water capacity, and hydrological responses (Shelton 1999). Hydroclimate is modeled separately for each sector, and the Upper Deschutes Basin is modeled by summing the area-weighted sector values (Shelton 1999).

A monthly time-step is used in the modeling because monthly temperature, precipitation, and snow course measurements are the only long-term, regional climate data readily available in the Upper Deschutes Basin. Water storage data for two of the three surface reservoirs are reported as monthly values, and only monthly estimates of irrigation diversions within the basin are practical (Shelton 1999). In addition, the dominance of groundwater storage and discharge in the runoff process dampens precipitation signals commonly exploited by shorter time steps. Representative monthly temperature and precipitation for each sector are estimated using weather data for Odell Lake (Figure 1) as the index for Wickiup and Crescent Lake sectors and Wickiup Dam weather data as the index for the Benham Falls and Little Deschutes sectors (Shelton 1999).

The 9 water years from October 1951 through September 1960 selected for the control climate simulation include a representative sample of monthly runoff variations commonly observed in the watershed. In addition, water diversions in the basin are limited during this period, thus reducing errors introduced by estimating monthly diversions. Mean monthly modeled control climate runoff and gaged runoff reconciled for water storage changes and summer irrigation releases from the reservoir are both 28 mm. The standard deviation of control climate runoff is 4.47 mm, compared to 4.98 mm for adjusted gaged runoff (Shelton 1999).

Since the mean and standard deviation might not sufficiently capture differences in the control climate and adjusted gaged runoff related to seasonal differences in precipitation and temperature, additional statistical measures sensitive to these characteristics are applied. The deviation of runoff volume measures the accumulated differences in monthly control climate runoff and adjusted gaged runoff. Complete agreement between control climate runoff and adjusted gaged runoff would produce a runoff deviation volume of 0. The value computed for the 108 months of this study is 0.0003 mm (Shelton 2001).

The root mean square error (RMSE) expresses the average error produced by the control climate model, the goal being for the RMSE to be as small as possible (Willmott 1984). The RMSE for the control climate model is 1.77 mm, and the unsystematic portion of RMSE for the control climate model is 1.58 mm or 89 percent of the RMSE (Shelton 2001). The unsystematic error should represent a large proportion of the RMSE when control climate runoff agrees closely with adjusted gaged runoff (Willmott 1984). All of the statistical measures indicate the SDMB model provides a realistic control climate representation of the runoff process in the Upper Deschutes Basin.

2xCO_2 Climate Watershed Simulation

GCMs have demonstrated an ability to reproduce important large-scale characteristics of global warming, but scaling methods are necessary for transferring GCM simulations of 2xCO_2 climate to the finer resolution required for modeling watershed processes. Regional scale changes in monthly temperature and precipitation reported by Giorgi *et al.* (1994) using the limited-area National Center for Atmospheric Research (NCAR)-Pennsylvania State University mesoscale model (MM4) nested in a doubled carbon dioxide equilibrium version of the NCAR Community Climate General Circulation Model are adopted for this study. The nested modeling system runs at a horizontal resolution of 60 km and satisfactorily reproduces the present-day seasonal temperature and precipitation cycle for the Pacific Northwest (Giorgi *et al.* 1993).

Adoption of varying monthly values has the advantage of incorporating changes in the mean and the variance of temperature and precipitation in achieving a realistic 2xCO_2 climate representation (Leavesley 1994). Biases reported by Giorgi *et al.* (1994) between monthly observed data and the nested MM4 present climate simulation are addressed by adjusting the 2xCO_2 monthly temperature and precipitation values to remove the reported bias (Shelton 2001). The bias-adjusted monthly temperatures and precipitation interpreted from Giorgi *et al.* (1994) and applicable to the Upper Deschutes River Basin are shown in Table 1.

