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IMPACTS OF CLIMATE CHANGE ON MISSOURI RIVER BASIN WATER YIELD[1]

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ABSTRACT: Water from the Missouri River Basin is used for multiple purposes. The climatic change of doubling the atmospheric carbon dioxide may produce dramatic water yield changes across the basin. Estimated changes in basin water yield from doubled CO_2 climate were simulated using a Regional Climate Model (RegCM) and a physically based rainfall-runoff model. RegCM output from a five-year, equilibrium climate simulation at twice present CO_2 levels was compared to a similar present-day climate run to extract monthly changes in meteorologic variables needed by the hydrologic model. These changes, simulated on a 50-km grid, were matched at a commensurate scale to the 310 subbasins in the rainfall-runoff model climate change impact analysis. The Soil and Water Assessment Tool (SWAT) rainfall-runoff model was used in this study. The climate changes were applied to the 1965 to 1989 historic period. Overall water yield at the mouth of the Basin decreased by 10 to 20 percent during spring and summer months, but increased during fall and winter. Yields generally decreased in the southern portions of the basin but increased in the northern reaches. Northern subbasin yields increased up to 80 percent: equivalent to 1.3 cm of runoff on an annual basis.
(KEY TERMS: global climate change; surface water hydrology; Missouri River Basin; meteorology/climatology; regional circulation model; water resources; reservoir modeling.)

INTRODUCTION AND OBJECTIVES

Projected increases in concentrations of atmospheric carbon dioxide (CO_2) and other greenhouse gases will likely result in a changed climate. Climate change will affect water availability in the Missouri River Basin. Water uses in this region include irrigation, flood control, navigation, hydropower, recreation, natural resources, and consumptive use: systems that are often in direct competition for the same resources. For example, crops and agricultural production cover approximately 46 percent of the Missouri River Basin, of which 5 percent is irrigated (Srinivasan *et al.*, 1994). These and other water resource needs make the Missouri River Basin extremely vulnerable to any hydrologic impacts of climate change.

A complete method has been developed for analyzing the impacts of climate change on water resources using a continuous daily time step model that numerically routes the water yield through the Missouri River Basin. The Soil and Water Assessment Tool (SWAT) has been modified to incorporate data from a Regional Climate Model (RegCM).

The objectives of this paper are to describe a reproducible method for evaluating climate change impacts on the Missouri River Basin and to analyze climate change impacts on basin water yields.

PREVIOUS MODELING EFFORTS

There have been several simulation studies of the potential effects of climate change on agricultural productivity for the Missouri River Basin, but only a few included water resources. Rosenberg completed a study on the Missouri, Iowa, Nebraska, and Kansas (MINK) region of the central U.S. Weather records of the 1930s 'dust-bowl' era were used as a surrogate climate change scenario (Rosenberg, 1993). It was concluded that if the 'dust-bowl' climate was to recur today, flows from the Missouri and Upper Mississippi

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would be reduced by 28 percent. Hurd *et al.* (1996) used variants of a two-layer Variable Infiltration Capacity (VIC-2L) hydrologic model to estimate the impacts of a set of predetermined changes in mean temperature and precipitation on water yield in four U.S. water resources regions including the Missouri River Basin. Three increments of temperature change (1.5, 2.5, and 5.0°C) and four increments of precipitation change (+15, 7, 0, and -10 percent) were applied. Changes in water yield ranged from +20.5 percent at 1.5°C to -56.8 percent at 5.0°C (Rosenberg *et al.*, 1999). Lettenmaier *et al.* (1999) combined VIC-2L with the output from three transient General Circulation Models (GCMs) and one double carbon dioxide ($2xCO_2$) GCM to evaluate potential effects of climate change on water resources in six river basins including the Missouri. Water yield decreases of 6, 24, and 34 percent were reported for transient climate scenarios and a 2 percent increase was reported for the $2xCO_2$ scenario.

METHODS

Modeling Procedure

The assessment process may be described in three modules: (1) a changed climate scenario was produced with a GCM at a resolution of about 5 degrees in physical space (Giorgi *et al.*, 1998); (2) a Regional Climate Model (RegCM) was used to downscale the climate data to a horizontal grid point spacing of 50 km; and (3) a Geographical Information System (GIS) was used to incorporate the RegCM data into a hydrologic model that was then used to assess impacts on water yield for a selected historic period.

Hydrologic Modeling

Many models have been developed to assess the impacts of climate change on water resources in various parts of the world. Simulation algorithms have progressed from empirical and statistical estimators to more physically based models (Jorgensen, 1996). Rainfall-runoff models like the Soil and Water Assessment Tool (SWAT) were developed for large-scale hydrologic modeling (Srinivasan *et al.*, 1998; Arnold *et al.*, 1999). However, the SWAT model has not yet been tied to"nested" RegCM simulation results for sub-continental climate change impact analysis as it was in this paper.

SWAT

SWAT is a continuous watershed scale model that simulates the major components of the hydrologic cycle on a daily time step. The hydrologic model is based on a water balance equation for soil water content as follows (Arnold *et al.*, 1998):

$$SW_t = SW_{t-1} + P_t - Q_t - ET_t - SP_t - QR_t \qquad (1)$$

where SW_t is the soil water content for the current day, SW_{t-1} is the soil water content for the previous day, P is precipitation, Q is surface runoff, ET is evapotranspiration, SP is percolation or seepage, and QR is return flow.

