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ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 409

Sensitivity Analysis of the Soil and Water Assessment Tool (SWAT) for Simulation of Climate Change Effects

by

Michael P. Hanratty

Prepared for

GRAZING LAND RESEARCH LABORATORY
Agricultural Research Service, U. S. Department of Agriculture
El Reno, Oklahoma

In Cooperation with

MID-CONTINENT ECOLOGY DIVISION
U. S. Environmental Protection Agency
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ABSTRACT

A sensitivity analysis of the input parameters of the Soil and Water Assessment Tool (SWAT), developed by the USDA Agricultural Research Service, was conducted. The effects of input parameters describing watershed characteristics and land management practices on SWAT results were analyzed using individual parameter perturbation. The model outputs were monthly streamflow (mm) and monthly averages for sediment yield (t/day), total phosphorus yield (kg/day), ammonia/organic N yield (kg/day), and nitrate/nitrite yield (kg/day). The results were reported qualitatively, not quantitatively, because of the large number of input parameters required for SWAT. Streamflow was most sensitive to the SCS runoff curve number, sediment yield to sediment routing parameters, total P and ammonia/organic N yields to land management practices and to P and N concentrations in the top soil layer, and nitrate/nitrate yield to N concentrations in the top soil layer. The effects of input parameters describing climate conditions were analyzed using error analysis. The climate parameters were monthly precipitation; monthly averages for maximum, minimum, and mean daily air temperature; and monthly averages for relative humidity, solar radiation, and wind speed. SWAT was run using historical weather data and modified historical weather data representing a doubling of atmospheric CO_2 concentration. The percent of the variations in the output variables that were explained by the variations in the climate parameters were calculated. Variations in precipitation and, when snowmelt was a significant part of the hydrologic budget, in temperature explained the variations in the model output the most.

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TABLE OF CONTENTS

LIST OF FIGURES

Figure 1a Simulated monthly streamflow (mm) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationship between the baseline streamflow simulation and the measured maximum daily temperature is represented by a gray curve.

Figure 1b Simulated monthly total phosphorus yield (kg/day) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationship between the baseline total P simulation and the measured maximum daily temperature is represented by a gray curve.

Figure 1c Simulated monthly ammonia/organic N yield (kg/day) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationships between the ammonia/organic N simulations and the measured and projected maximum daily temperatures are represented by gray curves.

Figure 1d Simulated monthly sediment yield (t/day) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationship between the baseline sediment simulation and the measured maximum daily temperature is represented by a gray curve.

Figure 1e Simulated monthly nitrate/nitrite yield (kg/day) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationships between the nitrate/nitrite simulations and the measured and projected maximum daily temperatures are represented by gray curves.

Figure 2a Simulated monthly streamflow vs. monthly climate input parameters for the Cottonwood River watershed. The non-linear relationship between the baseline streamflow simulations and the measured maximum daily temperatures is represented by a gray curve.

Figure 2b Simulated monthly total phosphorus yield vs. monthly climate input parameters for the Cottonwood River watershed.

Figure 2c Simulated monthly ammonia/organic nitrogen yield vs. monthly climate input parameters for the Cottonwood River watershed.

Figure 2d Simulated monthly sediment yield vs. monthly climate input parameters for the Cottonwood River watershed. The non-linear relationship between the baseline sediment yield simulations and the measured maximum daily temperatures is represented by a gray curve.

Figure 2e Simulated monthly nitrate/nitrite yield vs. monthly climate input parameters for the Cottonwood River watershed. The non-linear relationships between the nitrate/nitrite simulations and the measured and projected maximum daily temperatures are represented by gray curves.

Figure 3a Simulated monthly streamflow vs. monthly climate input parameters for the Little Washita River watershed.

Figure 3b Simulated monthly total phosphorus yield vs. monthly climate input parameters for the Little Washita River watershed.

Figure 3c Simulated monthly ammonia/organic nitrogen yield vs. monthly climate input parameters for the Little Washita River watershed.

Figure 3d Simulated monthly sediment yield vs. monthly climate input parameters for the Little Washita River watershed.

Figure 3e Simulated monthly nitrate/nitrite yield vs. monthly climate input parameters for the Little Washita River watershed.

LIST OF TABLES

Table 9	Sensitivity statistics for the SWAT simulation of the Cottonwood River watershed. The square of the Pearson correlation coefficient (r^2) is given for each pair of input and output variables for the baseline and $2xCO_2$ climate scenarios. If the value is marked with †, then the Nash-Sutcliffe coefficient (NS) is given.
Table 10	Pearson correlation coefficient for the relationships between the monthly climate parameters for the Cottonwood River watershed. Precipitation and air temperature data were measured in the watershed. Humidity, solar radiation, and wind speed were generated by SWAT based on historical monthly means and the precipitation and temperature data.
Table 11	Sensitivity statistics for the SWAT simulation of the Little Washita River watershed. The square of the Pearson correlation coefficient (r^2) for each climate parameter-output variable pair for the baseline and $2xCO_2$ simulations.
Table 12	Pearson correlation coefficients for the relationships between the monthly climate parameters for the Little Washita River watershed. Precipitation and air temperature data were measured in the watershed. Humidity, solar radiation, and wind speed were generated by SWAT based on historical monthly means and the precipitation and temperature data.

1. INTRODUCTION

As part of a research project on the potential effects of climate change on aquatic ecosystems, a basin scale hydrologic model, the Agricultural Research Service's (ARS) Soil and Water Assessment Tool (SWAT; Arnold *et al.,* 1994), was chosen to simulate the effect of climate change on the non-point source inputs from rural watersheds to lakes and impoundments (Hanratty, 1995). The goal of this study was to develop methods for conducting a regional analysis of watershed response to climate change. Therefore, the model was applied to three different watersheds, the Baptism River near Beaver Bay, MN, the Little Washita River near Ninnekah, OK, and the Cottonwood River near New Ulm, MN (Hanratty and Stefan, 1997a, b, and c, respectively). These three watersheds were chosen because they differ substantially in land use and climate conditions and because their runoff quantity and quality have been recorded. The Baptism River drains a mostly forested, 352 km^2 watershed on the north shore of Lake Superior. The Cottonwood River, a tributary of the Minnesota River, drains a 3400 km^2 agricultural watershed in southwestern Minnesota. At the USGS gauging station just upstream from Ninnekah, OK, the Little Washita River drains a 538 km^2 agricultural watershed. It flows into the Washita River about 9.5 km downstream of Ninnekah.

When calibrating and interpreting the output of a model, it is very helpful to know which model parameters are the most influential; *i.e.,* which parameters, when perturbed, will yield the largest change in the model output. It is also helpful to quantify the impact of the model parameters. This report describes the sensitivity analysis performed on SWAT when it was applied to three different watersheds. The analysis was performed on two types of input parameters: (1) the parameters that describe the watershed and (2) the parameters that describe the weather occurring in the watershed. The parameters that describe the watershed were used to calibrate the model and were used for a qualitative sensitivity analysis. The large number of parameters required for SWAT made a quanititative sensitivity analysis of the watershed parameters impractical. The parameters that describe the weather were used to simulate the change in climate under a projected $2xCO_2$ scenario and were used for a quantitative sensitivity analysis. The SWAT output variables studied were the monthly and mean monthly streamflow (mm/month), nitrate/nitrite yield (kg/day), total phosphorus yield (kg/day), ammonia/ organic N yield (kg/day), and sediment yield (t/day).

2. MODEL DESCRIPTION

A model of watershed hydrology and water quality, the Soil and Water Assessment Tool, 1996 version (SWAT96, Arnold *et al.,* 1994), was chosen from several available models (Hanratty, 1995) and modified for application to northern and forested watersheds (Hanratty and Stefan, 1997a,c). Because SWAT was designed to be applied to ungauged river basins, it was anticipated that the model could be used for analyzing many watersheds in a geographic region using readily available data. SWAT is a semi-empirical, distributed parameter model designed to predict the impact of management decisions on water, sediment, nutrient, and agricultural chemicals in large, ungauged basins. SWAT's hydrologic predictions are based on a mass balance of the soil moisture using up to ten soil layers. It incorporates well-established ARS hydrologic methods such as the SCS Curve Number method to determine infiltration and runoff and the Modified Universal Soil Loss Equation (MUSLE) to calculate erosion. Both of these methods employ variables which the model changes to represent current soil water and land cover conditions. SWAT uses physically-based methods for the computation of percolation, lateral subsurface flow, evapotranspiration, pond and wetland hydrology, channel transmission losses, soil nutrient dynamics, soil temperature, crop growth, pesticide dynamics, and agricultural management practices. The evapotranspiration algorithm includes the effect of atmospheric CO_2 concentration on plant transpiration, which is important to include in any study of the effects of carbon dioxide-induced climate change (Hanratty and Stefan, 1997a) and a snow cover factor to account for the decrease in soil evaporation due to snow cover (Hanratty and Stefan, 1997c). SWAT's groundwater algorithm is a simplified physically based method (Arnold *et al.,* 1993) and the snowmelt algorithm is a modified degree-day method (Hanratty and Stefan, 1997a). SWAT's channel flood routing is based on Manning's equation and channel geometry. Sediment routing uses particle fall velocity, flow travel time and a sediment delivery ratio. Nutrient and pesticide routing include chemical transformations within the stream channels. Weather data (*i.e.,* minimum and maximum daily temperature, daily solar radiation, mean daily humidity, mean daily wind speed, and daily precipitation) are required for model input and can be generated using statistical parameters from historical records. Alternatively, historical temperature and precipitation data can be input directly to the model. Future versions of SWAT will have the capacity to read in solar radiation data as well (for more information, see Arnold *et al.,* 1990, 1993, 1994).

Srinivasan and Arnold (1994) have created a geographic information system (GIS) interface for SWAT called SWAT/GRASS that runs under the GRASS GIS (CERL, 1988). SWAT/GRASS calculates the SWAT input parameters using GIS maps of topography, land use/land cover, soil types, and subbasin boundaries and assigns default values to parameters that cannot be calculated from the GIS data.

3. SITE DESCRIPTIONS

Baptism River

The three watersheds are compared in Table 1. The Baptism River watershed is located approximately 80 km northeast of Duluth, Minnesota on the north shore of Lake Superior. Most of its 352 km^2 is covered by mixed conifer/deciduous forest. The upper part of the watershed is relatively flat with many forested wetlands and the lower part of the watershed descends relatively steeply to Lake Superior. The watershed has shallow, rocky soils, with 2 m or less depth to bedrock over most of its area. The local climate is cold and wet, with an average annual precipitation of 730 mm, an average annual temperature of about 2.8°C, and an average annual dew point temperature of -1.2°C. The average annual streamflow is 449 mm.

Little Washita River

The Little Washita River watershed (Allen and Naney, 1991) is located in south-central Oklahoma between 97.8° W and 98.3° W and between 34.7° N and 35.0° N. It was chosen because it is exceptionally well instrumented. The river flows generally from west to east, with the western portion flowing southeast and the eastern portion flowing northeast, and drains into the Washita River. The watershed covers 625 km^2 and contains a mix of rangeland (~25%), cropland (~67%), and forest (~6%). The portion of the watershed used for this study, *i.e.,* the portion above the gauging station near Ninnekah, OK, covers 538 km^2. Most of the area consists of long, rolling hills, with steep banks surrounding many of the streams. In the western two-thirds, most of the riparian zones are forested, while in the eastern one-third many are not. The soil tends to be quite rocky, with bedrock outcroppings in the westernmost, easternmost, and north-central portions, and sandstone beneath the surface in the central (largest) portion. Alluvial deposits generally cover the bedrock in the valleys. The soils are deepest (>5 ft. to bedrock) in the northeastern portion due to alluvial deposits, in the south-central portion due to flatter terrain, and in the westernmost portion. From 1969 to 1982, 45 flood-control dams were installed on the watershed by the U.S. Soil Conservation Service. The watershed is relatively warm and dry, with an annual average precipitation of 728 mm, an average annual temperature of 16.6°C and an average annual dew point temperature of 7.6°C. The average annual streamflow is 47 mm.

Cottonwood River

The Cottonwood River basin is located in southwestern Minnesota between 94° 19'W and 96° 3'W and between 43° 53'N and 44° 32'N. The river flows generally from west to east, with the western portion flowing southeast and the eastern portion flowing east, and drains into the Minnesota River at New Ulm, Minnesota. The watershed covers

3400 km^2 and contains a mix of rangeland (~52%) and cropland (~46%). The rangeland is hilly and is located in the southwestern portion of the watershed where the tributaries all run to the northeast. The cropland is flat and is located in the northeastern portion of the watershed (Mulla and Mallawatantri, 1997). The surficial aquifers are in glacial till, ranging from less than 100 to about 400 feet in saturated thickness (Broussard *et al.*, 1973). The deeper aquifers are contained in Cretaceous, Cambrian, and Precambrian deposits. Most of the smaller tributaries have no natural storage and there are only ten small flood water retention ponds constructed in the entire watershed. The watershed is relatively cool and not as dry as the Little Washita River watershed, with an annual average precipitation of 666 mm, an average annual temperature of 6.9°C and an average annual dew point temperature of 0.7°C. The average annual streamflow is 86 mm.