An additional factor in modeling the watershed 2xCO_2 climate is consideration of the likely vegetation response to increased atmospheric carbon dioxide as an essential plant nutrient. Experimental studies indicate disagreement on natural ecosystem responses to

Table 1. Monthly Temperature and Precipitation Increases to Model a $2xCO_2$ Climate in the Upper Deschutes River Basin*

Period	Temperature (^oC)	Precipitation (mmd^{-1})
January	4.2	0.27
February	5.3	1.28
March	4.8	0.66
April	2.4	0.14
May	2.9	0.19
June	4.4	0.08
July	3.3	0.16
August	4.3	0.12
September	5.3	0.46
October	3.8	0.75
November	4.3	0.05
December	4.0	2.11
Annual	4.0	0.52

*Values adopted from Giorgi *et al.*, 1994, Figures 7, 15, and 17

elevated carbon dioxide. Consequently, vegetation changes observed by Knapp and Soulé (1996) at a relic site at Billy Chinook Reservoir (Figure 1) approximately 100 km north of the Upper Deschutes Basin are used for estimating future vegetation conditions in the study area (Shelton 2001).

The $2xCO_2$ climate is simulated for the 108 months from October 1951 to September 1960 by adjusting sector monthly temperature and precipitation according to the changes shown in Table 1. This is a version of the procedure known as the "delta" method for downscaling GCM climate simulations. It has the advantage that modeled runoff can be compared to historic gaged data (Hamlet and Lettenmaier 1999). The 108-month time series in Figure 2 shows that the $2xCO_2$ climate runoff is greater than control climate runoff in all but three of the 108 months, and it is more variable than the control climate runoff. The average monthly $2xCO_2$ climate runoff is 35 mm compared to 28 mm for the control climate, and the standard deviation is 5.8 mm and 4.5 mm for the $2xCO_2$ climate and the control climate, respectively.

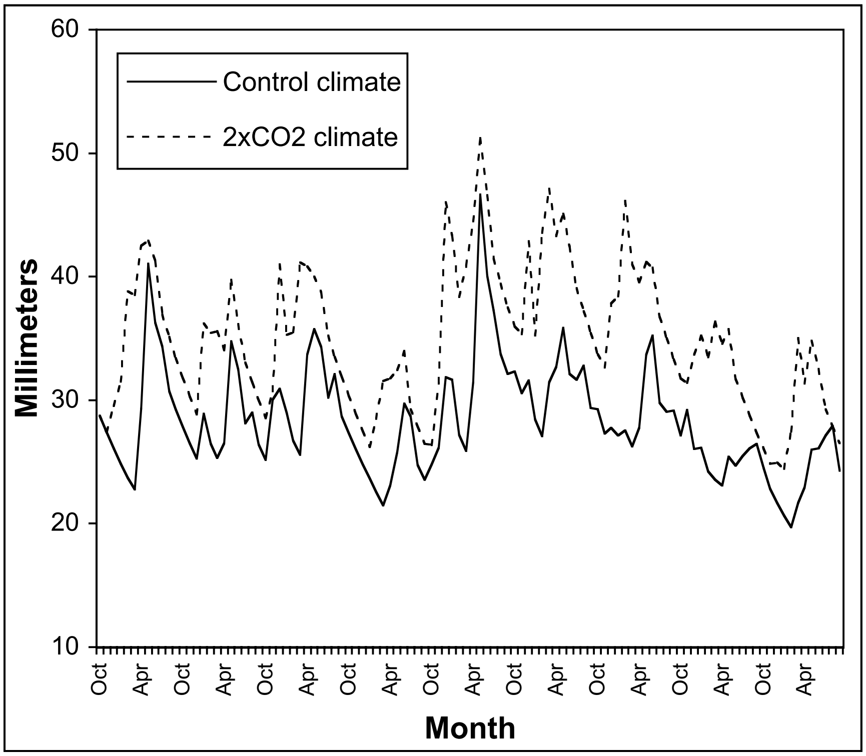

Figure 2. Monthly Control Climate Runoff and 2xCO_2 Climate Runoff for the Deschutes River at Benham Falls, Water Years 1952–60.

Water Supply Changes

Several hydroclimatic variables are relevant for examining 2xCO_2 water supply changes for the Upper Deschutes Basin, but water surplus and runoff are used because they incorporate the influences of other variables. Water surplus is the precipitation residual that eventually becomes runoff. It is surplus water in the sense that evapotranspiration and soil capillary storage are satisfied and this quantity is additional available moisture. Water surplus reveals the complex interaction of precipitation, snow accumulation and ablation, evapotranspiration, and soil moisture recharge. In addition, it represents the coupling between the surface and near-surface hydroclimatic process and groundwater storage and transmission that regulate water delivery to the stream system.

