Effects on Water Resources

Statement of the Problem

Climate change is likely to have significant impacts on the availability of fresh water. Already in short supply throughout many parts of the world, water for human consumption, agriculture, and industry will be a major factor in economic growth, ecological sustainability, and global conflict. Research was undertaken to make initial assessments of potential impacts of climate change on stream flow and water balance in the western United States—a region characterized by the shortage of water. Additionally, research was conducted to address the need for models which account for the spatial magnitude and extent of hydrologic processes. The models need to handle key parameters such as precipitation, soil moisture, and evaporation, in response to changing climatic conditions. The models must account for vegetation interactions with soil moisture. This is particularly important for simulating regional vegetation response to climate change since vegetation distribution is controlled in large part by the availability of soil moisture.

Approach

Research focused on developing and refining detailed watershed scale hydrology models to address stream dynamics and water storage. Regional-scale modeling research was directed toward developing physically and mechanically-based water balance models which can be spatially distributed at watershed, regional, and continental scales. The research effort contributed to developing methods for spatially distributing climatic data at scales appropriate for the models, and providing these data bases to the climate change research community. This ORD project has been completed; extensions of this research are continuing within the US Geological Survey.

Main Conclusions

The increasing demand for water by population and industrial growth is creating chronic water shortages throughout the world (Revenga 2000). Add to this the potential impacts of global climate change on water supplies and chronic shortages could reach crisis levels. Throughout much of the western United States the supply of water for human consumption, agriculture, and industry depends on snowpack and reservoir storage. Most global climate warming scenarios suggest warmer winters with more rainfall and less snowfall for much of the western United States, which would substantially reduce snow accumulation and shift the high flow season for many rivers from the spring to the winter (Lettenmaier et. al. 1992). A substantial amount of the natural storage of winter precipitation that presently occurs in the snowpack would be lost resulting in increased spills in the winter and lower reservoir levels in the summer and fall (Lettenmaier and Sheer 1991).

A significant increase in flood hazard in the western US could result from climate change, primarily due to an increase in rain-on-snow events (Lettenmaier and Gan

1990). Such events occur when warm, wet storms move over existing snowpack. Rapid melting of the snowpack is the result of a combination of warm air temperature, high wind and high humidity which cause significant condensation on the snow and is particularly severe in forest openings and forest clear-cuts (Marks et al. 1998). This research suggests that some mitigation of the adverse effects of global climate change may be achieved by adapting land and water management practices to changes in runoff patterns and maximizing the protective effects of natural vegetation.

Global climate changes are expected to be regional in nature, and affect land cover and land use. Key to understanding such regional effects on water supplies is the response of vegetation. Plant communities play a significant role in regional energy and water balance. While hydrologic models designed to simulate large river systems are good for operating reservoirs systems, they are not adequate for predicting changes to regional water balance and, hence, changes in regional vegetation (Marks et al.1993). Dolph et al. (1991) developed a spatially distributed regional water balance model to evaluate the sensitivity of large river basins to climate change. The model was exercised for the Columbia River Basin. This research demonstrated that the existing Historic Climate Network of climate monitoring stations underestimate precipitation primarily because mountainous areas are underrepresented. With climate warming, the model predicted increased evaporative loss, decreased runoff and soil moisture. These conditions could have profound effects on vegetation distribution and subsequently regional water resources.