Table 1 Comparison of the Baptism, Little Washita, and Cottonwood River watersheds.

	Baptism	**Little Washita**	**Cottonwood**
area (km^2)	352	625	3400
average annual precipitation (mm)	730	728	666
average annual streamflow (mm)	449	47	86
average annual air temperature (°C)	2.8	16.6	6.9
average annual dew point (°C)	-1.2	7.6	0.7
land use	mixed forest	rangeland, cropland, forest	rangeland, cropland

4. SENSITIVITY TO WATERSHED PARAMETERS

The sensitivities of the SWAT output to several input parameters were analyzed during calibration. The input parameters describe the watersheds and the land management practices employed in them. For each watershed, the individual parameters were perturbed, the model was run using historical weather data, and the results were compared to previous runs. The parameters that were given default values by SWAT/GRASS were examined. With the exception of the SCS runoff curve number, those that were calculated directly from physical features of the watershed were left unchanged. The relative sensitivity of the model output to the input parameter was recorded in one of three categories: smaller magnitude, same magnitude, or larger magnitude. All changes were measured relative to the input or output value. The most influential parameters produced a change in output that was larger than the change in the input parameter (*e.g.,* a 10% change in input yielded about a 20% or greater change in output). The least influential parameters produced a change in output that was smaller than the change in the input parameter (*e.g.,* a 10% change in input yielded a change in output of about 2% or less). Those in the middle produced a change in output of the same order of magnitude as the change in the input parameter (*e.g.,* a 10% change in input yielded a 5-15% change in output).

The sensitivity analysis was performed in two stages. First the parameters that affect the streamflow and then the parameters that affect the nutrient and sediment yields were analyzed. Because the flow of water is the main transport mechanism for nutrients and sediment, the parameters that produce a large magnitude change in streamflow often produce at least the same magnitude of change in nutrient and/or sediment yields. These parameters, however, were not used to calibrate the simulated nutrient and sediment yields. The simulated streamflow was calibrated first, then other parameters were used to calibrate the nutrient and sediment yields. Therefore, the parameters that have a large effect on streamflow were not included in the sensitivity analysis for nutrient and sediment yields. This approach left out some of the variables that have a large influence on simulated water quality from the water quality columns of Tables 2, 3, and 4. Because their influence on water quality was through changes in streamflow, they were only listed in the streamflow column.

Little Washita River Watershed

For the Little Washita River in Oklahoma, the change in the simulated monthly streamflow was smaller in magnitude than the change in groundwater delay, groundwater flow rate (alpha), groundwater (below the root zone) evaporation rate, deep aquifer recharge, and channel flow Manning's n (Table 2). The change in simulated monthly streamflow was about the same magnitude as the overland flow Manning's n and the effective hydraulic conductivity of the routing channel and larger in magnitude than the runoff curve number. Simulated streamflow was very sensitive to the runoff curve number

Table 2 Sensitivity analysis of the SWAT simulation of the Little Washita River watershed. Input parameters are listed that, when changed, produced a change in output of a smaller magnitude, of the same magnitude, or of a larger magnitude.

Output Variable	**Magnitude**		
	Smaller	**Same**	**Larger**
Streamflow	•groundwater delay •groundwater flow rate •groundwater evaporation •deep aquifer recharge •channel flow Manning's n	•overland flow Manning's n •effective hydraulic conductivity of routing channel	•runoff curve number
Sediment	•spring plowing •manure spread as fertilizer •weekly tilling to incorporate manure	•channel bed degradation calibration coefficient	•channel bed degradation calibration exponent
Nitrate/ Nitrite	•spring plowing •effective mixing rate for plowing •manure spread as fertilizer •manure incorporated as fertilizer		
Total P	•effective mixing rate for plowing		•spring plowing •manure spread as fertilizer •manure incorporated as fertilizer
Ammonia/ Organic N	•effective mixing rate for plowing		•spring plowing •manure spread as fertilizer •manure incorporated as fertilizer

because of the primary place that the SCS curve number method has in SWAT's simulation of watershed hydrology. The effective hydraulic conductivity of the routing channel plays an important role because it determines the rate of water loss through channel beds, it can vary over a few orders of magnitude, and, in watersheds the size of Little Washita or larger, there are many kilometers of channel bed through which water can infiltrate into the soil.

The water quality simulated by SWAT for the Little Washita River watershed varied in sensitivity to various watershed parameters and land management practices (Table 2). Two types of spring plowing were added to the management of the wheat and hay fields and two different manure management strategies were simulated. Addition of the manure to the watershed was simulated using two different pathways, (1) application to wheat, pasture, and hay fields as fertilizer and (2) application to wheat and hay fields as fertilizer and incorporated into the soil. Each of these application methods was simulated both with and without a tillage operation before planting in the subbasins where wheat or hay were the dominant crops. The spring plowing used either a 50% effective mixing of crop residue and nutrients or a conservation tillage of 25% effective mixing. The application of manure to fields as fertilizer was simulated by dividing the annual manure production into 43 equal weekly applications (the months of July and August were skipped, assuming that growing crops prohibited the manure spreading) and spreading it on the first soil layer (the first layer is 1 cm thick). For the manure application that was incorporated into the soil, the equal weekly applications were placed on the first soil layer and a weekly tilling operation using a 50% effective mixing rate was performed. A weekly tilling operation is much more frequent that the usual farming practice, but was used as an extreme case to examine the effects of high amounts of soil disturbance.

The sensitivity of the simulated water quality to the different manure application scenarios and input parameters is summarized in Table 2. The simulated yields of sediment changed very little between the spring plowing and no spring plowing scenarios (smaller magnitude). The spreading of manure had virtually no effect on sediment yield (smaller magnitude), but the weekly tilling to incorporate the manure resulted in slightly higher sediment yields (smaller magnitude). Simulated nitrate yields changed slightly with the addition of a spring plowing and/or manure to watershed (smaller magnitude). Nitrate yields were not very sensitive to the manure application and land management practices because the changes in the amount of nitrate available for transport were much smaller than the average nitrate yields. Since nitrate is water soluble, SWAT's simulations of nitrate yields involved both surface and sub-surface transport processes. Therefore, nitrate yields were not very sensitive to management practices performed on the surface of the land. Sediment yields, on the other hand, were sensitive to land management practices when the surface of the soil was disturbed often, as in the weekly tilling to incorporate manure into the soil. Simulated sediment yields also changed by the same magnitude as the channel bed degradation calibration coefficient and at a larger magnitude than the channel bed degradation calibration exponent.

Phosphorus and ammonia/organic N yields varied significantly between the land and manure management scenarios (Table 2). Simulated phosphorus and ammonia/organic N yields changed dramatically when manure was spread on the surface, when a spring plowing was added, and when manure was incorporated by tilling on a weekly basis (larger magnitude). The changes in simulated phosphorus and ammonia/organic N, however, were smaller in magnitude than a change in the depth of the spring plowing from an effective mixing rate of 50% (standard spring plowing) to a mixing rate of 25% (conservation tillage). Phosphorus and ammonia/organic N yields were sensitive to manure and land management practices because the movements of these two non-soluble, particle-associated nutrients were due to surface processes. Therefore, the amount of phosphorus and ammonia/organic N in the surface layer and the amount of runoff from the soil surface had a large influence on their yields.

Baptism River Watershed

Since Minnesota's Baptism River watershed is almost entirely covered by forest, the evapotranspiration (ET) of the trees has a significant impact on the streamflow at the watershed outlet. Tree ET, in turn, is affected by the maximum leaf area index of the forest and by the nutrient levels in the soils. Therefore, simulated streamflow changed at a larger magnitude than the change in maximum leaf area index and at the same magnitude as the change in initial organic phosphorus concentrations in the top soil layer (Table 3). Organic P levels in the soil affected streamflow by limiting the growth of the forest. The default values for initial organic P concentrations in the top soil layer are calculated in SWAT as a fraction of the initial organic N concentrations, so changes in the initial organic N concentration can change the initial organic P concentration. Therefore, even though phosphorus was the limiting nutrient for this simulated forest, when no value was specified for initial organic P in the top soil layer, streamflow also changed at the same magnitude as the change in the initial organic N concentration.

Simulated streamflow was also very sensitive (larger magnitude) to the temperature used to determine snowmelt. When the average daily air temperature was used, the peak of monthly streamflow in the spring was a month late. When the maximum daily air temperature was used, the peak occurred in the correct month. Although simulated streamflow changed at a smaller magnitude than the groundwater parameters (flow rate, delay, specific yield, evaporation coefficient, and deep aquifer recharge coefficient), they were important for calibrating streamflow for the Baptism River simulation. Some of the parameters were changed two or three orders of magnitude from the default values in order to represent the very shallow surficial aquifer in the Baptism River watershed.

Finally, simulated monthly streamflow changed at a smaller magnitude than the runoff curve number and the snow evaporation coefficient. The short amount of time required for percolation of water from the root zone into the surficial aquifer (0.2 days) allowed the surface and sub-surface flow to arrive at the basin outlet within the same

Table 3 Sensitivity analysis of the SWAT simulation of the Baptism River watershed. Input parameters are listed that, when changed, produced a change in output of a smaller magnitude, of the same magnitude, or of a larger magnitude.

Output Variable	**Magnitude** **Smaller**	**Same**	**Larger**
Streamflow	•groundwater delay •groundwater flow rate •groundwater evaporation •deep aquifer recharge •aquifer specific yield •runoff curve number •snow evaporation coefficient	•initial organic P in top soil layer •initial organic N in top soil layer	•maximum leaf area index •snowmelt temperature
Sediment		•routing channel erodibility •routing channel MUSLE cover factor •normal sediment concentrations in ponds, wetlands, and groundwater return flow •channel bed degradation calibration coefficient	•channel bed degradation calibration exponent
Nitrate/ Nitrite		•initial organic N in top soil layer	
Total P	•routing channel erodibility •routing channel MUSLE cover factor •normal sediment concentrations in ponds, wetlands, and groundwater return flow •channel bed degradation calibration coefficient	•initial organic P in top soil layer •Initial organic N in top soil layer	
Ammonia/ Organic N		•initial organic N in top soil layer	

month, which minimized the importance of the runoff curve number. The potential evaporation of snow was so small (due to temperatures well below 0°C) that the snow evaporation coefficient had little effect on the amount of accumulated snow and the resulting snowmelt.

Simulated sediment yield changed at the same magnitude as the change in the routing channel erodibility, the routing channel MUSLE cover factors, and the normal sediment concentrations in the ponds, wetlands, and groundwater return flow (Table 3). In the Baptism River watershed, the forest floor is subject to relatively small amounts of surface erosion, so these constants that determine in-stream and in-lake suspended sediment concentrations were the primary determinants of sediment yield.

Most of the phosphorus in the Baptism River was transported as sediment-associated particles. Therefore, phosphorus yields exhibited low sensitivity (smaller magnitude) to the sediment yield parameters (Table 3). In addition, phosphorus yields changed at the same magnitude as the initial concentration of organic P in the soil and, when no value was specified for initial organic P, at the same magnitude as the initial concentration of organic N. Similarly, ammonia/organic N and nitrate/nitrite yield changed at the same magnitude as the initial organic N concentration in the top 1 cm of soil.

Cottonwood River Watershed

The simulated hydrology of the Cottonwood River watershed in Minnesota was dominated by surface runoff. Simulated streamflow changed at a larger magnitude than the change in the SCS runoff curve number (Table 4). Simulated streamflow was also sensitive to the temperature used to determine snowmelt (larger magnitude). When the maximum daily air temperature was used, the peak of monthly streamflow in the spring was a month early. When the average daily air temperature was used, the peak occurred in the correct month.

A change in the saturated conductivity of the soil produced a smaller magnitude change in streamflow. A change in the snow evaporation coefficient produced the same magnitude of change in the spring peak for monthly streamflow by increasing the amount of accumulated snow during the winter. A change in Manning's n for overland flow in the rangeland subbasins also produced a smaller magnitude of change in simulated streamflow.

The sensitivities of nutrient and sediment yields to various parameters are summarized in Table 4. Simulated sediment yields changed at the same magnitude as the channel bed degradation calibration coefficient and at a larger magnitude than the channel bed degradation calibration exponent. Total phosphorus yields changed at the same magnitude as the initial organic phosphorus concentration in the top soil layer, and, when the initial organic P concentration was not input, at the same magnitude as the initial organic N concentration in the top soil layer. Ammonia/organic N yields also changed at the same magnitude as the initial organic N concentration in the top soil layer. Like the Little Washita River watershed, the addition of a spring plowing produced a large magnitude change in total P and ammonia/organic N yields, but a change in the rate of effective mixing from 50% to 25% produced a smaller magnitude change. Total P and ammonia/organic N yields were also changed at a smaller magnitude than a change in the rate of fertilization with a standard 28-10-10 (percent content of N, P_2O_5, and K_2O, respectively) fertilizer. Like the Little Washita River watershed, total P and ammonia/organic N yields in the Cottonwood River watershed were controlled primarily by surficial processes.