Surface runoff is modeled using a modified SCS Curve Number approach (USDA-SCS, 1972). The Runoff Curve Number (RCN) is a retention parameter that varies according to soil type, land use, cover, and water content. The RCN in SWAT is updated on a daily basis according to soil water content. Previous research has shown that the increased model complexity of methods such as the Green-Ampt equation over the relatively simple Curve Number approach does not necessarily translate to improved accuracy (Loague and Freeze, 1985; , Beven, 1989; Wilcox *et al.*, 1990).

Modeling algorithms for the major hydrologic processes in SWAT are shown in Table 1. SWAT also simulates the agriculture-based processes of biomass production, plant growth, and the fertilization and transpiration suppression effects of CO_2 enrichment (Arnold *et al.*, 1995). Modifications to the ET and radiation use efficiency algorithms account for the effects of changing atmospheric CO_2 (Arnold *et al.*, 1998).

SWAT was developed by the Agricultural Research Service (ARS) and the Texas Experimental Station (TES) for the Hydrologic Unit Modeling of the United States (HUMUS) project in response to the amended Resources Conservation Act (Srinivasan *et al.*, 1994). SWAT has been linked to GRASS, a Geographic Information System (GIS), by an interface that sets watershed boundaries and extracts necessary input variables from digital databases (Arnold *et al.*, 1995).

Missouri River Dataset

SWAT is a watershed-structured program that divides the area modeled into topographically defined watersheds. The Missouri River Basin model was divided using USGS-defined eight-digit watersheds (U.S. Geological Survey, 1987). The eight-digit watersheds are the smallest cataloging unit used by the USGS. The 310 eight-digit watersheds comprising the

TABLE 1. Modeling of Hydrologic Processes in SWAT (Arnold *et al.*, 1995).

Process	Algorithm
Precipitation	Observations or First-Order Markov Chain Model
Surface Runoff	SCS Curve Number Method
Channel Routing	Variable Storage Coefficient
Reservoir Routing	Stage-Storage or Reservoir Operating Procedures
Percolation	Storage Routing Combined With Crack-Flow Model
Snowmelt	Mean Air Temperature and Soil Layer Temperature
Lateral Subsurface Flow	Kinematic Storage Model
Ground Water Flow	Baseflow Period, Ground Water Storage, and Re-evaporation
Transmission Losses	Lane's Method
Evapotranspiration	Penman-Monteith, Hargreaves, or Priestley-Taylor Methods
Sediment Yield	Modified Universal Soil Loss Equation (MUSLE)

Missouri River Basin range in size from 2000 to 5000 km^2 and are shown in Figure 1.

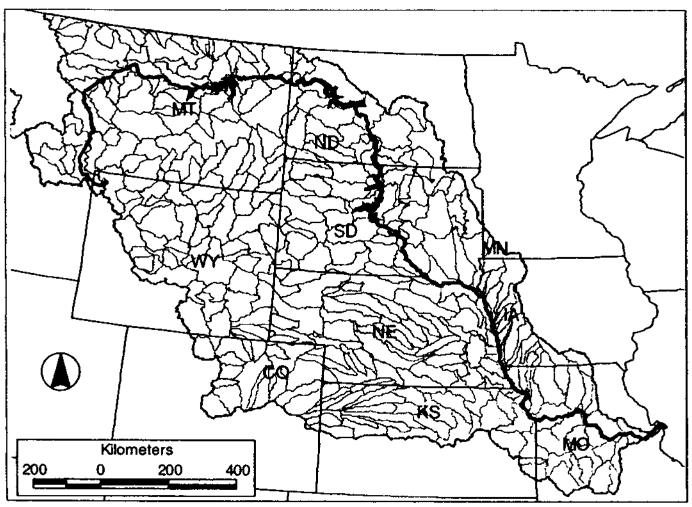

Figure 1. The Missouri River Basin Separated Into the 310 USGS Eight-Digit Subbasins.

Each eight-digit watershed was partitioned into as many as 15 additional subbasins based upon land use and soil composition resulting in 3,494 subbasins for modeling purposes. Input variables were extracted from the basin databases shown in Table 2 with GRASS GIS and an interface program linked to SWAT. Subbasin topography was defined using USGS Digital Elevation Model (DEM) databases. Channel dimensions, slope-lengths, and other topographic parameters were estimated from these data.

Weather Components

SWAT uses six daily time step weather variables: precipitation, maximum and minimum temperature, wind speed, solar radiation, and relative humidity. Precipitation and temperature can either be historic or stochastic. Historical precipitation and temperature data for the 1965 to 1989 simulation period were read from existing data files. Data for wind speed, solar radiation, and relative humidity are available but are generally incomplete over the simulation period. Therefore, statistical parameters were calculated and these variables were stochastically generated (Arnold *et al.,* 1995). All stochastically generated input was saved, resulting in one basic input dataset for the study (Hubbard, 1998).

Representative precipitation was found for each watershed by the Thiessen polygon method (Wanielista, 1990). Weather inputs are specific to each USGS eight-digit in the Missouri River Basin. Thus, there are 310 sets of weather data files corresponding to the 310 USGS eight-digit watersheds that form the Missouri River Basin. Each subwatershed within the eight-digit watersheds shares the same weather data file.