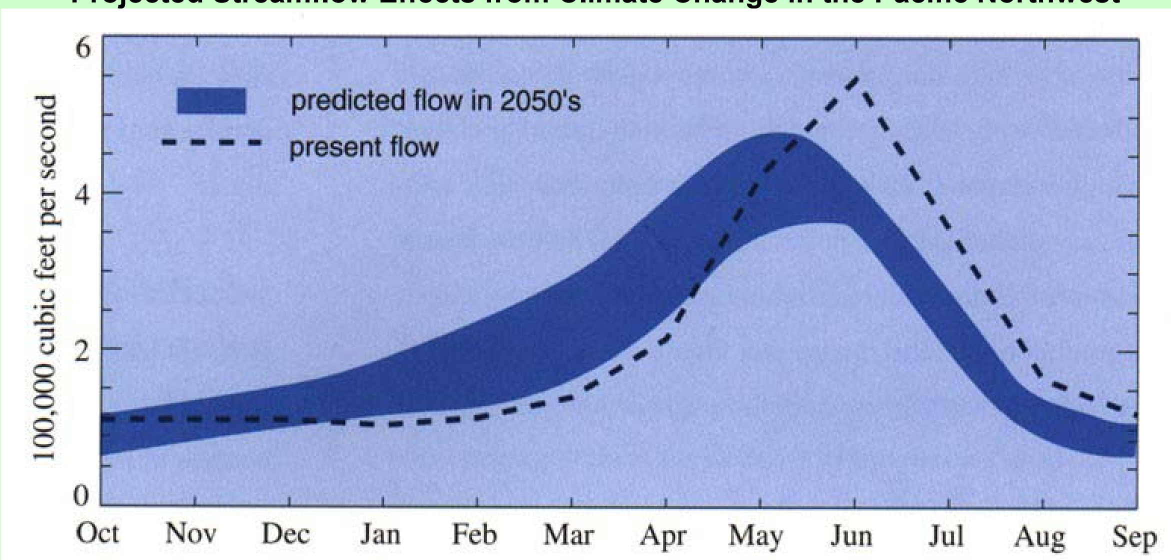
The ability to predict changes in regional vegetation is necessary to evaluate the effects of climate change on forest resources, agriculture, and water supplies. Changes in soil moisture and evapotranspiration resulting from climate will have large impacts on water and vegetation. If changes in the regional water balance are significant, major shifts in vegetation patterns and condition are a likely (Marks et al. 1993). Neilson and Marks (1994) incorporated a distributed water balance model with a vegetation model to produce a biogeographic model, MAPSS (Mapped Atmosphere-Plant-Soil System). This model was used to predict changes in vegetation leaf area index, site water balance and runoff as well as changes in biome boundaries. When applied to potential climate change scenarios, two areas exhibiting among the greatest sensitivity to drought-induced forest decline were determined to be eastern North America and Eastern Europe to western Russia.

Effects of Global Climate Change (GCC) on streamflow

With climate warming, mountain snow accumulation would be substantially reduced, and river's high flow season would shift from the spring to the winter (Lettenmaier et al. 1992). Actual evaporation would peak in late spring and early summer due to reduced summer soil moisture. The result would be increased spills in the winter, lower reservoir levels in the summer and fall, and increased risk of flooding (Lettenmaier and Sheer 1991).

Hydrologic sensitivities across a large part of the western US are driven primarily by runoff shifts due to temperature change, not changes in total precipitation (Lettenmaier and Gan 1990). The exception to the temperature dominance would be in river system with large reservoir storage relative to the mean annual flow. In these cases shifts in the seasonality of runoff would be less important than the changes in the mean annual flow, which would be sensitive to precipitation as well as temperature changes. In populated areas of the western US such as California, changes in water demand will almost certainly overshadow the possible effects of GCC over the next century.