Table 4 Sensitivity analysis of the SWAT simulation of the Cottonwood River watershed. Input parameters are listed that produced a change in SWAT output of a smaller magnitude, of the same magnitude, or of a larger magnitude than the change in the parameter.

Output Variable	**Magnitude** **Smaller**	**Same**	**Larger**
Streamflow	•soil saturated conductivity •overland flow Manning's n	•snow evaporation coefficient	•runoff curve number •snowmelt temperature
Sediment	•spring plowing •effective mixing rate for plowing	•channel bed degradation calibration coefficient	•channel bed degradation calibration exponent
Nitrate/ Nitrite	•spring plowing •effective mixing rate for plowing •Initial organic N in top soil layer	•28-10-10 fertilizer	
Total P	•effective mixing rate for plowing •28-10-10 fertilizer	•initial organic P in top soil layer •initial organic N in top soil layer	•spring plowing
Ammonia/ Organic N	•effective mixing rate for plowing •28-10-10 fertilizer	•initial organic N in top soil layer	•spring plowing

Because the simulated hydrology was primarily driven by surface runoff, the nitrate/nitrite yields in the Cottonwood were also controlled primarily by surficial processes, but not in the same way as total P and ammonia/organic N yields. Nitrate/nitrite yields changed at a smaller magnitude than the initial organic N concentration in the top soil layer and the addition of a spring plowing produced a small magnitude change in nitrate/nitrite yield (Table 4). Nitrate/nitrite yields also changed at a smaller magnitude than the date of spring planting; *i.e.,* there were no discernible changes in yield when the date of spring planting was changed to an earlier date. Nitrate/nitrite yields were, however, sensitive to fertilizing operations. They changed at the same magnitude as the rate of fertilization with a standard 28-10-10 fertilizer when the fertilizer was added on a specific date or was added when the crops were stressed by the lack of nitrogen.

Sensitivity to Land Use/Land Cover

The land use/land cover data used to define the input for simulating the Little Washita River and Cottonwood River watersheds did not include information on the crops grown in the watersheds. Therefore, the dominant crops grown were determined from U.S. Census data and randomly distributed over the cropland in the watershed. In order to determine the variation in streamflow between different, random permutations of the dominant crops in the Little Washita River watershed, a sensitivity analysis was performed. Four different permutations were examined. For the first three, the cells in the GIS land use/land cover map of the Little Washita River watershed that contained cropland were randomly assigned to spring wheat, hay, or pasture in equal numbers. SWAT/GRASS was then run to determine the dominant crop for each of the watershed's 55 subbasins. The fourth permutation was determined by assigning directly to each subbasin a dominant crop, so that the number of subbasins with each dominant crop was equal. The number of subbasins assigned to each dominant crop is given in Table 5 for each of the four land use permutations.

Table 5 Different permutations of land use for the Little Washita River watershed used for sensitivity analysis. The number of subbasins for each land cover type is listed for four permutations.

	Land Use Permutation			
Land Cover/Crop	**1**	**2**	**3**	**4**
Spring Wheat	15	4	9	10
Hay	6	7	19	10
Pasture	9	19	2	10
Rangeland	25	25	25	25

SWAT/GRASS was used to calculate the input parameters for each of the four land use permutations and then the runoff curve numbers were decreased by 20% from the values calculated by SWAT/GRASS. The simulations were compared to the measured streamflow and the resulting standard errors (SE) and Nash-Sutcliffe coefficients (NS) were calculated (Table 6). The type and distribution of crops in the watershed had a definite impact on the simulated streamflow. The standard errors ranged from 1.20 mm to 5.99 mm and the Nash-Sutcliffe coefficients from 0.72 to -0.54.

Table 6 Analysis of the sensitivity of monthly and mean monthly streamflow to land use in the Little Washita River watershed. The simulated streamflow for each of four permutations of land use is compared to the measured streamflow in the Little Washita River near Ninnekah, OK for the period 1963 to 1979.

		Land Use Permutations			
		1	**2**	**3**	**4**
Mean	SE (mm)	1.20	2.15	1.77	1.47
Monthly	NS	0.72	0.12	0.40	0.59
Monthly	SE (mm)	3.56	5.99	3.16	3.01
	NS	0.46	-0.54	0.57	0.61

5. INFLUENCE OF CLIMATE PARAMETERS

In contrast to the individual parameter perturbation method used for the SWAT watershed parameters, an error analysis approach was used to study the sensitivity of SWAT's output to various climate parameters (Bartell *et al.,* 1986; Gardner *et al.,* 1981). Error analysis improves the accuracy of the ranking of the most influential input parameters to non-linear systems by examining the relationship between input parameters and output variables in the context of the natural ranges, variations, and correlation structure of the input parameters. Typically, large sets of field data to be used as input parameters are not available for error analysis. Therefore, the variation and correlation structure of input parameters are generated artificially and then Monte Carlo iterations of a model are run to determine the relationship between the variation of the input and output parameters (McKay, 1988).

There were, however, long records of precipitation and air temperature for each of the three watersheds in this study. These climate data already contained the natural variation and correlation structure. Therefore, about twenty years (240 months) of daily precipitation, maximum daily air temperature, and minimum daily air temperature data from the period 1960-1979 were used as input to the model for the Baptism, Cottonwood, and Little Washita River watersheds. Furthermore, SWAT generated humidity, solar radiation, and wind speed data from historical monthly means, the precipitation data, and the air temperature data. These generated weather input parameters were used for error analysis as well.

The historical climate data, however, did not include the ranges that would be expected under a 2xCO_2 climate change scenario. Therefore, SWAT was also run with the weather parameters expected after a doubling of atmospheric CO_2. These were obtained by applying monthly increments to the historical climate data. The monthly climate increments were obtained from the output of a Global Circulation Model (GCM), the second generation of the Canadian Climate Center model (CCC; Boer *et al.,* 1992; McFarlane *et al.,* 1992).

When measuring sensitivity, the slopes of the relationships between the input parameters and the output variables are typically used. For this study, linear regressions were calculated between the simulation outputs and each of the climate input parameters. The outputs examined were the monthly streamflow (mm/month) and the monthly means for total P (kg/day), ammonia/ organic N (kg/day), sediment (t/day), and nitrate/nitrite yields (kg/day) for both the historical conditions and the 2xCO_2 climate scenario. The coefficients of determination (CoD) were then calculated using Equation 1. This statistic, typically referred to as r^2, provides the strength, or goodness of fit, of a linear relationship between the input parameters and the output variables (McCuen and Snyder, 1986).

$$CoD = 1 - \frac{\sum (obs - pred)^2}{\sum \left(obs - \overline{obs}\right)^2} \qquad \textbf{(1)}$$

When the relationship between an input parameter and an output variable was shown to be clearly non-linear by a scatter plot of the output variable vs. the input parameter, a non-linear curve was fit to the data. The moving average of the output variable, with a period of 20 data points, was used as the curve that describes the non-linear relationship between the input parameter and the output variable. The coefficient of determination (Equation 1) was then calculated. The advantage of using the moving average to represent the non-linear relationship between an input parameter and an output variable was that the coefficient of determination would be bounded by 0 and 1. That is, the residual between the moving average and the data (the numerator in Equation 1) would always be less than or equal to the distance between the data and the mean of the data (the denominator in Equation 1). Since the coefficient of determination is also bound by 0 and 1 for its typical application to a linear regression, the application of the coefficient of determination to the moving average provides a meaningful comparison between the strengths of the linear and non-linear relationships.

The climate parameters that were most influential in determining the response of the simulated watershed, then, were those that had the highest coefficient of determination (CoD). There are conditions under which a high CoD over-estimates the influence of an input parameter, such as when an output variable changes very little. In that case, a linear regression between the output variable and an input parameter would yield a nearly horizontal line with a high CoD. There are also conditions under which the CoD may under-estimate the influence of a parameter, such as when an output variable changes a lot in response to a small change in an input parameter, but there is a high amount of scatter in the data. To avoid misinterpreting the CoD, therefore, all of the relationships between the climate input parameters and the output variables were graphed as two dimensional scatter plots. Simulations of monthly streamflow (mm/month) and of the monthly means for total P (kg/day), ammonia/organic N (kg/day), sediment (t/day), and nitrate/nitrite yields (kg/day) were plotted against monthly precipitation (mm/month), the monthly means for minimum, maximum, and average daily air temperature (°C), and the monthly means for relative humidity (dimensionless), solar radiation (langleys/day), and wind speed (m/sec). There were none of the above inaccuracies in ranking the influence of input parameters in this analysis.

Finally, the correlations between the input parameters were calculated for both the baseline climate (historical conditions) and the $2xCO_2$ climate scenario and included in this report in order to provide a more complete description of the climate parameters.

Baptism River

Overall, the streamflow and water quality in the Baptism River watershed were most influenced by precipitation and air temperature. In the baseline simulation, non-linear relationships with temperature dominated the variation of the model output because SWAT uses air temperature to calculate snowmelt. In the $2xCO_2$ simulation, snow accumulation was decreased and snowmelt was spread out over more months than in the baseline simulation. Therefore, linear relationships with rainfall and, to a lesser extent, non-linear relationships with temperature were the best predictors of variation in the simulated streamflow and water quality.

Table 7 Sensitivity statistics for the SWAT simulation of the Baptism River watershed. The coefficient of determination (CoD) is given for each pair of input and output variables for the baseline and $2xCO_2$ climate scenarios. If the value is marked with †, then a non-linear relationship was used to calculate the CoD. If the value is marked with ‡, the CoD has been calculated after removing outliers.

Scenario	Parameter	Streamflow	Total P	NH3/Org N	Sediment	NO3/NO2
Baseline	Precip	0.16	0.05	0.20	0.10	0.01
	Max Temp	0.34†	0.15†	0.10†	0.23†	0.23†
	Min Temp	0.07	0.01	0.03	0.03	0.01
	Mean Temp	0.07	0.01	0.03	0.03	0.01
	Humidity	0.01	0.03	0.01	0.02	0.08
	Solar Rad	0.08	0.05	0.02	0.07	0.04
	Wind Speed	0.00	0.01	0.00	0.01	0.04
	Soil Water	0.09	0.08	0.04	0.10	0.07
2xCO2	Precip	0.38‡	0.20	0.24	0.36‡	0.02‡
	Max Temp	0.01‡	0.00	0.08†	0.01‡	0.11‡, 0.18†
	Min Temp	0.02‡	0.00	0.01	0.01‡	0.12‡
	Mean Temp	0.01‡	0.00	0.01	0.01‡	0.11‡
	Humidity	0.00‡	0.00	0.00	0.00‡	0.01‡
	Solar Rad	0.01‡	0.01	0.01	0.01‡	0.00‡
	Wind Speed	0.00‡	0.00	0.00	0.00‡	0.02‡
	Soil Water	0.07‡	0.02	0.01	0.05‡	0.09‡

The sensitivity statistics comparing the monthly climate data to the monthly SWAT output for the Baptism River watershed are shown in Table 7 and the correlations between parameters are shown in Table 8. Linear relationships between the climate parameters and streamflow in the Baptism River yielded coefficients of determination (CoD) of only 0.0 to 0.18. Therefore, the graphical comparisons between the climate parameters and the streamflow (Fig. 1a) were examined for possible non-linear relationships. The graph of streamflow vs. maximum daily air temperature showed a definite non-linear relationship between the two, with streamflow increasing with temperature below about 10°C and decreasing with temperature above about 10°C. The moving average of the monthly streamflow data was used to define the non-linear relationship and the CoD was calculated to be 0.34. The spring snowmelt created most of the variation in streamflow in the Baptism River in the baseline simulation. The change in monthly streamflow with respect to the monthly average of the maximum daily temperature, as represented by the absolute value of the slope of the non-linear curve, was highest in the range from about 5°C to 12°C (Fig. 1a).

In the $2xCO_2$ simulation, however, precipitation was the most influential climate parameter (Table 7). When the two most extreme events were not included in the calculation, the CoD was 0.38. The projected increase in temperature under the $2xCO_2$ conditions decreased the amount of snow accumulation and spread out the snowmelt over more months, so precipitation became a more important predictor than temperature.

Table 8 Pearson correlation coefficient for the relationships between the monthly climate parameters for the Baptism River watershed. Precipitation and air temperature data measured near the watershed. Humidity, solar radiation, and wind speed were generated by SWAT based on historical monthly means and the precipitation and temperature data.