Runoff expresses how climate, the entire suite of watershed processes, and time and space variations in the groundwater processes are integrated. Consequently, a focus on water surplus and runoff permits separation of the climatic and groundwater storage and transfer influences. The control climate simulation provides the benchmark for assessing water supply changes associated with a 2xCO_2 climate.

Monthly water surplus for the control climate occurs in all months, but the May maximum of 79 mm is more than 15 times greater than the minimum in September and October (Figure 3). A secondary water surplus minimum in February is related to a large increase in the January and February snow pack when a major proportion of precipitation, especially at the higher elevations, is in the

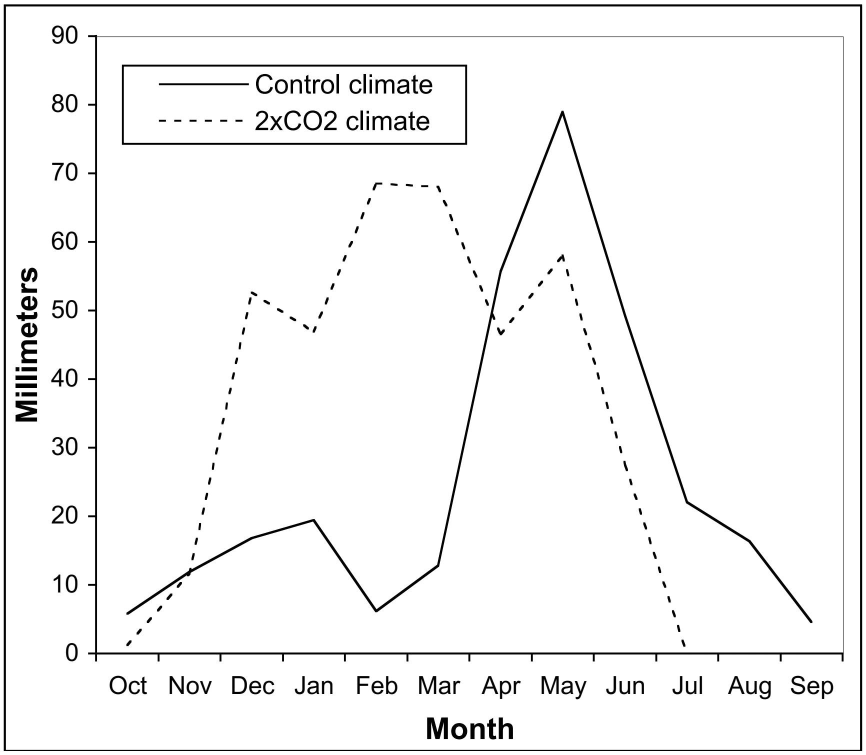

Figure 3. Average Monthly Upper Deschutes Basin Water Surplus for Control Climate and 2xCO_2 Climate, Water Years 1952–60.

form of snow. The influence of snowmelt and spring rainfall is evident in the substantial water surpluses in April to June that account for 61 percent of the annual water surplus.

Water surplus occurs in only 9 months in the 2xCO_2 climate, but the 2xCO_2 climate annual surplus of 401 mm is 27 percent greater than the control climate annual surplus. The increased water surplus is proportionately greater than the precipitation increase due to the cool-season moisture regime that continues to be dominant in the wetter 2xCO_2 climate. In addition, the temperature increase in the 2xCO_2 climate accounts for a greater proportion of the precipitation occurring as rain rather than snow, resulting in a larger water surplus earlier in the year (Shelton 2001). The seasonal occurrence of surplus shifts from late spring to winter in the 2xCO_2 climate, and the 2xCO_2 climate maximum surplus in February and March is 2 months earlier in the year than the maximum for the control climate. December through May water surpluses account for 90 percent of the 2xCO_2 climate annual total, while these months account for 64 percent of the total for the control climate. In the 2xCO_2 climate, the May-to-July contribution is reduced to 22 percent of the annual water surplus compared to the control climate surplus of 50 percent of the annual total in these 3 months.