Incorporating the Main Stem Reservoirs

The U.S. Army Corps of Engineers (USACE) operates a series of six main stem reservoirs in the upper Missouri River Basin (Figure 2). The reservoirs are extremely important because they control the 55 percent of the area upstream from the reservoirs and are capable of storing up to three times the mean annual runoff from this area. The reservoirs are operated to meet the prioritized purposes of flood

TABLE 2. Digital Databases Used as Input in Assembling Models.

Database or Data Source	Used For
USGS Digital Elevation Models (DEMs)	Topography, Basin Delineation
USGS Land Use/Land Cover	Land Cover
USGS Maps	Hydrography
STATSGO	Soils Data
Census of Agriculture, Department of Commerce City Map	Crop Type
Tillage Residue Database	Cropping Practice
Shallow Aquifer Baseflow Period Map	Aquifer Data

control, irrigation, downstream water supply and water quality, navigation and power, and fish and wildlife as set forth in the Master Manual (U.S. Army COE, 1979).

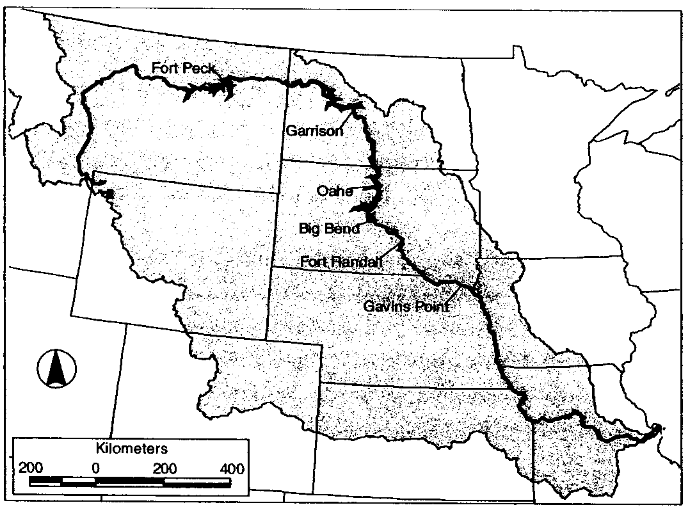

Figure 2. The Six Missouri River Main Stem Reservoirs.

The original SWAT code algorithms determined reservoir releases using simple uncontrolled spillways, obviously insufficient for modeling releases from the main stem Missouri River reservoirs. Jorgensen (1996) implemented new algorithms to simulate historical releases based upon seasonal considerations and system priorities. A complete discussion of the algorithm development and USACE rules of operation can be found in Jorgensen (1996) and Hotchkiss *et al.* (2000).

Climate Modeling

The climate change scenario for this project was developed using a nested regional modeling technique whereby the RegCM was nested within control and doubled CO_2 runs of the Commonwealth Scientific and Industrial Research Organization (CSIRO) GCM (Watterson *et al.,* 1995). The GCM was run with a spatial resolution equivalent to 3.2 degrees latitude (400 km) by 5.6 degrees longitude (500 km). The initial and lateral boundary conditions for the RegCM were provided from the CSIRO GCM at eight-hourly intervals; these data were linearly interpolated to the regional climate model time step of three minutes. The RegCM was run at a spatial resolution of 50 km. A description of the nested modeling runs used in this project is found in Giorgi *et al.* (1998).

Model selection is important, as variations in climate change predictions will impact study results. The CSIRO GCM was selected as the nesting model over the study region because of its relatively high degree of accuracy when used to estimate current climate. The CSIRO model produced a very high quality simulation over North America (Giorgi *et al.,* 1998). Predicted changes in climate by the CSIRO GCM are consistent with models reviewed by the Intergovernmental Panel on Climate Change Second Assessment Report (IPCC, 1995). Great uncertainty exists in the accuracy of regional GCM results. However, CSIRO GCM results are similar to many regional results for North America regarding percentage change in precipitation and range of temperature change.

This type of scenario was chosen for the study in large part due to its high spatial resolution. Given the resolution of the sub-basins making up the study area, using a climate change scenario on a spatial resolution similar to that of the sub-basins is much preferred, and may result in more physically meaningful results. Scenarios developed from these runs of the RegCM have also been used in several agricultural assessments (Brown *et al.,* 1999; Mearns *et al.,* 1999; Mearns *et al.*, 2001). Mearns *et al.* (1999) recently established that the resolution of climate change scenarios can effect the determination of the impacts of climate change on simulated regional crop yields in the Central Plains of the U.S. Mearns *et al.* (2001) also found that the scale of climate change scenario substantially affected the simulation of changes in crop yields on various levels of spatial aggregation in the southeastern U.S. Stone (2000) found that changes in predicted water yields as a result of climate change were dependent on climate change model resolution.

Implementing Climate Change Data

The RegCM was run at a 50 km grid point spacing; thus the Missouri River Basin is covered by a matrix of 28 by 42 grid points. The northern border of the Missouri River Basin coincides with the north boundary of the usable grid points (outside the interpolation region on the borders). The impact of boundary effects were found to be negligible in this study (Hubbard, 1998). The RegCM produced output for each grid point in the entire region. Regional model grid points were correlated with the USGS eight-digit watersheds for climate change modeling purposes (see Figure 3).