Scenario	Parameter	Max Temp	Min Temp	Mean Temp	Humidity	Solar Radiation	Wind Speed
Baseline	Rainfall	0.55	0.56	0.56	0.09	0.23	-0.11
	Max Temp		0.99	1.00	0.09	0.46	-0.17
	Min Temp			1.00	0.12	0.37	-0.16
	Mean Temp				0.10	0.42	-0.16
	Humidity					-0.18	-0.08
	Solar Rad						-0.04
2xCO2	Rainfall	0.47	0.48	0.48	0.04	0.37	-0.20
	Max Temp		0.99	1.00	0.03	0.53	-0.38
	Min Temp			1.00	0.05	0.45	-0.37
	Mean Temp				0.04	0.49	-0.37
	Humidity					-0.10	-0.04
	Solar Rad						-0.10

The relationships between the monthly climate parameters and the SWAT simulations of monthly total P (Fig. 1b) and sediment (Fig. 1d) were very similar to the relationships between the climate parameters and streamflow (Table 7). Air temperature was the strongest predictor for total P and sediment in the baseline simulation with CoDs of 0.15 and 0.23, respectively, calculated using a non-linear relationship with maximum daily temperature. Precipitation was the strongest predictor for total P and sediment in the $2xCO_2$ simulation. The relationship between total P and precipitation yielded a CoD of 0.20 and, when two extreme events were removed, the CoD for the influence of precipitation on sediment yield was 0.36.

For ammonia/organic N yields (Fig. 1c), precipitation was the most influential parameter for both the baseline and the $2xCO_2$ simulations: 0.20 and 0.24 CoDs, respectively, using a linear relationship (Table 7). Air temperature had a smaller, non-linear influence. The CoDs were 0.10 and 0.08 for the non-linear relationship between maximum daily temperature and ammonia/organic N in the baseline and $2xCO_2$ simulations, respectively.

Nitrate/nitrite yields (Fig. 1e), on the other hand, were most influenced by temperature. The non-linear relationship between nitrate/nitrite yields and maximum daily temperature in the baseline simulation yielded a CoD of 0.23. In the $2xCO_2$ simulation, the relationship with temperature was weaker. When the two most extreme events were omitted, the CoDs were 0.11 and 0.18, respectively, for a linear and non-linear relationship with maximum daily temperature (Table 7).

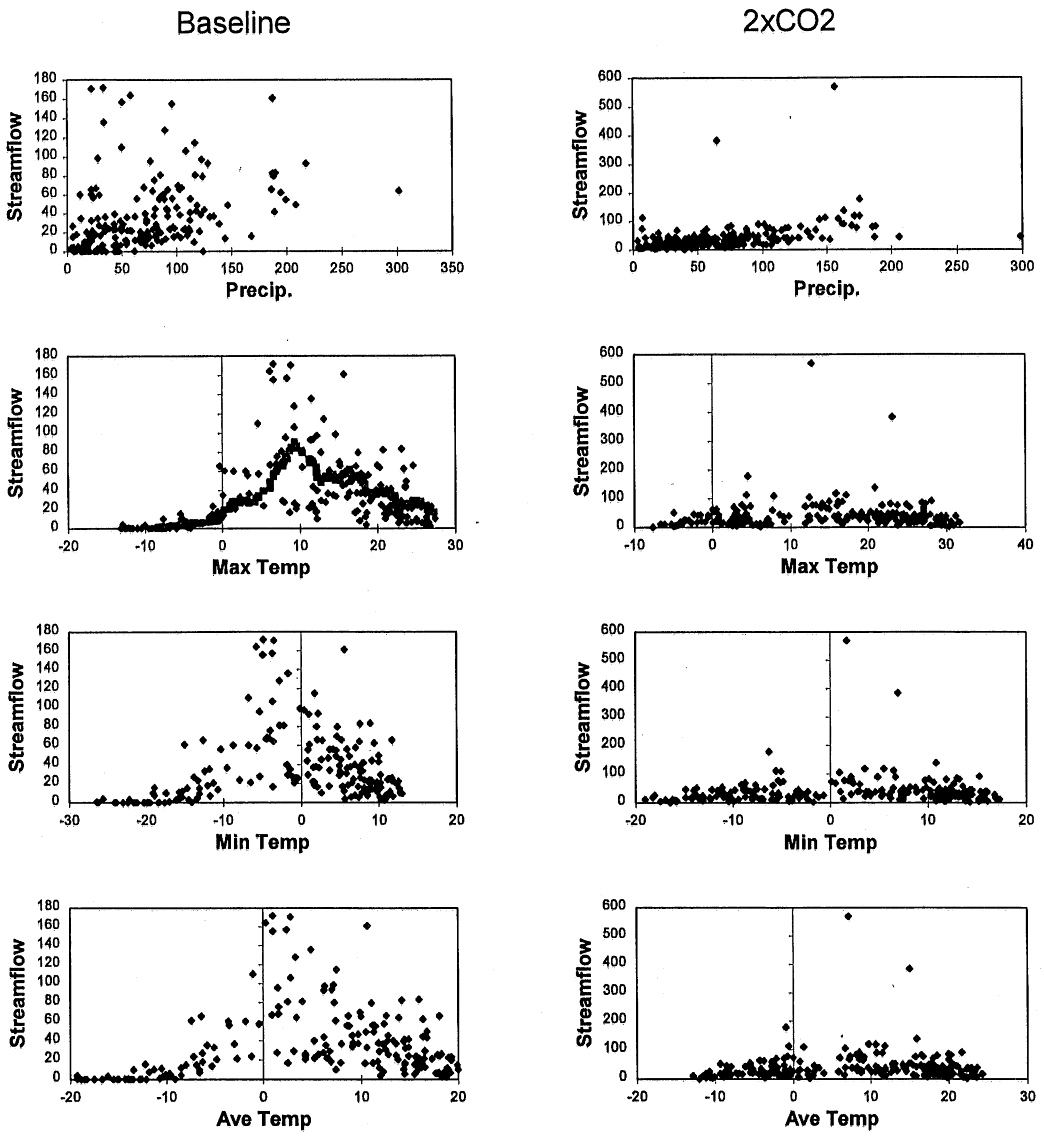

Figure 1a Simulated monthly streamflow (mm) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationship between the baseline streamflow simulation and the measured maximum daily temperature is represented by a gray curve.

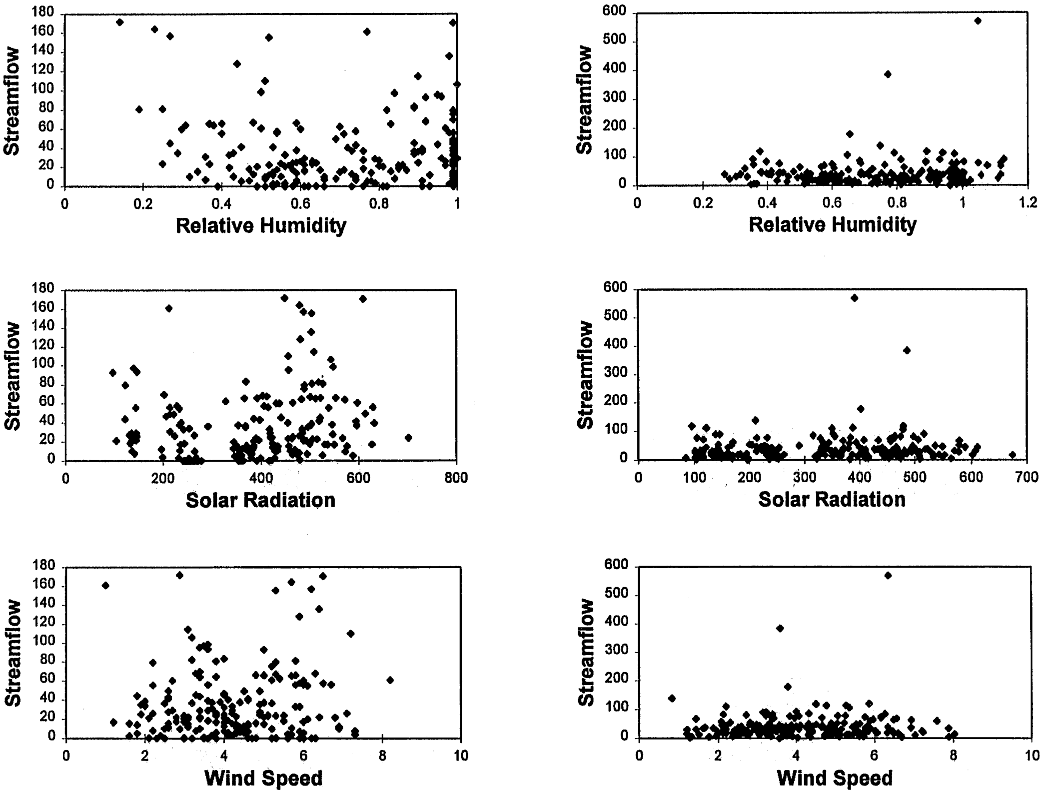

Figure 1a **(Cont'd.)** Simulated monthly streamflow (mm) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationship between the baseline streamflow simulation and the measured maximum daily temperature is represented by a gray curve.

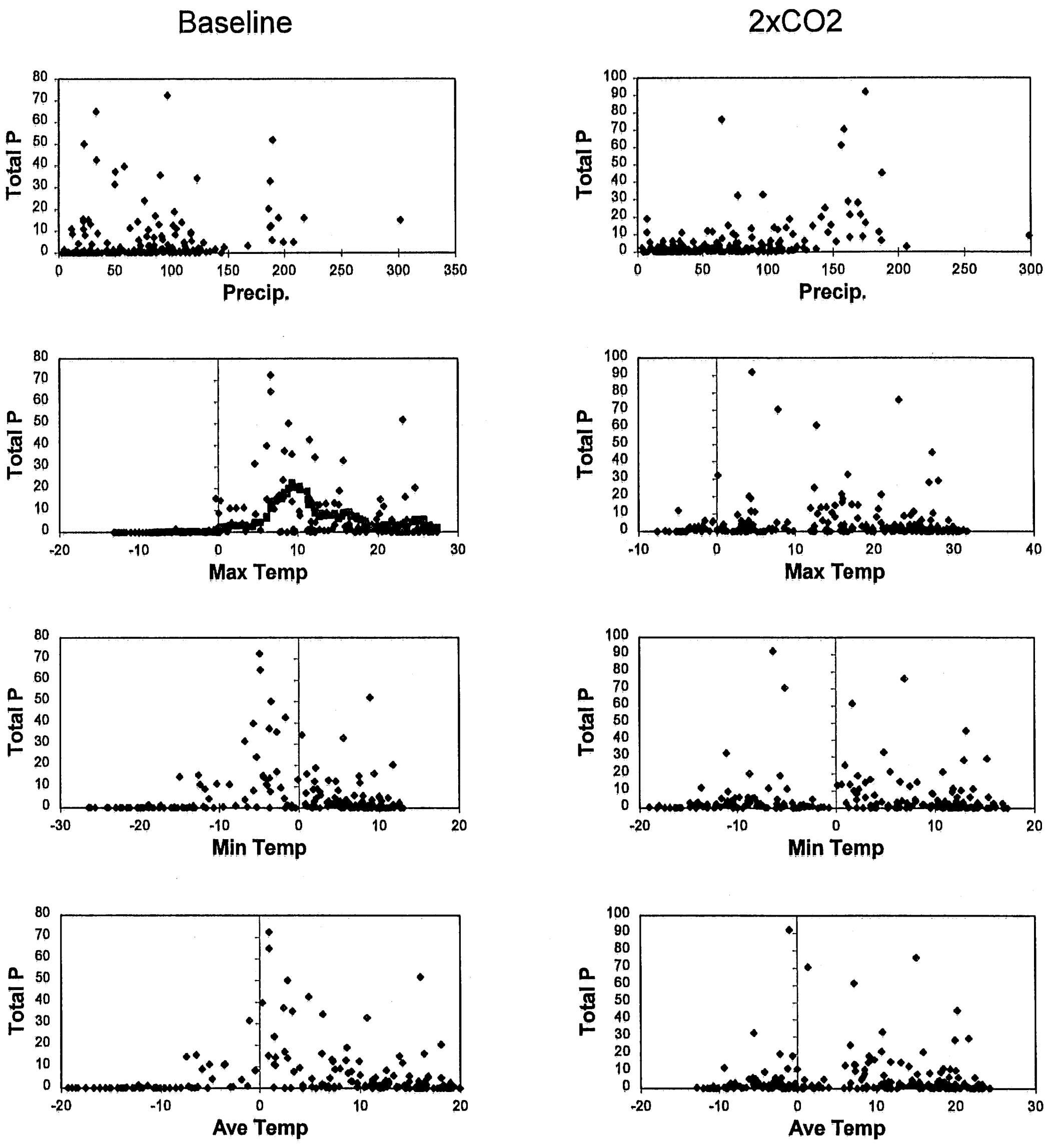

Figure 1b Simulated monthly total phosphorus yield (kg/day) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationship between the baseline total P simulation and the measured maximum daily temperature is represented by a gray curve.