Projected Streamflow Effects from Climate Change in the Pacific Northwest

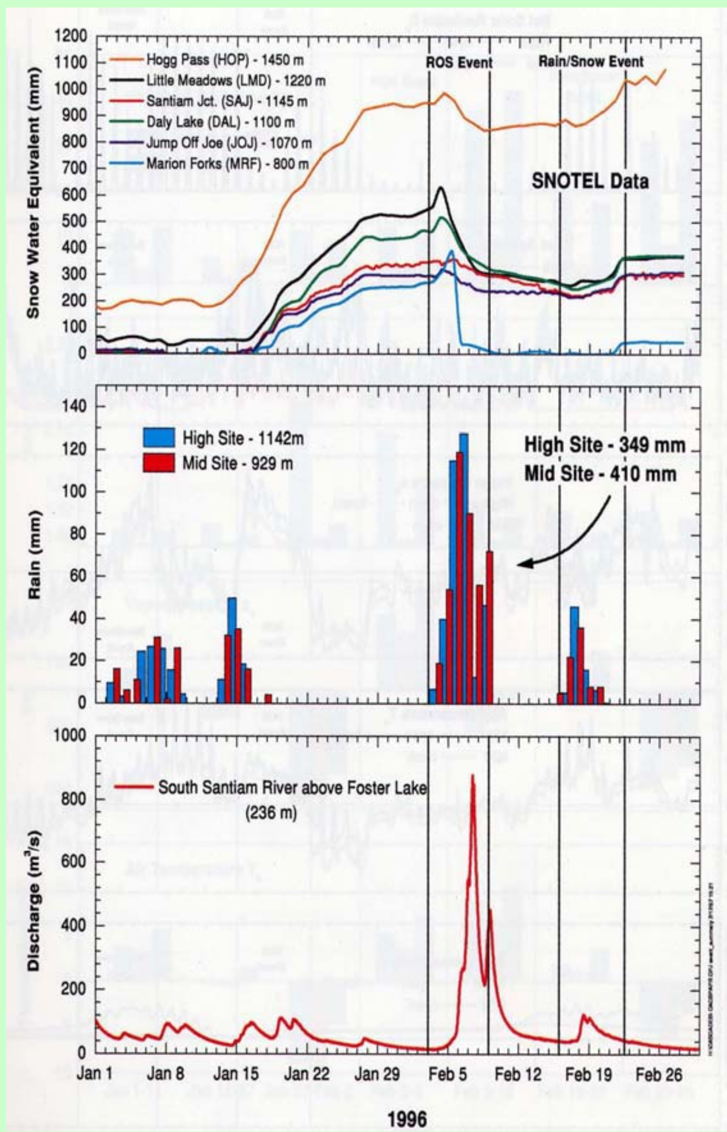


Relative to present flows (dashed), the wetter winters and drier summers simulated by climate models are very likely to shift peak streamflow earlier in the year, increasing the risk of late-summer shortages. Source: Hamlet, A.F. and D.P. Lettenmaier. 1999. (As shown in the National Assessment Synthesis Team report 2001).

Rain-on-snow

Willamette River, Oregon 1996 flood

Marks et al. (1998) used an energy balance snowmelt model to simulate snowmelt processes during a warm, very wet Pacific storm that caused significant flooding in the Pacific Northwest during the Winter of 1996. Data from paired open and forested sites located just below the Pacific Crest were used to drive the model. The model accurately simulated snow cover mass and depth during the development and ablation of the snow cover prior to, during, and following one of the most extreme rain-on-snow events on record. The model demonstrated that the melt was caused by condensation on the snow surface during the event, and by the fact that a cold storm had deposited significant snow cover down to relatively low elevations within the snow transition zone. In the snow transition zone of the Cascade Mountains, clear-cutting is a common forest practice. This study showed that during this event, snowmelt was enhanced in forest openings and clear-cuts. If GCC results in a shift to warmer winters such rain-on-snow events could become more frequent.



Effects on regional water balance

A spatially distributed regional water balance model was used to look at the sensitivity of the Columbia Basin to climate change (Dolph et al. 1991). A wet year (1972) and a dry year (1977) were simulated and compared to recorded data. The modeled total runoff was significantly less than measured runoff—implying that precipitation data from the Historic Climate Network was underestimated by the existing network of measurement stations in mountainous regions. In response to this need, several new methods for estimating precipitation at regional scales were developed (Phillips et al. 1992, Daly et al. 1994). Spatial data bases of precipitation, temperature, vapor pressure, evapotranspiration, and wind were created for both current conditions and 2xCO_2CO_2 scenarios for several GCMs and were made publicly available for the global climate change research community (NOAA / EPA 1992, 1997).