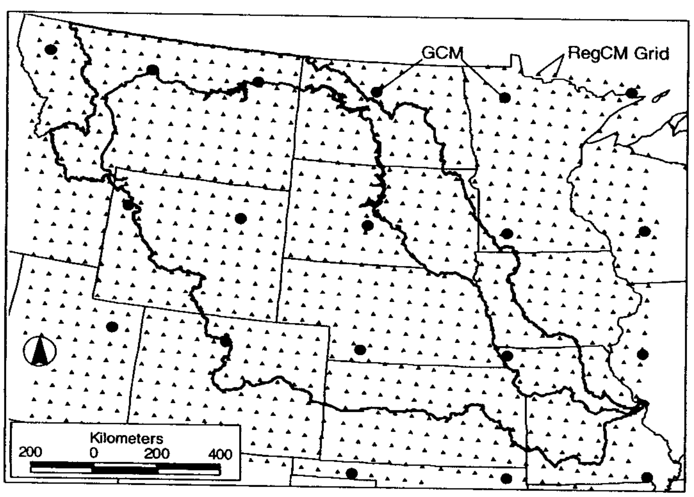

Figure 3. Missouri River Basin GCM and RegCM Grid Spacing.

The RegCM simulates the six variables needed to drive the hydrologic model. The model was run for control conditions (with 330 ppm CO_2) and for doubled CO_2 conditions (660 ppm). Five years of each run were completed. From daily regional model output, five-year monthly averages of the variables used by SWAT were produced.

The RegCM for the changed climate conditions simulated increases in both temperature and precipitation. Seasonal warming of 4 to 6°C and precipitation increases of 6 to 24 percent were produced. The largest changes were found in the northern part of the river basin. Detailed descriptions of the regional modeling results can be found in Giorgi *et al.* (1998) and Mearns *et al.* (1999).

Creating the Climate Change Scenarios for Input into SWAT

The $2xCO_2$ scenario for input to SWAT was created by combining the differences or ratios from the monthly $2xCO_2$ and control run outputs with the baseline climate data set. Differences were used for temperature and ratios for all other variables. Examples of RegCM results as applied to three selected basins are shown in Figure 4. Precipitation ratios are significantly greater in the Upper Missouri Basin, and are accompanied by higher temperatures each month of the year. Temperatures are also warmer as applied to the Upper Niobrara basin and the Lower Missouri, but precipitation ratios are much closer to one.

MODELING RESULTS

Water Yield Changes

Water yield changes are summarized by three-month seasonal averages with winter beginning in January. Average water yields for each season from each eight-digit watershed for the 1965 to 1989 period were calculated from the extracted data for the baseline run and for the $2xCO_2$ run. The percent changes in water yield from baseline conditions were calculated using the GRASS GIS interface and are shown in Figures 5 through 8.

Model water yields for the spring, summer, and fall seasons show more distinct spatial trends than water yields for the winter months. SWAT simulation results exhibit dramatic increases in water yields across the northern and northwestern portions of the Missouri River Basin in the spring, summer and fall. Water yields in these areas increase by 70 percent and much more in certain eight-digit subbasins. The southeastern portions of the basin display an overall decrease in water yields during these three seasons. Most of the southeastern USGS eight-digit watersheds show decreases in water yields of less than 20

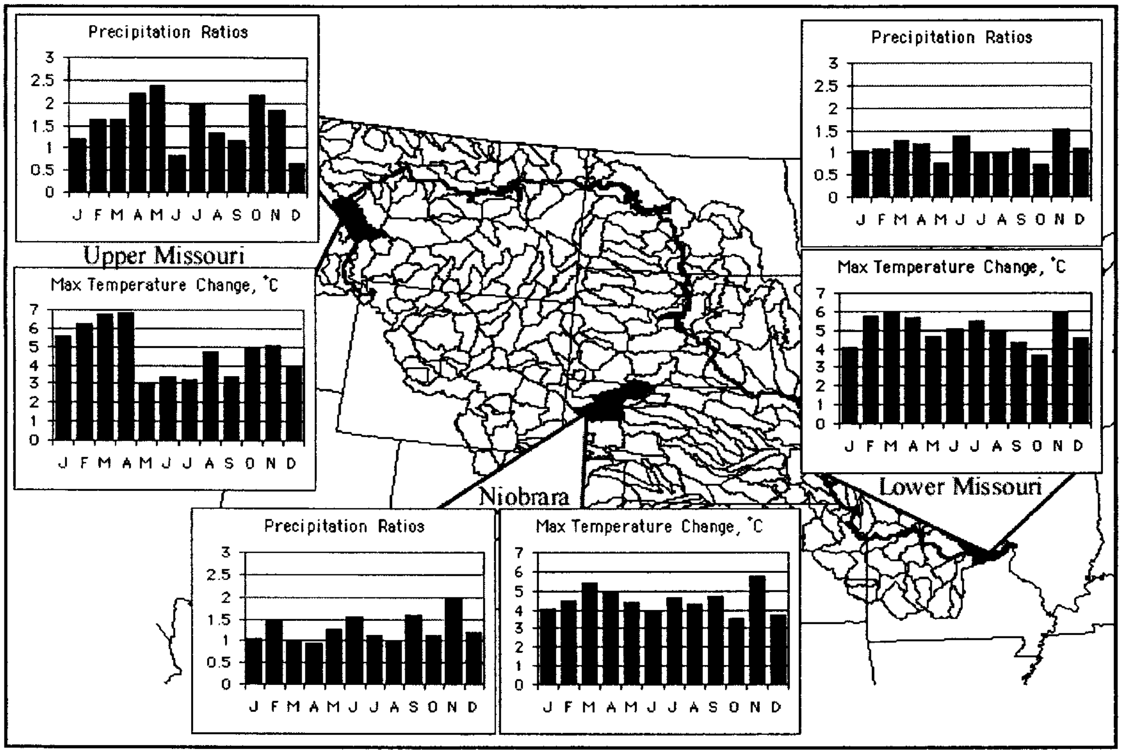

Figure 4. Precipitation Ratios and Changes in Maximum Temperature for Three Subbasins.

percent but some decrease by 80 percent or more. In spring and summer the decreasing water yields from the southeastern portions of the Missouri River Basin are enough to lower the total water yield of the basin by 10 to 20 percent. Water balance summaries for principal tributaries are shown in Figure 9 and portray the large increase in runoff in the northern basins and decreased runoff in the south.