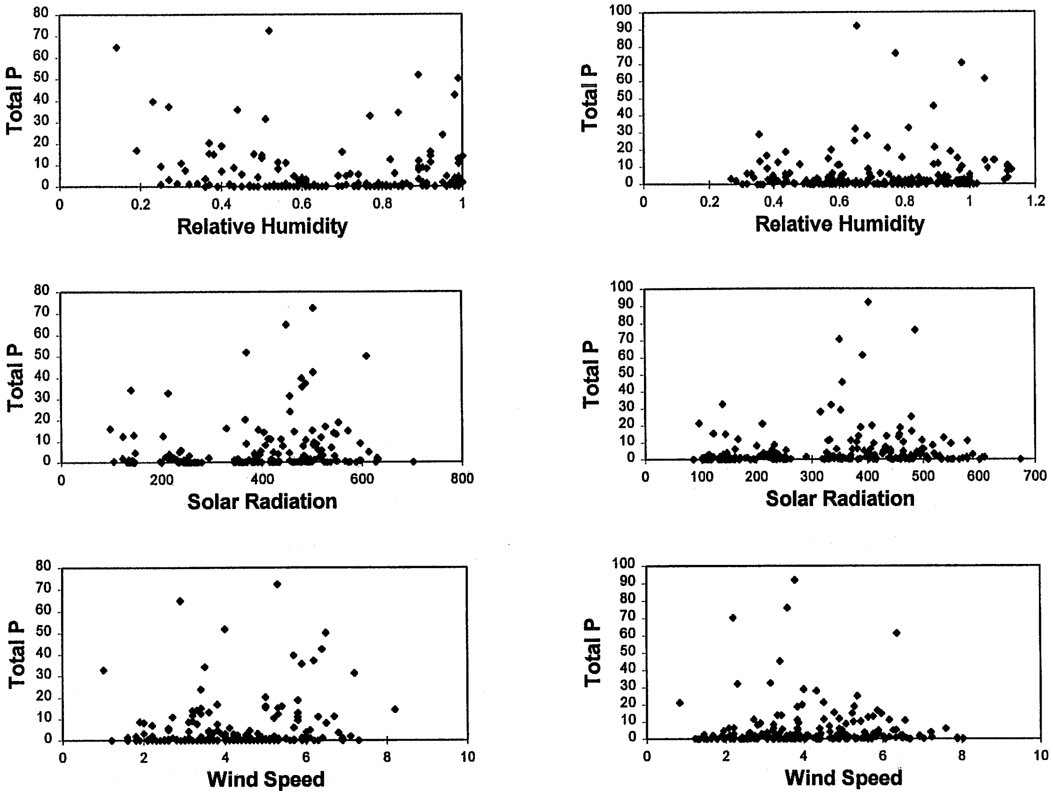

Figure 1b **(Cont'd.)** Simulated monthly total phosphorus yield (kg/day) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationship between the baseline total P simulation and the measured maximum daily temperature is represented by a gray curve.

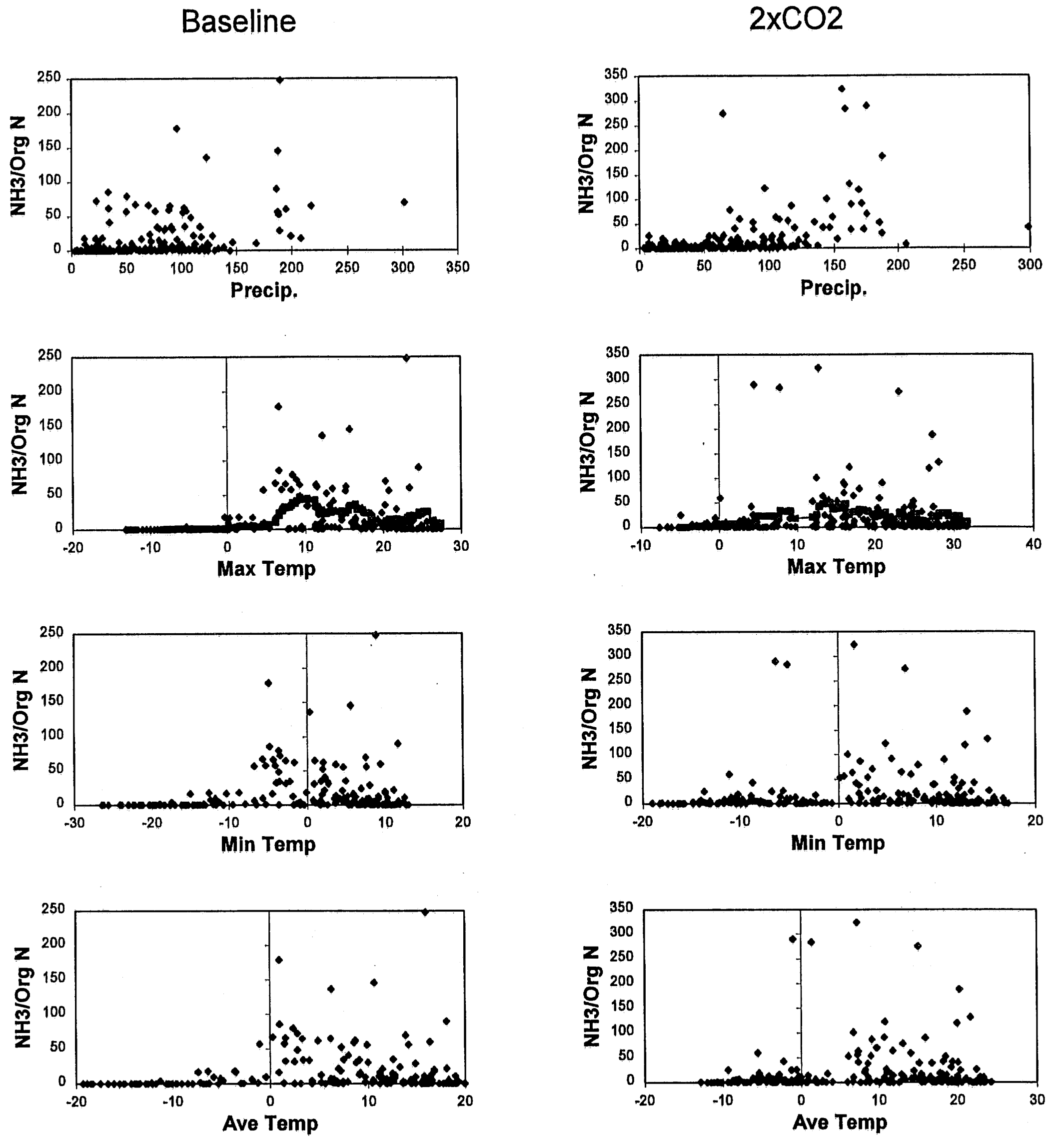

Figure 1c Simulated monthly ammonia/organic N yield (kg/day) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationships between the ammonia/organic N simulations and the measured and projected maximum daily temperatures are represented by gray curves.

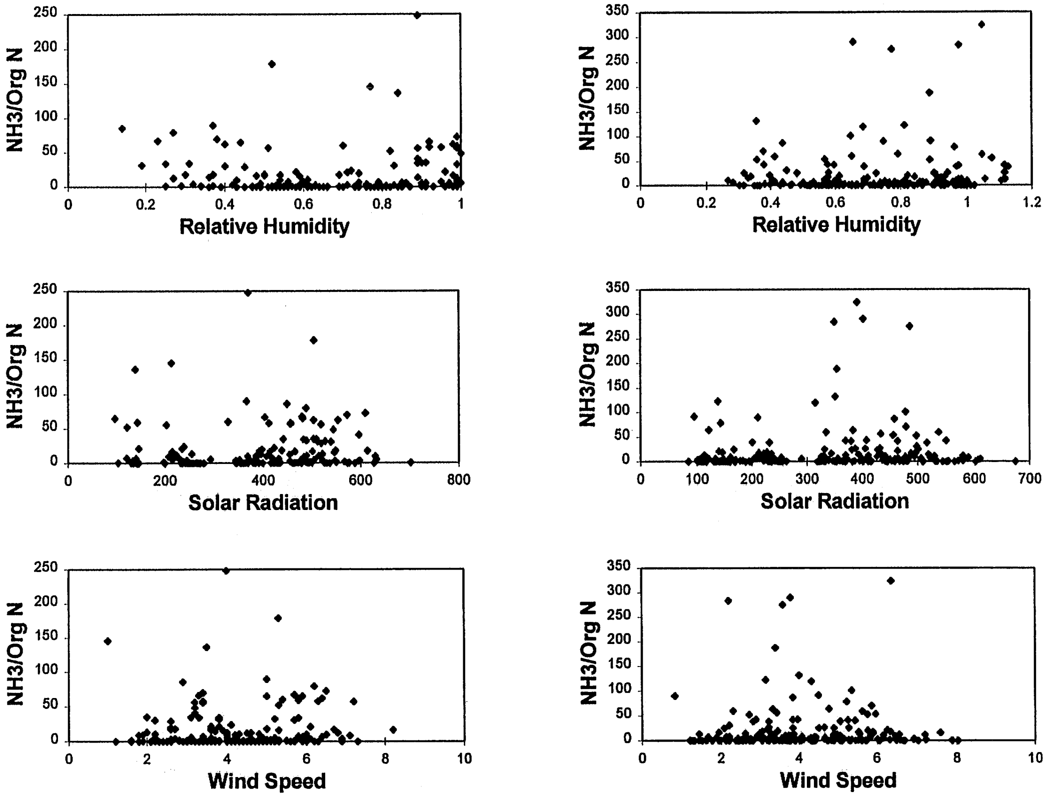

Figure 1c **(Cont'd.)** Simulated monthly ammonia/organic N yield (kg/day) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationships between the ammonia/organic N simulations and the measured and projected maximum daily temperatures are represented by gray curves.

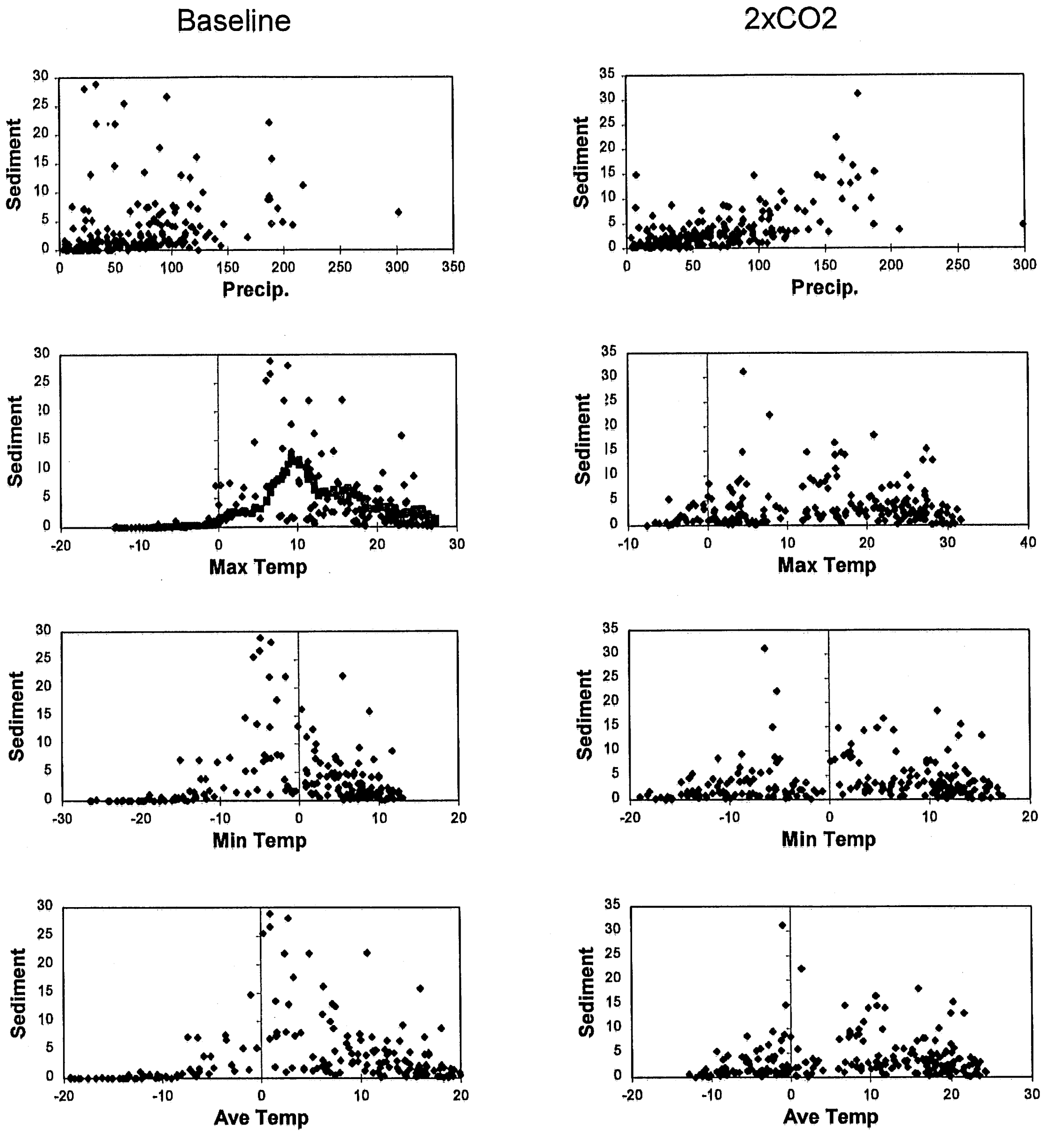

Figure 1d Simulated monthly sediment yield (t/day) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationship between the baseline sediment simulation and the measured maximum daily temperature is represented by a gray curve.