The 108-month control climate and 2xCO_2 climate water surplus time series (Figure 4) reveal important characteristics masked by the average monthly data. Water surplus decreases from a total of 72 months for the control climate to 67 months for 2xCO_2 climate, but the changes in the occurrence and magnitude of water surplus are most evident. May is the month of maximum surplus for the control climate in 7 of the 9 years, and the maximum occurs in April and June the other 2 years. The maximum surplus is in March in 4 of the 9 years for the 2xCO_2 climate, and the maximum occurs in December through February in the other 5 years. It is notable that the month of maximum surplus is 2 months earlier in the 2xCO_2 climate in 1 year, 3 months earlier in 5 years, 4 months earlier in 2 years, and 5 months earlier in 1 year.

For the control climate months with a water surplus, the mean is 37.5 mm and the standard deviation is 30.5 mm. Twelve of the 72 months have a surplus that exceeds 68 mm or 1 standard deviation

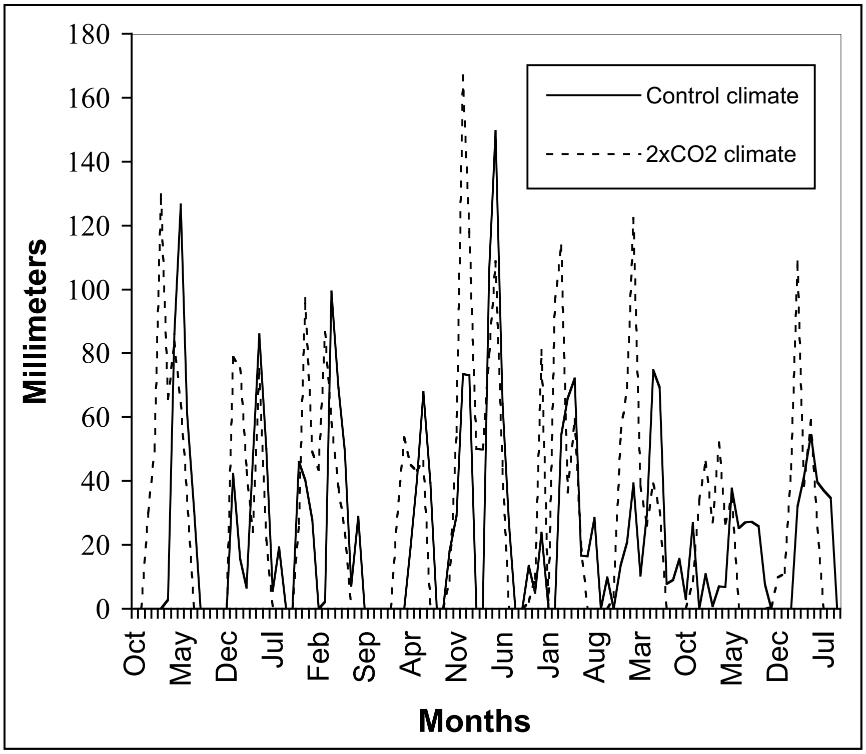

Figure 4. Monthly Upper Deschutes Basin Water Surplus for Control Climate and $2xCO_2$ Climate, Water Years 1952–60.

above the mean. The $2xCO_2$ climate has 18 months that exceed 68 mm. This indicates an important water supply alteration in that the $2xCO_2$ climate water surplus occurs earlier in the year, and it is characterized by a 50 percent increase in quantities that exceed 1 standard deviation above the mean for the control climate. Although flooding is not a common hazard in the Upper Deschutes Basin, the greater number of large water surplus values indicates increased problems for reservoir storage operations.

The aggregate influence of climatic forcing and the time and space variability of watershed processes responding to the climatic forcing are evident in runoff. Mean monthly control climate runoff is 28 mm, the maximum average monthly runoff is 34 mm in May, and February and March both have the lowest average monthly runoff of 25 mm (Figure 5). The relatively consistent Deschutes River flow is clearly indicated by these data. May runoff is only 43 percent as large as May water surplus, due to dampening by storage residence times in the groundwater system. February control climate runoff is four times greater than February water surplus because 74 percent of February precipitation is retained in the snow pack. The monthly variation of control climate water surplus is eight times greater than the monthly variation of runoff.