The water balance approach incorporating a physically based model of potential evapotranspiration and explicit calculation of soil water holding capacity, improved our ability to simulate soil moisture under current and future climate conditions. A 2xCO_2 scenario generated by the GFDL global circulation model provided climate conditions to run the Dolph et al. (1991) water balance model. The model predicted increased PET, and ET, and decreased runoff and soil moisture. Marks et al. (1993) predicted that changes in soil moisture and evapotranspiration resulting from global climate change will have large impacts on water and vegetation resources.

If changes in the regional water balance are significant, major shifts in vegetation patterns and condition are a likely result of global climate change. Neilson and Marks (1994) incorporated a distributed water balance model with a biogeographic vegetation model, MAPSS (Mapped Atmosphere-Plant-Soil System) to predict changes in vegetation leaf area index, site water balance and runoff as well as changes in biome boundaries. 2xCO_2 scenarios from five different global circulation models (GCMs) were used to predict vegetation changes globally. Increased PET due to higher temperatures generally offsets increased precipitation under all 2xCO_2 scenarios. Eastern NA and Eastern Europe to western Russia were among the most sensitive regions to drought-induced forest decline.

The table below presents annual water balance results for a very wet (1972) and a very dry (1977) water year, and for 2xCO_2 climate conditions predicted by the GFDL general circulation model for the US portion of the Columbia River Basin. All values are in mm H2O per unit area, so they represent an average depth of water over the basin. Measured annual runoff at the basin outflow has been corrected to reflect only discharge from the US portion. Annual values refer to water years (Oct. to following Sep.). NA: data not available or not applicable. Standard deviation (SD; in parentheses) is used to indicate the extent of deviation from the basin average reported in the table; no SD is given for measured runoff from1972 and 1977 because it is derived from single values measured at the basin outflow; SD is given for the long-term average measured runoff because it is based on 40 annual values (Marks et al. 1993).

Year	*Measured annual precip.*	*Measured annual runoff*	*Modeled annual runoff*	*Annual PET*	*Modeled annual ET*	*Soil initial storage*	*Soil final storage*
Wet year 1972	776 (547)	1447[a]	437 (475)	878 (315)	311 (151)	65 (61)	93 (60)
Dry year 1977	507 (377)	332 [a]	259 (295)	898 (325)	254 (150)	65 (57)	59 (63)
Long-term average	NA	741 [b] (490)	NA	NA	NA	NA	NA
GFDL 2xCO_2 scenario	636[c] (543)	NA	276 (319)	1627 (470)	396 (215)	63 (57)	27 (37)

[a]Annual runoff over the US portion of the Columbia River Basin (Canadian portion of the flow subtracted out) from gage measurements at the basin outflow, adjusted for storage effects.

[b]40-year average unit runoff for the US portion of the Columbia River Basin (Canadian portion of the flow subtracted out) using historical runoff data.

[c]Average precipitation for the US portion of the Columbia River Basin calculated from the 1972 and 1977precipitation data.

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Hamlet, A. F., and D. P. Lettenmaier. 1999. Effects of climate change on hydrology and water resources objectives in the Columbia River basin, Journal of the American Water Resources Association, 35(6),pp.1597-1625.

Lettenmaier, D. P., K. L. Brettmann, L. W. Vail, S. B. Yabusaki, and M. J. Scott. 1992. Sensitivity of Pacific Northwest water resources to global warming. The Northwest Environmental Journal 8:265-283.

Lettenmaier, D. P. and D. P. Sheer. 1991. Climatic sensitivity of California water resources. J. Water Resources Planning and Management 117.1: 108-125.

Lettenmaier, D. P. and T. Y. Gan. 1990. Hydrologic sensitivities of the Sacramento-San Joaquin river basin, California, to global warming. Water Resources Research 26:69-86.

Marks, D., J. Kimball, D. Tingey, and T. Link. 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: a case study of the 1996 Pacific Northwest flood. Hydrol. Process. 12:1569-1587.

Marks, D., G. A. King, and J. Dolph. 1993. Implications of climate change for the water balance of the Columbia River Basin, USA. Clim. Res. 2:203-213.

Neilson, R. P. and D. Marks. 1994. A global perspective of regional vegetation and hydrologic sensitivities from climatic change. J. of Vegetation Science 5:715-730.