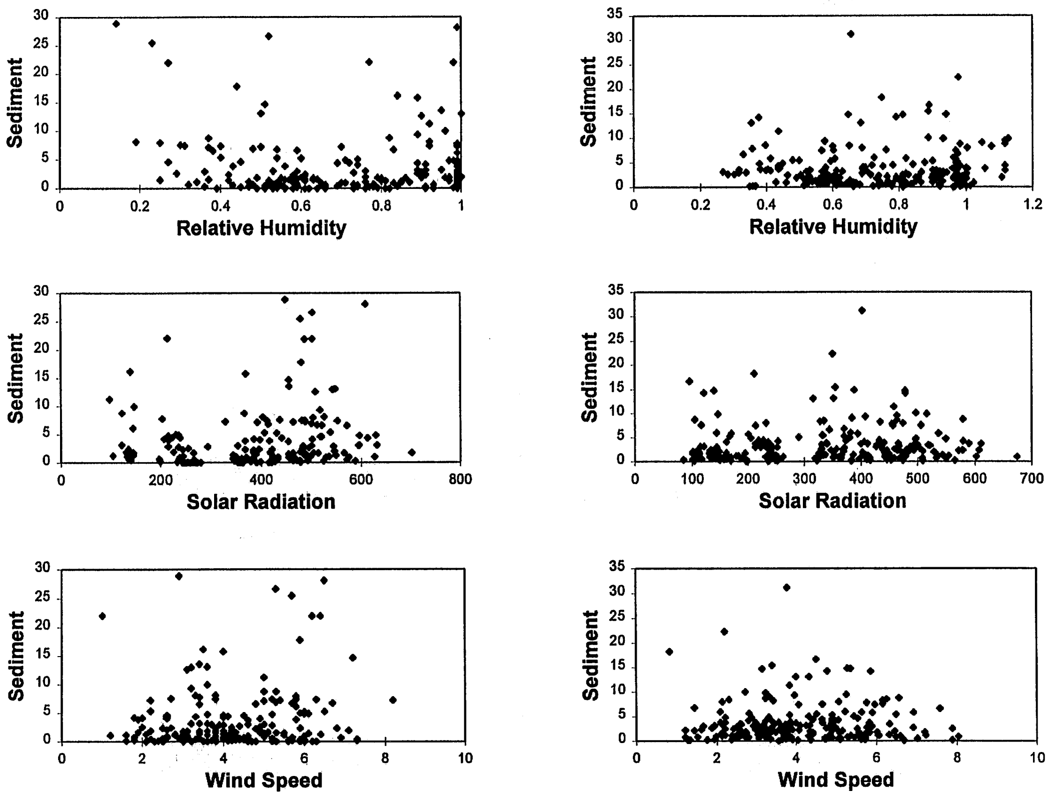

Figure 1d (Cont'd.) Simulated monthly sediment yield (t/day) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationship between the baseline sediment simulation and the measured maximum daily temperature is represented by a gray curve.

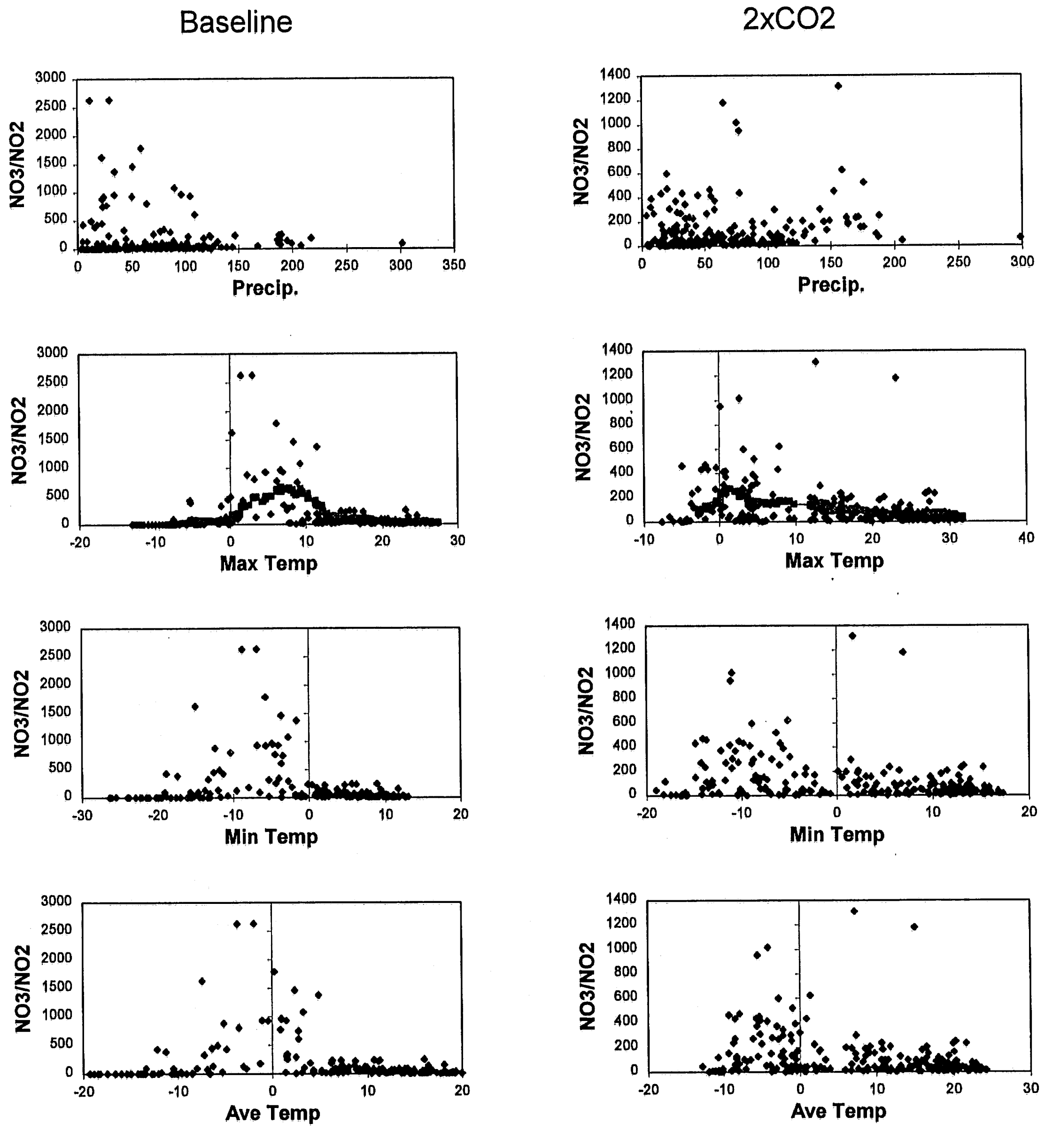

Figure 1e Simulated monthly nitrate/nitrite yield (kg/day) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationships between the nitrate/nitrite simulations and the measured and projected maximum daily temperatures are represented by gray curves.

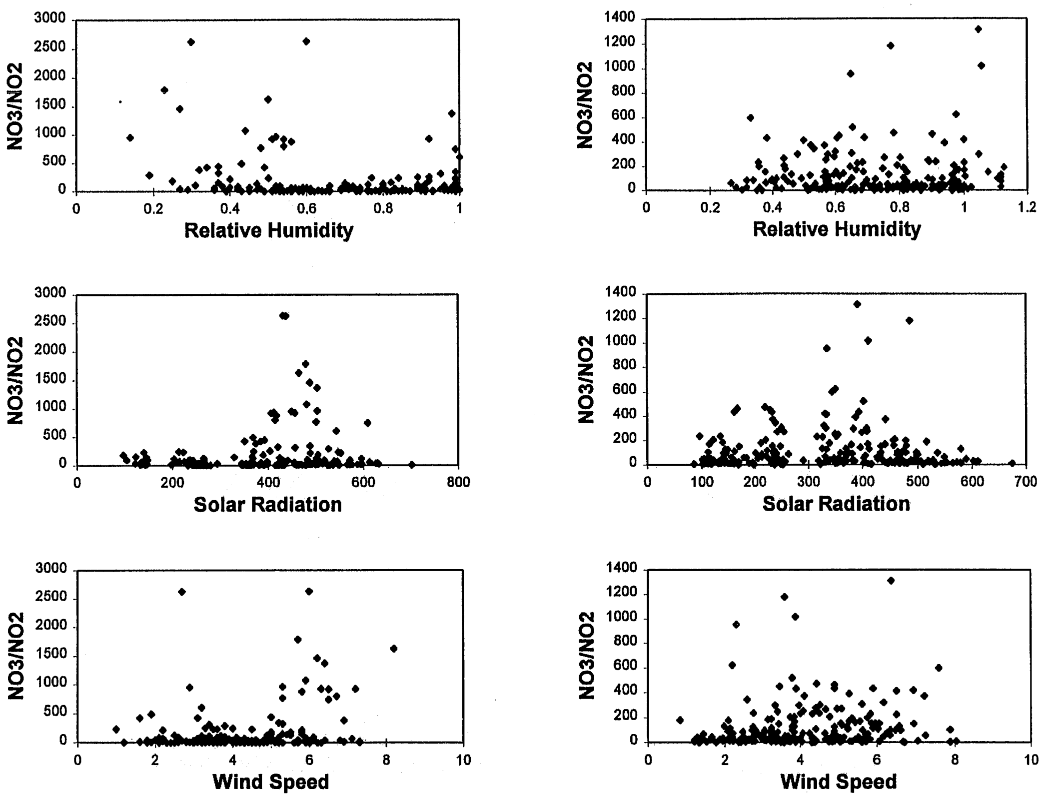

Figure 1e **(Cont'd.)** Simulated monthly nitrate/nitrite yield (kg/day) vs. monthly climate input parameters for the Baptism River watershed. The non-linear relationships between the nitrate/nitrite simulations and the measured and projected maximum daily temperatures are represented by gray curves.

Cottonwood River Watershed

Overall, precipitation was the best predictor for changes in streamflow and water quality in the Cottonwood River watershed. Air temperature was also a good predictor for some of the water quality parameters. Soil water, which reflects the precipitation and temperature input from past months was as good or better at predicting changes in streamflow and water quality as precipitation and temperature. For the most part, because of the decrease in snowmelt and snow accumulation, temperature decreased in its influence when the 2xCO_2 simulation was run. Furthermore, precipitation decreased in its ability to explain changes in nutrient yields in the 2xCO_2 simulation due, in part, to the decrease in annual average nutrient yields.

The statistics comparing monthly climate parameters to monthly SWAT output for the Cottonwood River watershed are shown in Table 9 and the correlations between climate parameters are shown in Table 10. Many of the linear relationships between the climate parameters and the SWAT output were stronger than the same relationships in the Baptism River watershed. For example, the CoD for the linear relationship between streamflow and precipitation in the 2xCO_2 simulations was 0.44 (Table 9). In the baseline simulation, however, the CoD was only 0.13 for the same relationship and the CoD was only 0.12 for the non-linear relationship between streamflow and maximum daily temperature (Fig. 2a, Table 9). The linear relationship between streamflow and solar radiation yielded a CoD of 0.11; solar radiation was highest during April through August. This time period included the spring snowmelt, *i.e.,* the time of year when streamflow is usually the highest. The best individual predictor of streamflow in the baseline simulation was the simulated amount of water in the soil. The CoD for the linear relationship between streamflow and soil water was 0.27. Soil water acted as an indicator of past precipitation and temperature. For example, when precipitation was high in the fall before the soil froze, water retention in the soil led to higher snowmelt runoff in the spring than when the fall was dry.

In the 2xCO_2 simulation, warmer air temperatures led to a decline in the importance of snowmelt, so the non-linear relationship with temperature that had a large peak due to the spring snowmelt disappeared; the CoDs for solar radiation and soil water decreased to 0.01 and 0.09, respectively, and precipitation became the most important predictor (CoD = 0.44) of streamflow (Table 9). Because of the warmer climate of the the 2xCO_2 scenario, less of the precipitation was in the form of snow and more was rain. Therefore, there was not as much of a delay between the time of precipitation and the resulting runoff, which caused the correlation between streamflow and precipitation to be much stronger.

The influence of solar radiation and soil water on the simulated water quality in the Cottonwood River followed the same pattern and can be explained by the same line of reasoning as for streamflow. Because of the role of temperature in determining snowmelt runoff, the linear relationships between maximum daily temperature and sediment and nutrient yields had CoDs from 0.11 to 0.31 in the baseline simulations, but because of the decrease in the importance of snowmelt, the CoDs shrank to 0.0 to 0.13 in the 2xCO_2 simulations (Table 9).