Mean monthly $2xCO_2$ climate runoff is 35 mm or 25 percent greater than the control climate runoff. The maximum average monthly $2xCO_2$ climate runoff is 40 mm in May, and this is 21 percent greater than the May maximum runoff for the control climate. October and November $2xCO_2$ climate runoff of 30 mm is the low-

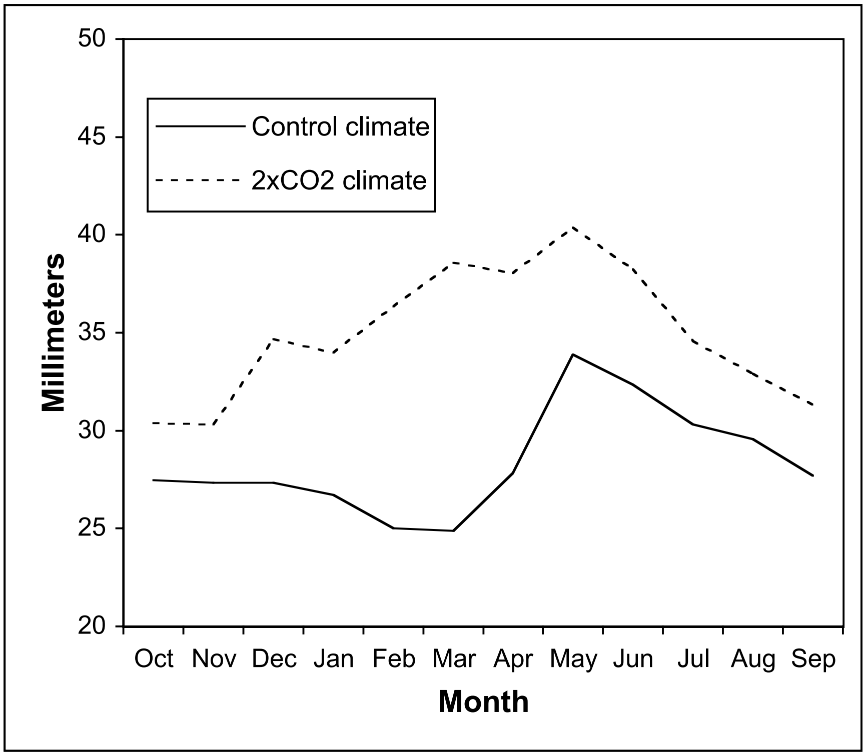

Figure 5. Average Monthly Upper Deschutes Basin Runoff for Control Climate and $2xCO_2$ Climate, Water Years 1952–60.

est average monthly runoff. Nevertheless, 30 mm in these 2 months is 20 percent greater than the low runoff in March for the control climate. March displays the greatest difference between the $2xCO_2$ climate and control climate average monthly runoff—14 mm, or a 55 percent increase. The smallest average monthly differences between the control climate and the $2xCO_2$ climate are 3 mm for August to November. Overall, the $2xCO_2$ climate produces runoff increases greater than 25 percent for the months of December to April and runoff increases of less than 20 percent for the months of May to November.

While the average monthly runoff data provide a useful overview for comparing control climate and $2xCO_2$ climate runoff, the monthly time series reveal a greater variety of changes (Figure 2). The two time series show that the monthly $2xCO_2$ climate runoff is greater than control climate runoff in all but 3 of the 108 months. The two largest differences are 16.5 mm and 18.6 mm in February 1958 and February 1959, respectively. However, March accounts for the largest annual difference in the other 7 years.

The maximum monthly runoff occurs in May 1956 in both time series, but the $2xCO_2$ climate value is 10 percent greater. The minimum control climate runoff is 19 mm in February 1960, and the minimum for the $2xCO_2$ climate is 24 mm in January 1960. However, a more striking feature of the two time series from a water supply perspective is the recurring difference in the occurrence of high and low runoff. The control climate has 15 months with runoff less than 1 standard deviation below the mean and 13 months with runoff greater than 1 standard deviation above the mean. The $2xCO_2$ time series has 65 months with runoff greater than 33 mm that is the control climate 1 standard deviation above the mean boundary. The $2xCO_2$ climate time series has no values below the 1 standard deviation below the mean boundary of 24 mm. This implies that extreme high monthly runoff is likely to occur four times more frequently with a $2xCO_2$ climate. In contrast, low monthly runoff in a $2xCO_2$ climate will exceed present values substantially. The 1 standard deviation boundary for $2xCO_2$ climate monthly runoff is 29 mm, or 21 percent greater compared to the control climate. In addition, it is important to note that the $2xCO_2$ climate runoff equal to 1 standard deviation below the mean is 1 mm greater than the control climate average monthly runoff.