Main Stem Reservoir Changes

The total main stem reservoir storage changes dramatically from baseline conditions (Figure 10). The difference between the releases from the reservoir system for baseline and $2xCO_2$ simulations can be used for mitigating the negative impacts of climate change or optimizing the benefits. The difference in the releases from the reservoir system represent the difference in available water to the system. If releases from the reservoir system are higher for the $2xCO_2$ climate situation than for the baseline climate situation, the additional releases represent extra water that is available for use for the $2xCO_2$ climate conditions.

The average reservoir system releases for the baseline and $2xCO_2$ simulations are 670 m^3/s and 1160 m^3/s respectively, representing 3.5 and 4.8 cm of runoff over the entire Basin. Planned increases in irrigation projects for the northern half of the basin have yet to be implemented. If the projects were built, there would be an additional 2.4 cm of water available for the irrigated area. Basinwide, because less than 5 percent of the entire basin is under irrigation, the increase in water available for all irrigated lands in the entire Missouri River Basin is approximately 24 cm annually.

DISCUSSION AND CONCLUSIONS

The method of analyzing the impacts of climate change on the spatial and temporal distribution of water resources outlined in this project is an excellent tool for exploring the potential impacts of climate change scenarios and possible mitigation schemes. Water resources availability and distribution and agricultural production are vital to the plains region of the United States. Therefore, a method of analysis, such as this, that evaluates impacts of climate change on water resources across the region, is an extremely beneficial tool for developing management strategies to deal with climate changes. Moreover, care has been

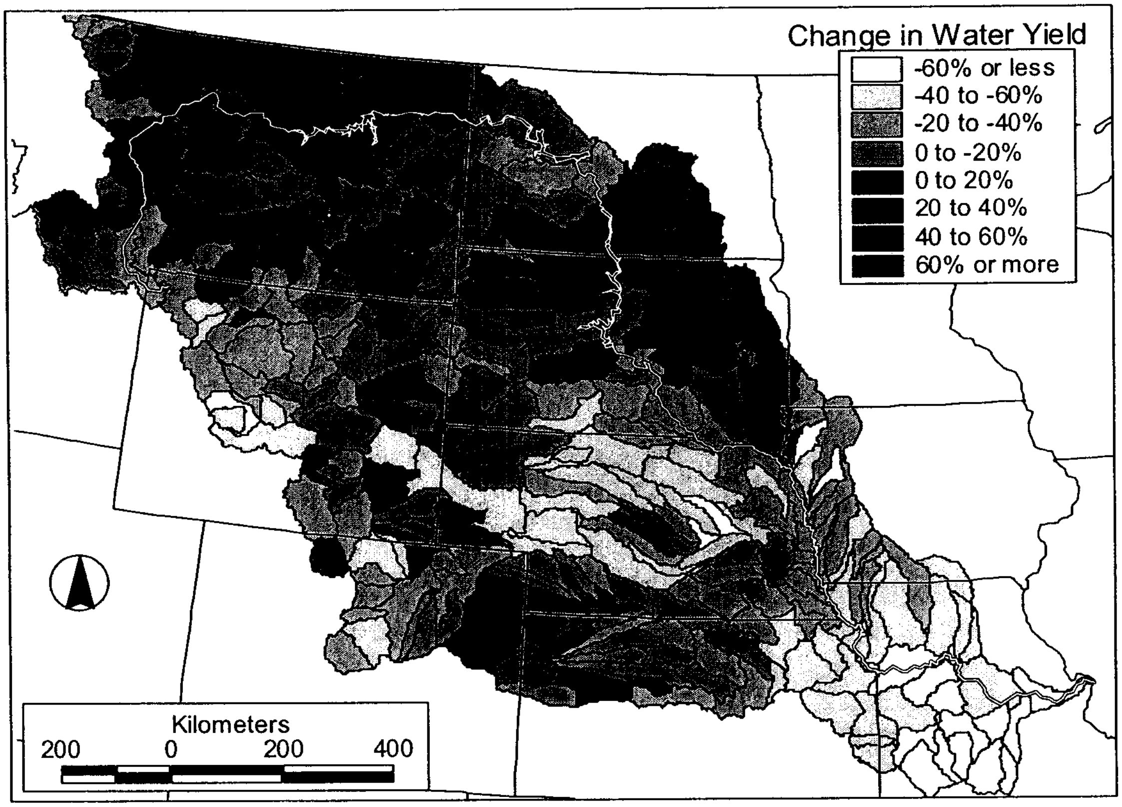

Figure 5. Percent of Change in Water Yield From Baseline Conditions for Winter (January through March).