Table 9 Sensitivity statistics for the SWAT simulation of the Cottonwood River watershed. The coefficient of determination (CoD) is given for each pair of input and output variables for the baseline and 2xCO_2 climate scenarios. If the value is marked with †, then a non-linear relationship was used to calculate the CoD.

Scenario	Parameter	Streamflow	Total P	NH3/Org N	Sediment	NO3/NO2
Baseline	Precip.	0.13	0.44	0.50	0.23	0.04
	Max Temp	0.12†	0.15	0.18	0.12†	0.11†
	Min Temp	0.00	0.18	0.21	0.04	0.00
	Mean Temp	0.00	0.16	0.19	0.03	0.00
	Humidity	0.00	0.03	0.03	0.01	0.01
	Solar Rad	0.11	0.20	0.22	0.11	0.20
	Wind Speed	0.00	0.02	0.02	0.00	0.00
	Soil Water	0.27	0.16	0.12	0.21	0.31
2xCO2	Precip.	0.44	0.36	0.11	0.27	0.03
	Max Temp	0.03	0.10	0.04	0.02	0.17†
	Min Temp	0.03	0.12	0.04	0.03	0.01
	Mean Temp	0.03	0.11	0.04	0.02	0.01
	Humidity	0.00	0.00	0.00	0.01	0.00
	Solar Rad	0.01	0.13	0.04	0.01	0.08
	Wind Speed	0.00	0.00	0.00	0.00	0.02
	Soil Water	0.09	0.00	0.02	0.04	0.08

For total phosphorus yields, precipitation and temperature retained about the same importance between the two climate scenarios. A linear relationship with precipitation yielded CoDs of 0.44 and 0.36 for the baseline and 2xCO_2 simulations of total phosphorus yields, respectively, and a linear relationship with mean daily air temperature yielded CoDs of 0.16 and 0.11. Ammonia/organic N yields, on the other hand, saw a sharp decrease in the strength of their relationship with precipitation and mean daily air temperature: the CoDs dropped from 0.50 and 0.19, respectively, to 0.11 and 0.04. The decreases in the influence of precipitation and temperature were most likely related to the sharp decrease in ammonia/organic N yields between the two scenarios (Fig. 2c). The decrease in simulated ammonia/organic N available for transport was so large that changes in runoff from precipitation had a relatively small effect on the ammonia/organic N yields (Hanratty and Stefan, 1997c).

The relationships between the simulated sediment yields and climate parameters were only a little different from the streamflow-climate parameter relationships. In the baseline scenario, soil water was a good predictor (CoD = 0.21) for sediment yield and the non-linear relationship between sediment yields and maximum daily temperature yielded a CoD of 0.12 (Fig. 2d). A linear relationship between sediment and precipitation, however, was as good a predictor (CoD = 0.23) of the variation in sediment yields as soil water. In the $2xCO_2$ scenario, the best predictor of sediment yield was precipitation (CoD = 0.27).

Table 10 Pearson correlation coefficient for the relationships between the monthly climate parameters for the Cottonwood River watershed. Precipitation and air temperature data were measured in the watershed. Humidity, solar radiation, and wind speed were generated by SWAT based on historical monthly means and the precipitation and temperature data.

Scenario	Parameter	Max Temp	Min Temp	Mean Temp	Humidity	Solar Radiation	Wind Speed
Baseline	Rainfall	0.54	0.58	0.56	-0.17	0.36	-0.09
	Max Temp		0.99	1.00	-0.24	0.47	-0.27
	Min Temp			1.00	-0.24	0.48	-0.28
	Mean Temp				-0.24	0.48	-0.28
	Humidity					-0.30	0.07
	Solar Rad						-0.07
2xCO2	Rainfall	0.49	0.54	0.51	-0.06	0.41	-0.13
	Max Temp		0.99	1.00	-0.16	0.63	-0.34
	Min Temp			1.00	-0.16	0.65	-0.33
	Mean Temp				-0.16	0.64	-0.33
	Humidity					-0.21	0.00
	Solar Rad						-0.10

Monthly nitrate/nitrite yields in the Cottonwood River were not linearly related to the monthly precipitation and temperatures. Furthermore, the CoDs for the non-linear relationship between nitrate/nitrite and maximum daily temperature were only 0.12 and 0.17 in the baseline and $2xCO_2$ scenarios, respectively (Table 9, Fig. 2e). The most likely explanation is that the largest changes in the simulated transport of nitrate/nitrate were due to snowmelt and fertilization. This explanation is supported by the strong linear relationship with soil water (CoD = 0.31) in the baseline simulation, by the weak linear relationship with soil water in the $2xCO_2$ simulation (CoD = 0.08) and by the maximum daily temperatures at the time of the peak nitrate/nitrite yields (about 10 to 20°C for the baseline simulation and about 20 to 25°C for the $2xCO_2$ simulation). The change in the relationships between temperature and nutrient yields and between soil water and nutrient yields supports the conclusion that decreasing snowmelt was a cause for large changes in nutrient yields, as was discussed earlier. The temperature-nitrate/nitrate relationships also show that fertilization was a cause for large changes in nitrate/nitrite yields in the $2xCO_2$

simulation. Much of the simulated fertilization was in spring to early summer, when maximum daily temperatures range from about 15 to 25°C. That temperature range coincides with the largest changes in nitrate/nitrite yields.

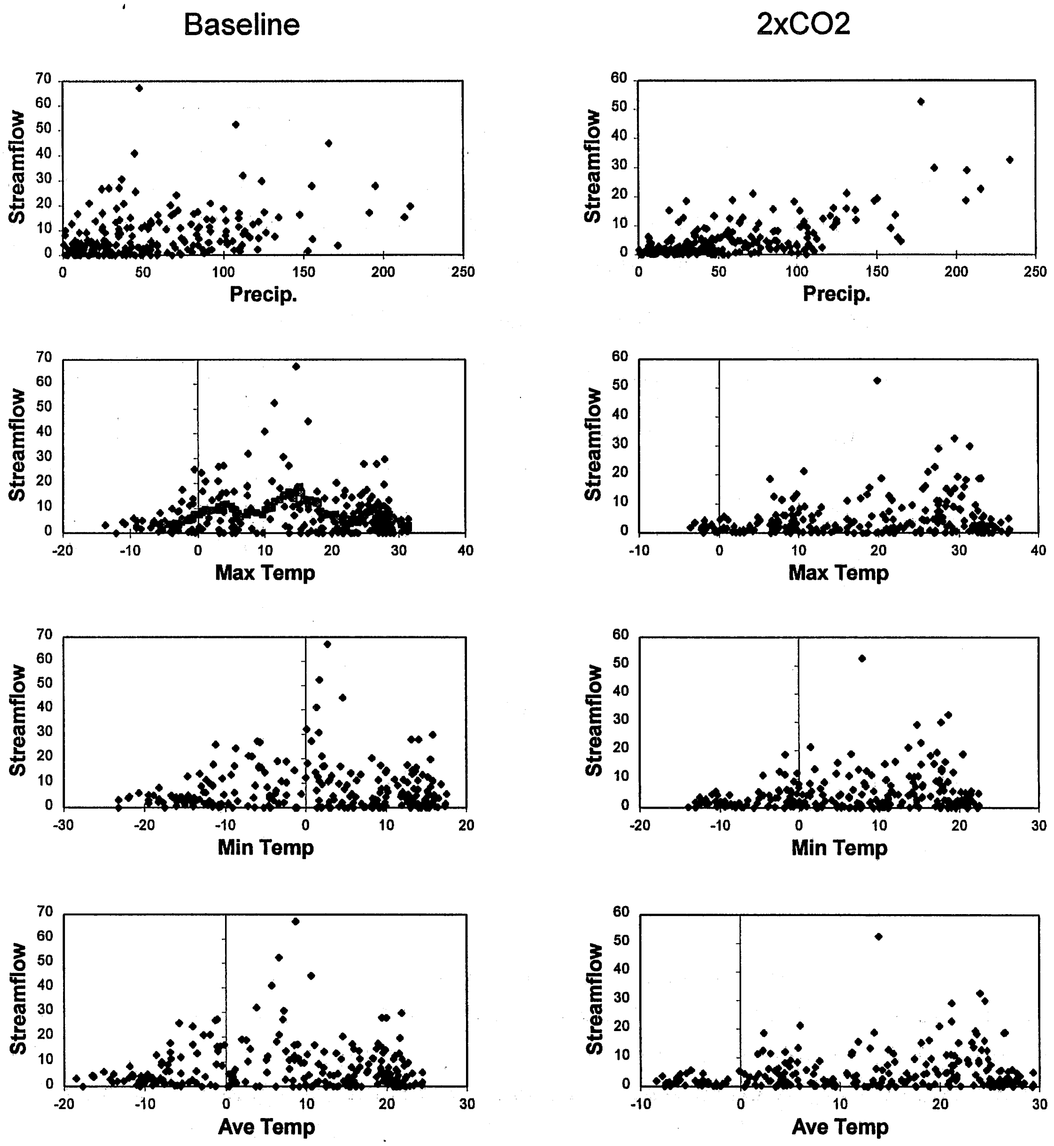

Figure 2a Simulated monthly streamflow vs. monthly climate input parameters for the Cottonwood River watershed. The non-linear relationship between the baseline streamflow simulations and the measured maximum daily temperatures is represented by a gray curve.

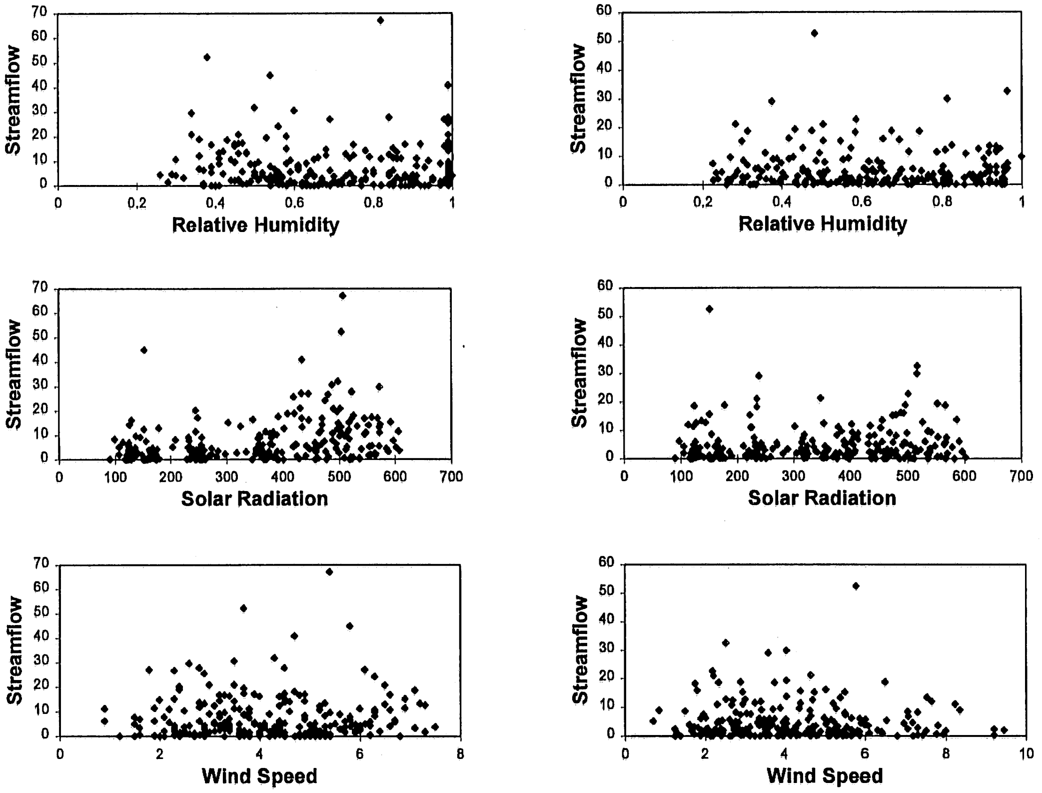

Figure 2a **(Cont'd.)** Simulated monthly streamflow vs. monthly climate input parameters for the Cottonwood River watershed. The non-linear relationship between the baseline streamflow simulations and the measured maximum daily temperatures is represented by a gray curve.