Figure 2 also reveals that a $2xCO_2$ climate produces important changes in the seasonal occurrence of high and low runoff. The $2xCO_2$ climate maximum runoff month is 2 to 5 months earlier than the control climate runoff in 5 of the 9 years. In 7 years, the minimum runoff month occurs 1 to 5 months earlier in the year in the $2xCO_2$ climate. These changes have important ramifications for water use in the basin since they indicate a substantial shift in the timing of minimum runoff related to a $2xCO_2$ climate, even though the minimum runoff is greater than at present.

Implications of Water Supply Change

The $2xCO_2$ climate simulation for the Upper Deschutes Basin implies that increased rain and less snow have a greater influence on the future water supply than warmer temperatures and increased evapotranspiration. The greater watershed sensitivity to precipitation is attributed to the dominant cool-season precipitation regime that amplifies $2xCO_2$ climate changes in the magnitude and form of precipitation. More rain, less snow, and an accelerated rate of spring snowmelt in the Upper Deschutes Basin combine to produce more rapid, earlier, and greater spring runoff. These runoff changes will make managing the water supply more difficult. Water storage in Crane Prairie and Wickiup reservoirs and Crescent Lake will require new operating procedures because there will be less snow to fill reservoirs later in the spring. The Wickiup sector $2xCO_2$ climate runoff provides a focused perspective on this problem because the two largest reservoirs are located in this sector.

The Wickiup sector (Figure 1) drains 27 percent of the Upper Deschutes Basin, but it accounts for 53 percent of the control climate average annual runoff and 56 percent of the $2xCO_2$ climate average annual runoff. Although the runoff time series for the Upper Deschutes Basin and the Wickiup sector display many similarities, the changes represented by the Wickiup sector $2xCO_2$ climate runoff are notably more complex.

The Wickiup sector average monthly control climate runoff is 55 mm, and the average monthly $2xCO_2$ climate runoff is 73 mm.

The monthly $2xCO_2$ climate runoff is greater than the control climate runoff in all but 5 months, and it is the same as the control climate runoff for 2 of these months (Figure 6). The greatest difference between Wickiup sector control climate and $2xCO_2$ climate runoff is 43 mm in May 1959. This difference exceeds the control climate runoff of 39 mm for this month. All monthly differences greater than 25 mm occur in February through May.

The most revealing change in Wickiup sector runoff is evident when monthly $2xCO_2$ runoff is compared to the average monthly control climate runoff and its variability. One hundred of the 108 months of $2xCO_2$ climate runoff exceed the control climate average of 55 mm. Fifteen control climate months exceed 1 standard deviation above the mean runoff, and 19 months are below 1 standard

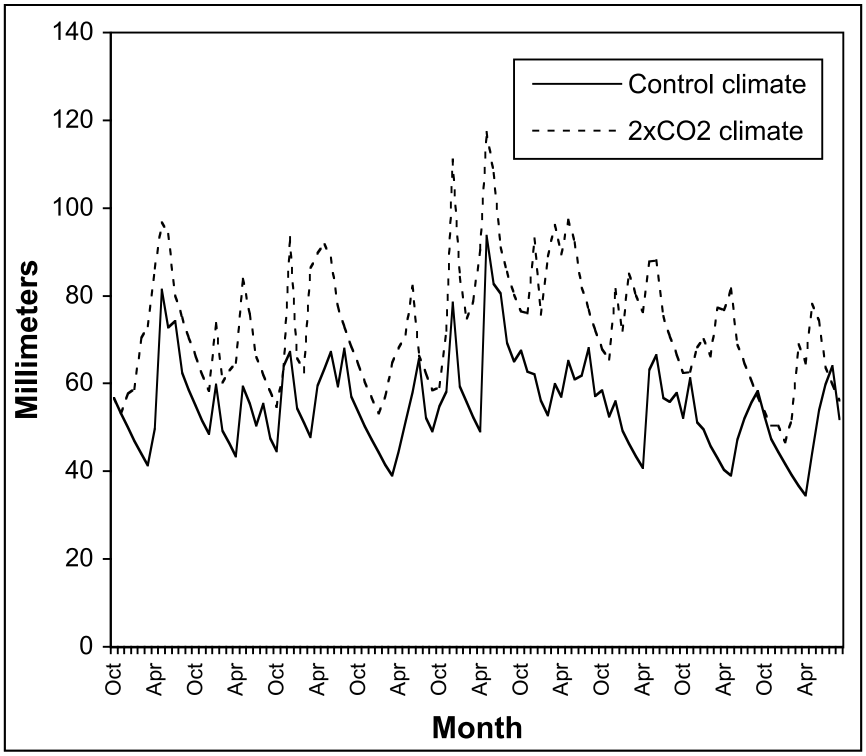

Figure 6. Monthly Wickiup Sector Runoff for Control Climate and $2xCO_2$ Climate, Water Years 1952–60.