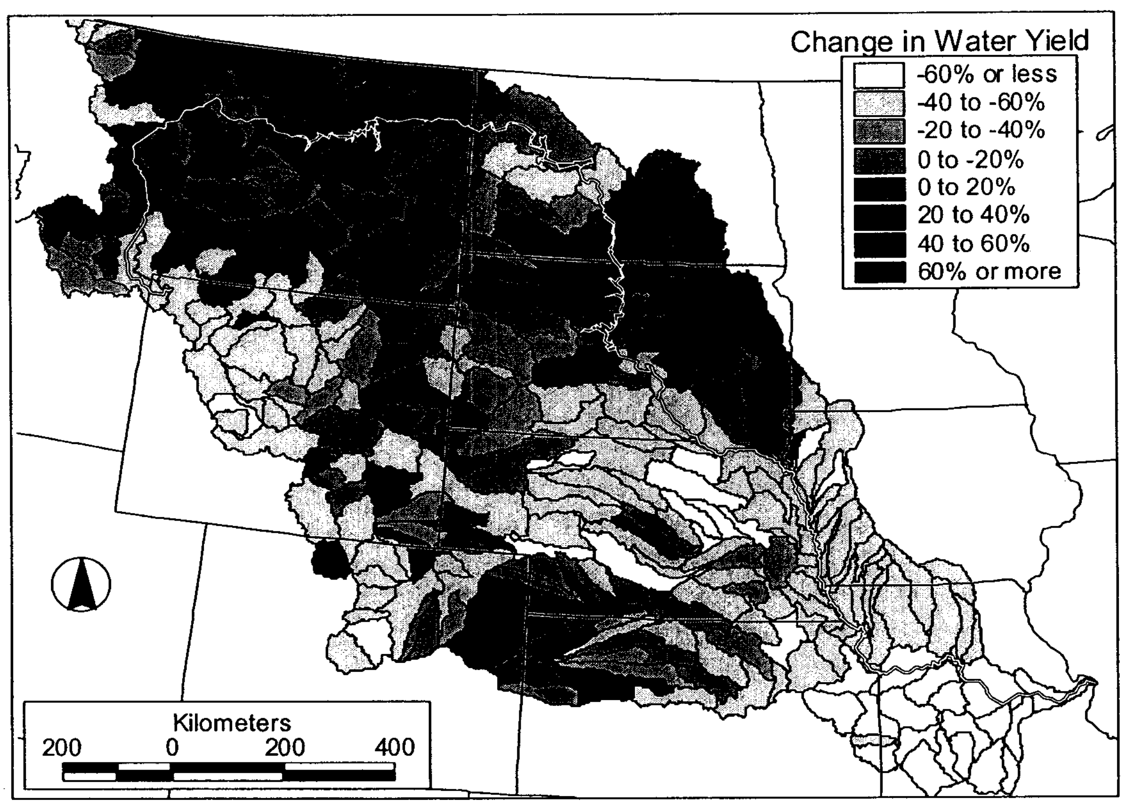

Figure 6. Percent of Change in Water Yield From Baseline Conditions for Spring (April through June).

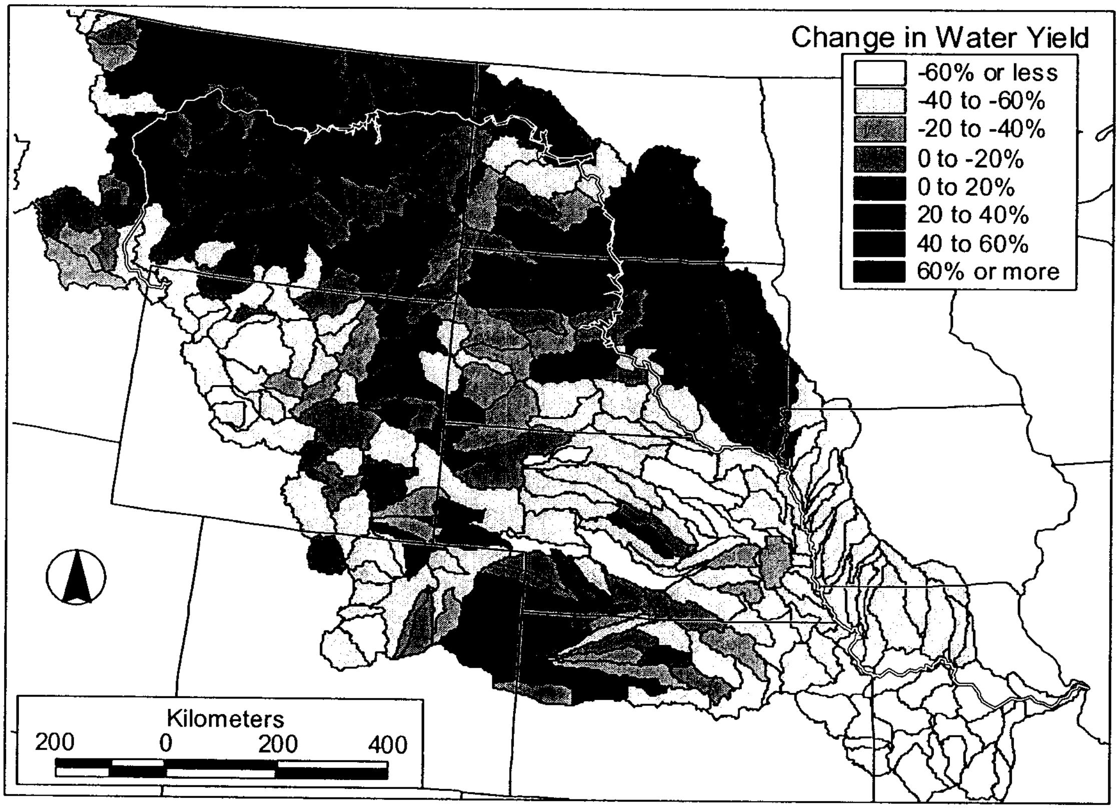

Figure 7. Percent of Change in Water Yield From Baseline Conditions for Summer (July through September).