National Assessment Synthesis Team. 2001. Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change, Report for the US Global Change Research Program, Cambridge University Press, Cambridge UK,620pp.

NOAA / EPA. 1992. Global Ecosystems Database, Disc A. National Oceanic & Atmospheric Administration / National Geophysical Data Center – Boulder, CO, and U.S. Environmental Protection Agency / Environmental Research Laboratory – Corvallis, OR.

NOAA / EPA. 1997. Global Ecosystems Database, Disc B. National Oceanic & Atmospheric Administration / National Geophysical Data Center – Boulder, CO, and U.S. Environmental Protection Agency / Environmental Research Laboratory – Corvallis, OR.

Phillips, D.L., J. Dolph, and D. Marks. 1992. A comparison of geostatistical procedures for spatial analysis of precipitation in mountainous terrain. Agric. & Forest Meterol. 58: 119-141.

Revenga, C., J. Brunner, N. Henninger, K. Kassem, and R. Payne. 2000. Pilot analysis of global ecosystems: Freshwater systems. World Resources Institute Washington, DC (This report is also available at http://www.wri.org/wr2000).

Annotated Bibliography of WED Research

Dolph, Jayne, Danny marks and George A. King. 1992. Sensitivity of the regional water balance in the Columbia River Basin to climate variability: application of a spatially distributed water balance model. *In* New Perspectives for Watershed Management: Balancing Long-term Sustainability with Cumulative Environmental Change; R.J. Naiman and J.R. Sedell, editors. Pp 233-265.

A one-dimensional water balance model was developed and used to simulate the water balance for the Columbia River Basin. The model was run over a 10 km digital elevation grid representing the U.S. portion of the basin. The regional water balance was calculated using a monthly time step for a relatively wet year (1972 water year), a relatively dry year (1977 water year), and a double (2xCO_2) climate scenario. Input data, spatially distributed over the grid, included precipitation, maximum soil moisture storage capacity, potential evapotranspiration (PET), and threshold baseflow. The model output provides spatially distributed surfaces of actual evapotranspiration (ET), runoff, and soil storage. Model performance was assessed by comparing modeled ET and runoff with the input precipitation data, and by comparing modeled runoff with measured runoff. The model reasonably partitions incoming precipitation to evapotranspiration and runoff. However, modeled total annual runoff was significantly less than measured runoff, primarily because precipitation is underestimated by the network of measurement stations and because of limitations associated with the interpolation procedure used to distribute the precipitation across the grid. Estimated precipitation is less than measured runoff, a physical impossibility. Under warmer 2xCO_2 climate conditions (January 4.0°K warmer, July 6.5°K warmer), the model predicts that PET increases by about 80%, ET increases, and runoff and soil moisture decrease. Under these climate conditions, the distribution and composition of forests in the region would change dramatically, and water resources would become more limited.

Lettenmaier, Dennis P., Kenneth L. Brettmann, Lance W. Vail, Steven B. Yabusaki and Michael J. Scott. 1992. Sensitivity of Pacific Northwest water resources to global warming. The Northwest Environmental Journal 8:265-283.

The potential effect of increasing atmospheric concentrations of carbon dioxide and other so-called greenhouse gases on the land surface environment is not well understood. Generally, there is some consistency among computer models of global climate that surface temperatures will increase and that, in many areas, precipitation and evaporation also may increase. However, determining the effects of such changes on the distribution and circulation of water at the land surface, and on water management systems, remains problematic. The American River, Washington, a mountainous tributary of the Yakima River, is typical of rivers in the Columbia Basin states of Washington, Oregon, Idaho, and western Montana, as well as southern British

Columbia. Using the American River as a case study, this investigation developed computer models to simulate and identify water management conflicts that might arise in this region under a general climate warming of both 2° C and 4° C. For warmer climates, it was found that snow accumulation would be substantially reduced, and the river's high flow season would shift from the spring to the winter. Potential evaporation would increase throughout the year (mostly in the summer), but peak actual evaporation would shift to the late spring and early summer, due to reduced summer soil moisture. The effect of the streamflow pattern that would accompany a warmer climate was tested on small and moderate sized hypothetical multi-purpose reservoirs. The results showed that water supply reliability would be significantly degraded by the earlier spring runoff pattern that would accompany a warmer climate, especially for small reservoirs. The result was that hydroelectric revenues might increase due to larger reservoir releases needed during the winter peak demand season. An investigation of alternative operating policies for the reservoir system showed that more efficient reservoir operation alone would not mitigate the degraded reliability of water supply that would accompany a warmer climate.