deviation. The $2xCO_2$ climate has 70 months with runoff greater than the control climate 1 standard deviation value of 65.6 mm, and no month equal to or less than 44.6 mm, which is 1 standard deviation below the control climate mean. In addition, the control climate has 5 months with runoff greater than 2 standard deviations above the mean, and the $2xCO_2$ climate has 40 months with runoff greater than the control climate 2 standard deviation value. Overall, the $2xCO_2$ climate runoff is strongly skewed to significantly higher values compared to control climate runoff, and the high runoff equivalent to the control climate 2 standard deviation runoff occurs eight times more frequently. Perhaps equally striking is that 6 other Wickiup sector $2xCO_2$ climate months produce runoff that exceeds the May 1956 control climate monthly maximum runoff.

Additional understanding of Wickiup sector runoff changes is gained by focusing on the annual runoff regime. During 3 of the first 5 years, the peak runoff occurs in the same month in both time series. In the other 2 years, the $2xCO_2$ maximum runoff occurs 1 month earlier. The month of minimum runoff displays a similar pattern during these years. In the last 4 years, the maximum runoff month in the $2xCO_2$ time series occurs 4 months earlier in 1959 and 3 months earlier in 1957 and 1960. This represents a significant shift in the runoff regime and the character of the water supply for the Wickiup sector that complicates reservoir storage operations.

The increased $2xCO_2$ runoff heightens the risk of downstream flooding. Presently, flooding is uncommon due to the role of groundwater storages and transfers that dampen high runoff events (Shelton 1985). The greater number of months with extremely high runoff in the $2xCO_2$ climate indicates that riparian areas used by wildlife could be damaged by high flows and elevated water tables. Much of the Deschutes River channel above Benham Falls is bounded by relatively low banks and broad riparian areas unprotected from potential flooding by elevated $2xCO_2$ climate runoff. The capacity of the groundwater system to store and transmit larger water surpluses is unknown, and development of additional surface reservoir storage in the watershed is hindered by the basalts that render most sites unsuitable due to significant leakage.

The residential and recreational community at Sunriver may be at risk from 2xCO_2 runoff increases. The streambank locations and views attractive for homes and tourist facilities in this development are vulnerable to the greater runoff and more frequent extremely high runoff simulated for the 2xCO_2 climate. Also, water table increases might interfere with golf courses, bike paths, and other recreational facilities.

Conclusions

Evaluating the adequacy of future regional water supplies is hindered by uncertainties related to the natural variability of the hydrologic cycle, growing population, and the prospect that climate change will alter the hydrologic cycle. However, water supply systems designed and operated on the assumption that future climate will be like past climate are likely to be inadequate for addressing future water issues.

Monthly simulation of a 2xCO_2 climate for the Upper Deschutes Basin reveals important water supply changes compared to the 1951–1960 control climate. The 2xCO_2 climate displays greater runoff in all months, with notably larger runoff in December to June. The basin's cool-season precipitation concentration and the reduced proportion of precipitation occurring as snow combine to make February rather than May the month of greatest available water in the 2xCO_2 climate. Although the 2xCO_2 climate evaporative demand is greater than in the control climate, this change exerts less influence on the water supply than warmer temperatures accelerating the melt of a reduced winter snow pack.

Until the large uncertainties associated with GCM simulations are resolved, watershed modeling is useful for estimating the water supply impact of climate change. This study and many regional modeling studies suggest that even modest changes in temperature and precipitation can lead to changes in water availability outside the range of historical hydrologic variability. Maintaining water development options and incorporating flexibility in operational plans are important for designing efficient water supply programs, and these traits are especially necessary for addressing changes in population and water demands that must be made against a background of climate change uncertainty.

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