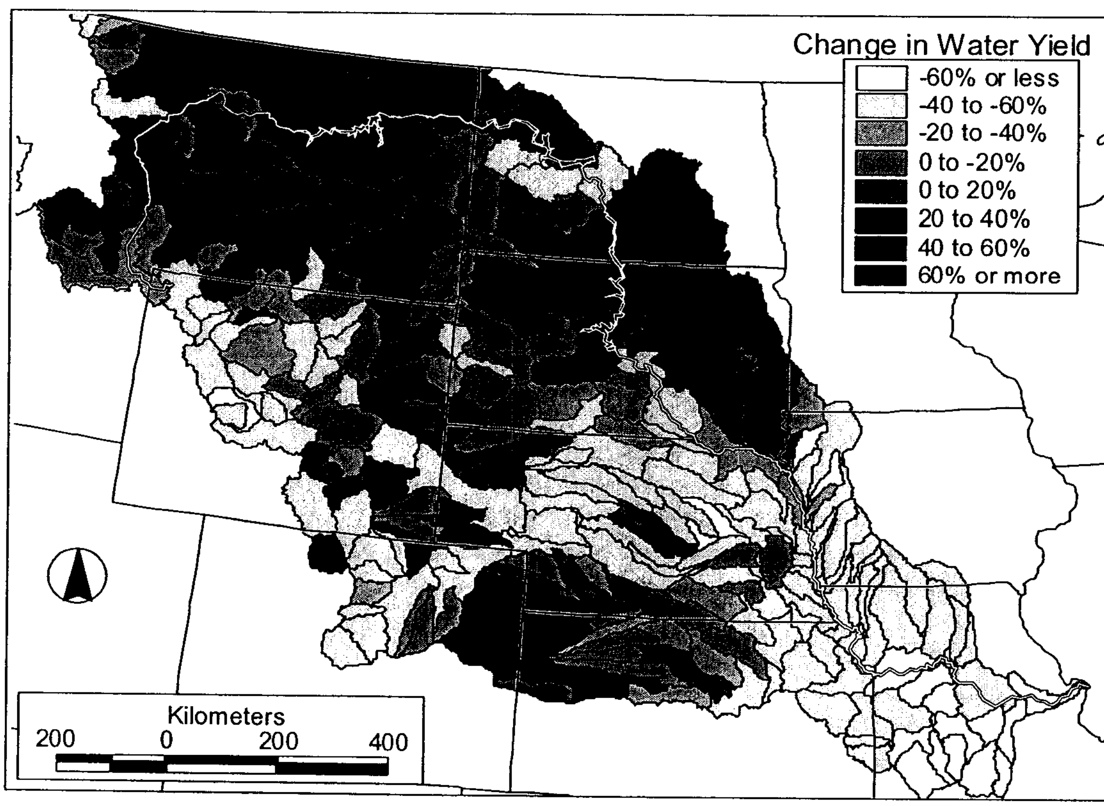

Figure 8. Percent of Change in Water Yield From Baseline Conditions for Fall (October through December).

taken to match the scale of climatic input from the RegCM to the scale of the SWAT model.

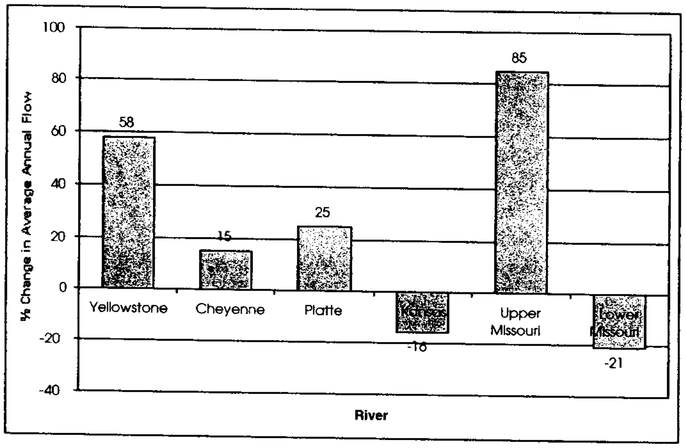

Figure 9. Percent of Change in Average Annual Flow for Six Tributaries.

Despite continuous advancements in the areas of climate and hydrologic modeling, several factors still limit the predictive capability of these models. This prohibits the use of model results as deterministic outcomes and focuses attention on the idea of strategizing and scenario modeling. Hydrologic models are increasingly more complex and capable of modeling large regions in detail. This capability is in part limited by the predictive capabilities of the climate models that provide meteorological inputs to the hydrologic model. GCM and RegCM models are considered the ideal approach to climate modeling because predictions are based on the physical laws governing atmospheric processes. As computing capabilities grow and assumptions that limit the accuracy of climate models become unnecessary, GCM and RegCM models will become increasingly useful as predictive tools for climate change.