Lettenmaier, Dennis P. and Thian Yew Gan. 1990. Hydrologic sensitivities of the Sacramento-San Joaquin River Basin, California, to global warming. Water Resources Research 26:69-86.

The hydrologic sensitivities of four medium-sized Mountainous catchments in the Sacramento and San Joaquin River basins to long-term global warming were analyzed. The hydrologic response of these catchments, all of which are dominated by spring snowmelt runoff, were simulated by the coupling of the snowmelt and the soil moisture accounting models of the U.S. National Weather Service River Forecast System. In all four catchments the global warming pattern, which was indexed to CO_2 doubling scenarios simulated by three (global) general circulation models, produced a major seasonal shift in the snow accumulation pattern. Under the alternative climate scenarios more winter precipitation fell as rain instead of snow, and winter runoff increased while spring snowmelt runoff decreased. In addition. large increases in the annual flood maxima were simulated, primarily due to an increase in rain-on-snow events, with the time of occurrence of many large floods shifting from spring to winter.

Lettenmaier, Dennis P. and Daniel P. Sheer. 1991. Climatic sensitivity of California water resources. Journal of Water Resources Planning & Management 117:108-125.

The possible effects of climate change on the combined Central Valley Project-California State Water Project (CVP/SWP) were evaluated using a three-stage approach. In the first stage, runoff from four headwater “study catchments” was simulated using rainfall/snowmelt-runoff models, with climatic input taken from CO_2

doubling scenarios from three general circulation models (GCMs). In the second stage, long-term inflows to the CVP/SWP reservoir system were simulated, conditioned on the study catchment flows, using a stochastic disaggregation model. In the third stage, a system simulation model was used to evaluate performance of the reservoir system. For all of the alternative climate scenarios, runoff would be shifted from the spring to the winter. Significantly lower water deliveries from the SWP would occur under the CO_2 doubling scenarios. The reduced deliveries would occur because some of the increased winter runoff would be spilled from the reservoirs instead of being stored in the snowpack, even though the mean annual runoff increased slightly under some climate scenarios. Annual San Francisco Bay delta flows would increase under all three climate scenarios; however, flows to the bay would be substantially increased in winter and somewhat decreased in spring and summer.

Marks, Danny, John Kimball, Dave Tingey, and Tim Link. 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: a study of the 1996 Pacific Northwest flood. Hydrological Processes 12:1569-1587.

A warm, very wet Pacific storm caused major flooding in the Pacific Northwest during February 1996. Rapid melting of the mountain snow cover contributed to this flooding. An energy balance snow melt model is used to simulate snow melt processes during this event in the Central Cascade mountains of Oregon. Data from paired open and forested experimental sites at locations at and just below the Pacific Crest were used to drive the model. The event was preceded by cold, stormy conditions that developed a significant snow cover down to elevations as low as 500m in the Oregon Cascades. At the start of the storm, the depth of the snow cover at the high site (1142 m) was 1·97m with snow water equivalent (SWE) of 425 mm, while at the mid site (968 m) the snow cover was 1·14 with SWE of 264 mm. During the 5-6 day period of the storm the high site received 349 mm of rain, lost 291 mm of SWE, and generated 640 mm of runoff, leaving only 0.22 m of snow on the ground. The mid site received 410 mm of rain, lost 264 mm of water to melt, and generated 674 mm of runoff, completely depleting the snow cover. Simulations at adjacent forested sites showed significantly less snow melt during the event. The snow cover under the mature forest at the high site lost only 44 mm of SWE during the event, generating 396 mm of runoff, and leaving 0.69 m of snow. The model accurately simulated both depth and SWE during the development of the snow cover prior to the storm, and the depletion of the snow cover during the event. This analysis shows that because of the high temperature, humidity, and relatively high winds in the open sites during the storm, 60-90% of the energy for snow melt came from sensible and latent heat exchanges. Because the antecedent conditions extended the snow cover to very low elevations in the basin, snow melt generated by condensation during the event made a significant contribution to the flood. Lower wind speeds beneath the canopy during the storm reduced the magnitude of the turbulent exchanges at the snow surface, so the contribution of snow melt to the runoff from forested areas was significantly less. This experiment shows the sensitivity of snow melt processes to both climate and land-cover, and illustrates how canopy structure is coupled to the hydrologic cycle in mountainous areas.

Marks, Danny, George A. King and Jayne Dolph. 1993. Implications of climate change for the water balance of the Columbia River Basin, USA. Climate Research 2:203-213.

Global climate change will affect the terrestrial biosphere primarily through changes i n regional energy and water balance. Changes in soil moisture and evapotranspiration will particularly affect water and forest resources. Existing spatially lumped hydrologic models are not adequate to analyze the potential effects of climate change on the regional water balance over large river basins or regions primarily because they do not satisfactorily account for the spatial and temporal variability of hydrologic processes. Here we summarize application of a spatially distributed water balance model that was tested using historical data from the U.S. portion of the Columbia River Basin in the Pacific Northwest for a very dry (1977) and very wet (1972) water year. The model adequately partitions incoming precipitation into evapotranspiration and runoff. Because precipitation in the basin is underestimated from measured data, modeled runoff is less than measured runoff from the basin during both the wet and dry years. The potential effects of climate change on runoff and soil moisture in the Columbia River Basin were simulated using 2xCO_2 scenario data from the Geophysical Fluid Dynamics Laboratory (GFDL) general circulation model (GCM). The predicted future climate conditions significantly increase potential evapotranspiration, causing a 20% reduction in runoff relative to input precipitation, and a 58 % reduction in soil moisture storage. If these changes in regional water balance are realized, the distribution and composition of forests in the Northwest would change markedly, and water resources would become more limited. Because of uncertainties in future climate scenarios, and limitations in the implementation of the water balance model, the 2 x CO_2 results should be viewed only as a sensitivity analysis.

Neilson, Ronald P. and Danny Marks. 1994. A global perspective of regional vegetation and hydrologic sensitivities from climatic change. Journal of Vegetation Science 5:715-730.

A biogeographic model, MAPSS (Mapped Atmosphere-Plant-Soil System), predicts changes in vegetation leaf area index (LAI), site water balance and runoff, as well as changes in biome boundaries. Potential scenarios of global and regional equilibrium changes in LAI and terrestrial water balance under 2 X CO_2 climate from five different general circulation models (GCMS) are presented. Regional patterns of vegetation change and annual runoff are surprisingly consistent among the five GCM scenarios, given the general lack of consistency in predicted changes in regional precipitation patterns. Two factors contribute to the consistency among the GCMs of the regional ecological impacts of climatic change: (1) regional, temperature-induced increases in potential evapotranspiration (PET) tend to more than offset regional increases in precipitation; and (2) the interplay between the general circulation and the continental margins and mountain ranges produces a fairly stable pattern of regionally specific sensitivity to climatic change. Two areas exhibiting among the greatest sensitivity to drought-induced forest decline are eastern North America and eastern Europe to western Russia. Regional runoff patterns exhibit much greater spatial variation in the sign of the response than do the LAI changes, even though they are deterministically linked in the model. Uncertainties with respect to PET or vegetation water use efficiency calculations can alter the simulated sign of regional responses, but the relative responses of adjacent regions appear to be largely a function of the background climate, rather than the vagaries of the GCMS, and are intrinsic to the landscape. Thus, spatial uncertainty maps can be drawn even under the current generation of GCMS.