Results of this analysis show an overall decrease in the surface water yields from the Missouri River Basin. The spatial pattern of changes in predicted

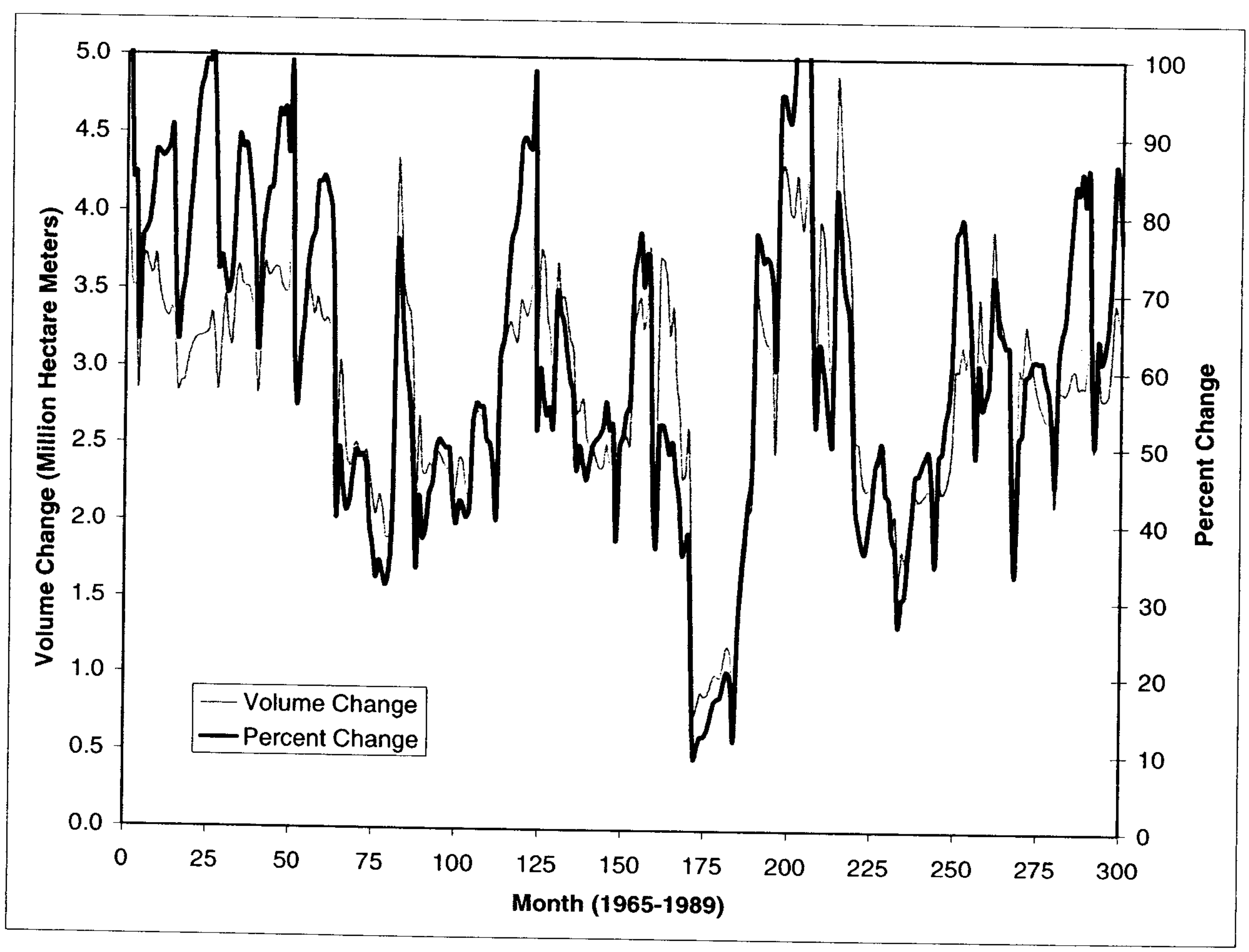

Figure 10. Volume Change and Percent Change in Average Daily Cumulative Reservoir Storage.

water resources is heavily influenced and related to the spatial patterns of the predicted changes in climate conditions. Climate variables in the northern region of the Missouri River Basin change the most in the predicted climate change regime. Precipitation and temperature both increase more in the north than anywhere else in the Great Plains (Giorgi *et al.*, 1998). Thus, the north also experiences the greatest changes in predicted water yields and agricultural production.

Model results indicate the reservoirs release enough additional water under double CO_2 climate conditions to provide 24 cm of additional water for all irrigated areas in the Missouri River Basin annually. The average annual release from the reservoirs for the $2xCO_2$ simulation is nearly double the average release of the baseline simulation. An additional 1.57 million hectare-meters of water are available from the reservoirs for each year of the $2xCO_2$ simulation. The extra water can be diverted from the reservoirs for irrigation of the upper Missouri River Basin or reservoir releases can be increased and the water can be withdrawn downstream from the reservoirs to supplement irrigation of the lower half of the Missouri River Basin.

Results from this study are similar to those obtained in previous modeling efforts. The 10 to 20 percent reductions in basin water yields are similar to the study results by Rosenberg *et al.* (1999), Hurd *et al.* (1996), and the transient results of Lettenmaier *et al.* (1999). It is interesting to note that the $2xCO_2$ scenario completed by Lettenmaier produced a 2 percent increase in water yield. This is likely due to variations in climatic inputs and hydrologic modeling techniques.

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