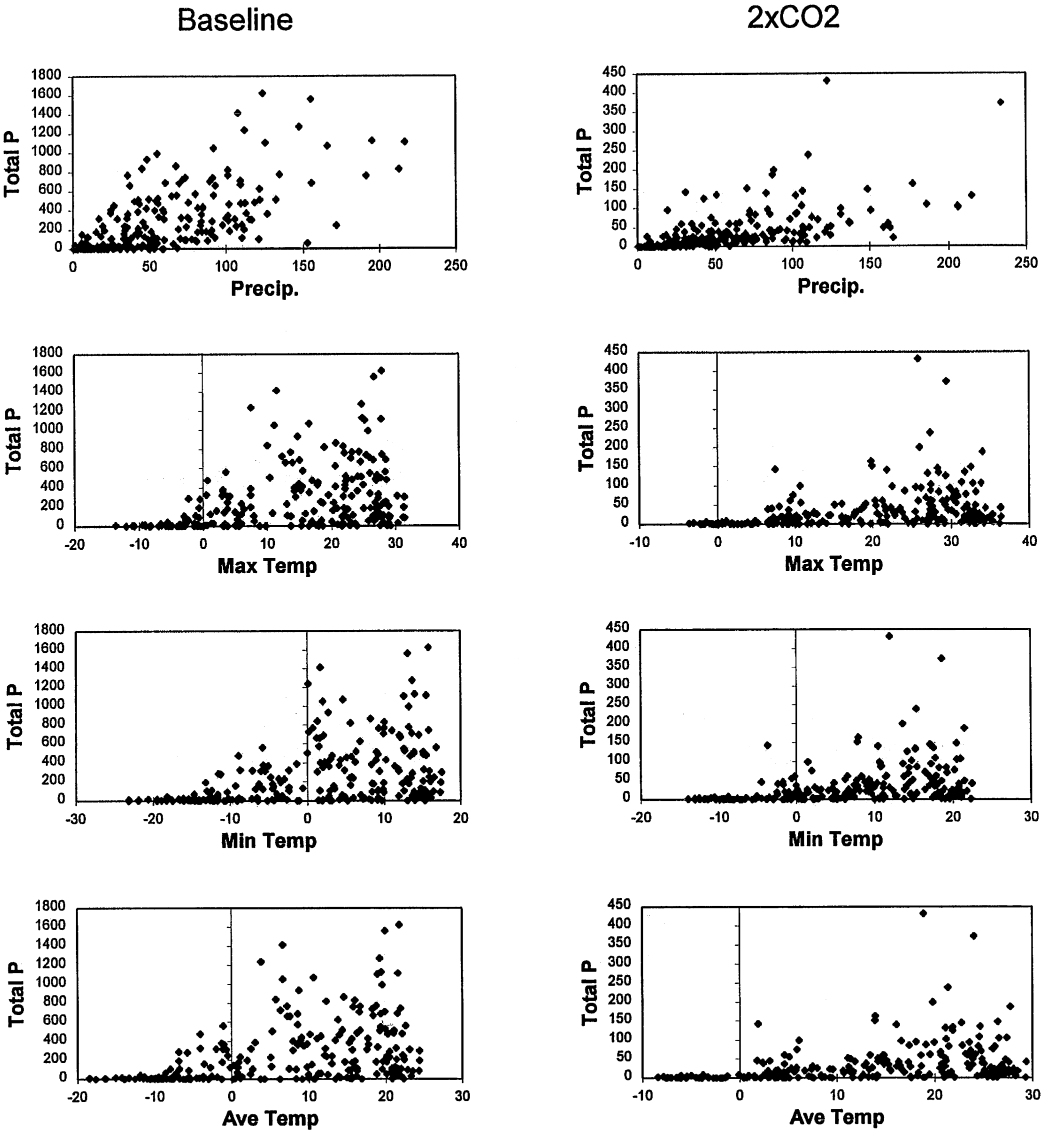

Figure 2b Simulated monthly total phosphorus yield vs. monthly climate input parameters for the Cottonwood River watershed.

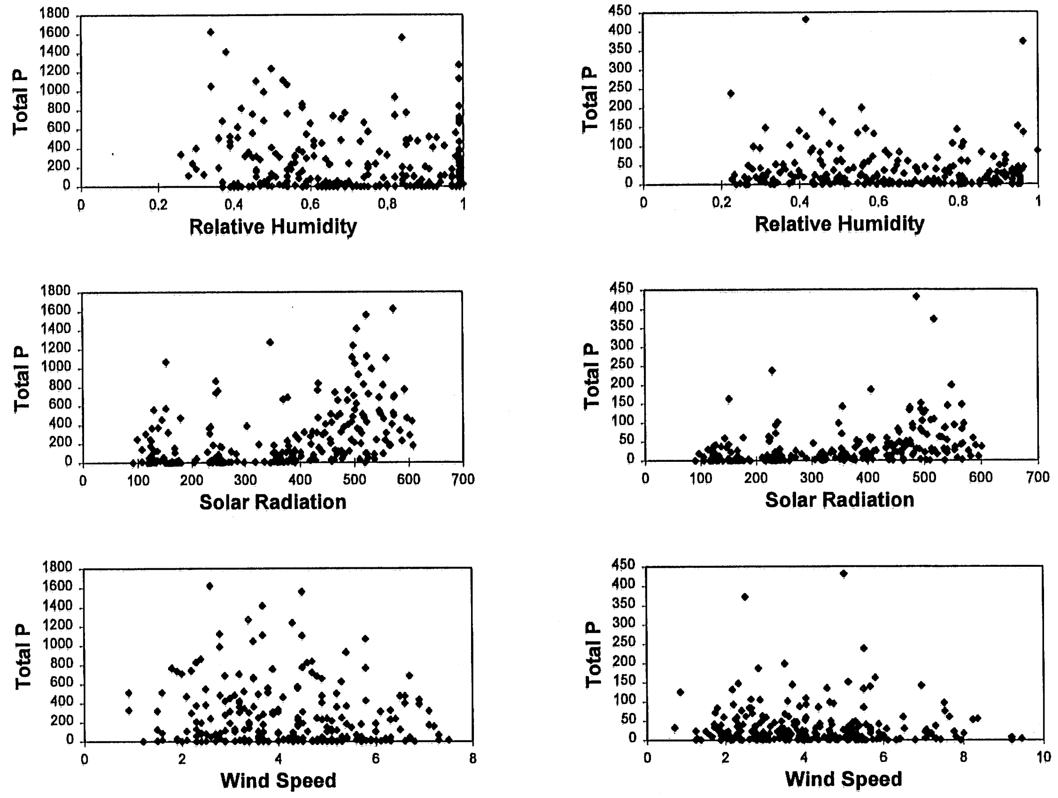

Figure 2b **(Cont'd.)** Simulated monthly total phosphorus yield vs. monthly climate input parameters for the Cottonwood River watershed.

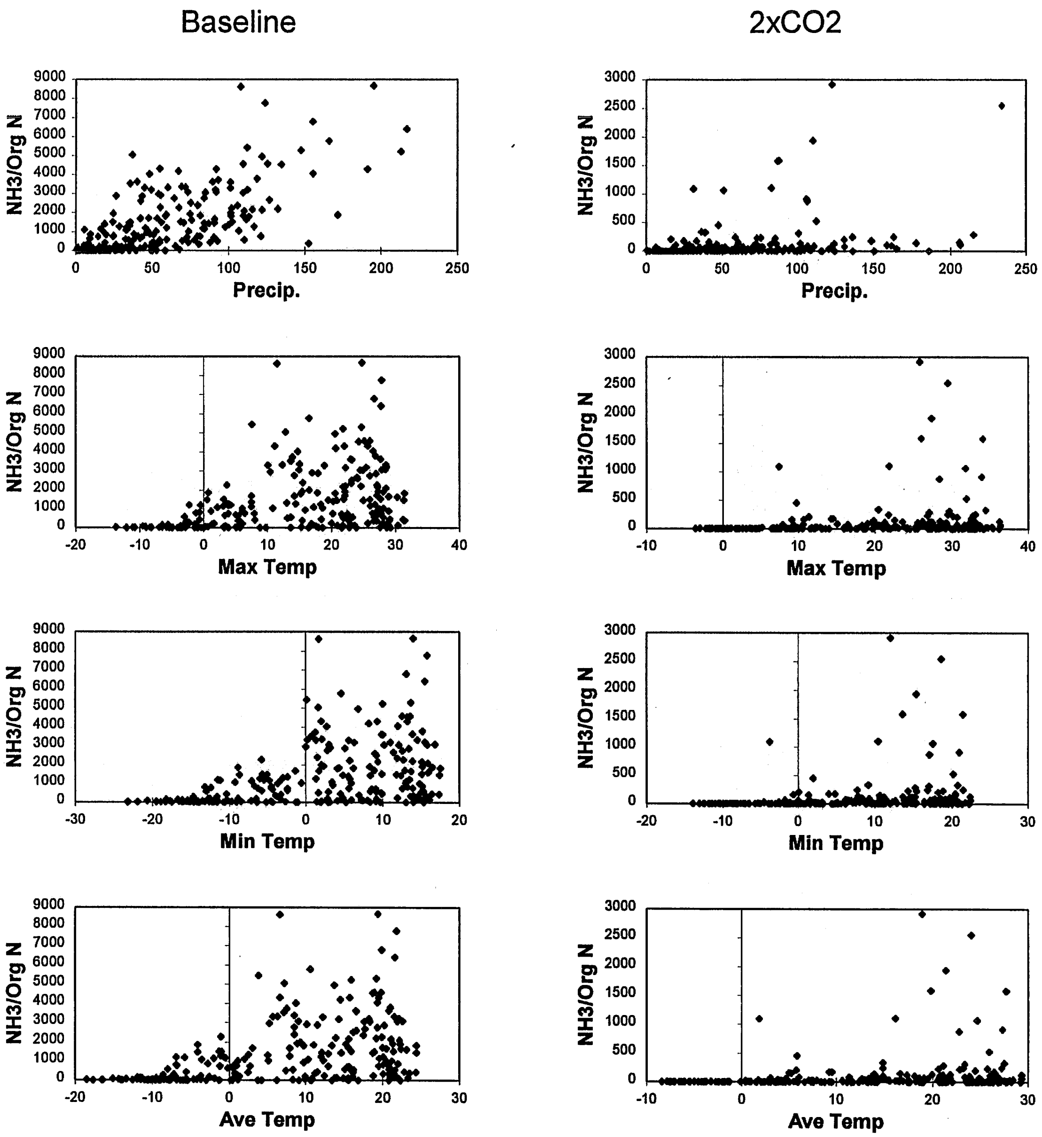

Figure 2c Simulated monthly ammonia/organic nitrogen yield vs. monthly climate input parameters for the Cottonwood River watershed.

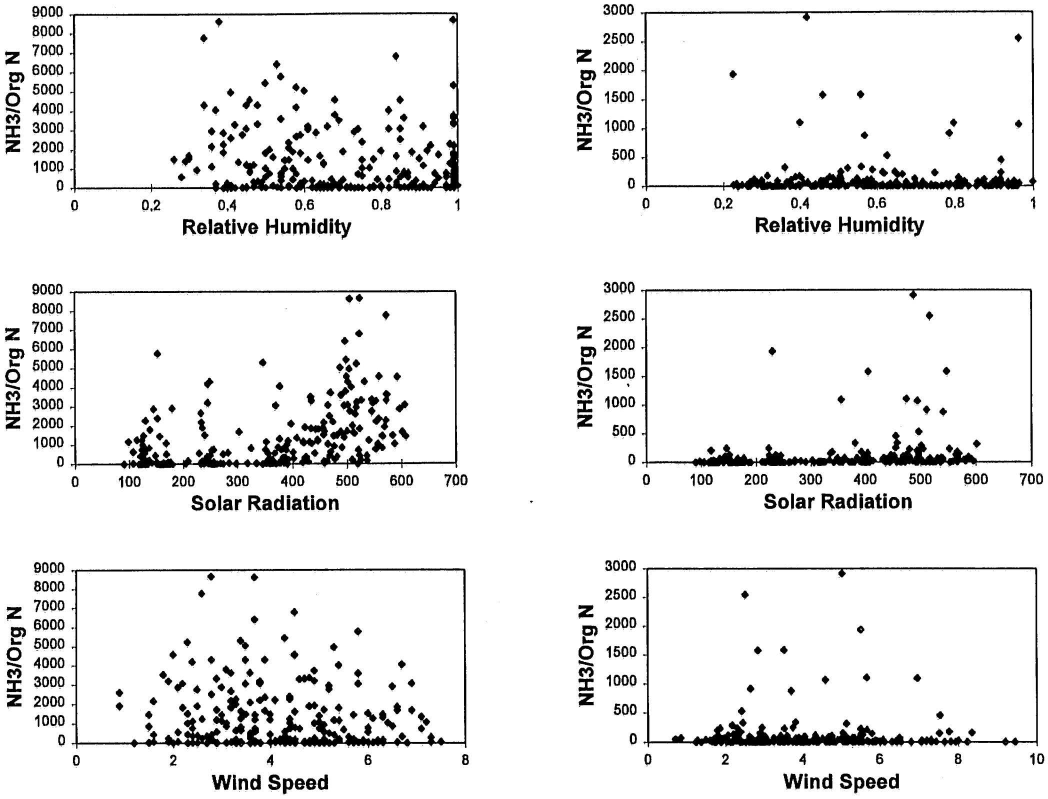

Figure 2c **(Cont'd.)** Simulated monthly ammonia/organic nitrogen yield vs. monthly climate input parameters for the Cottonwood River watershed.

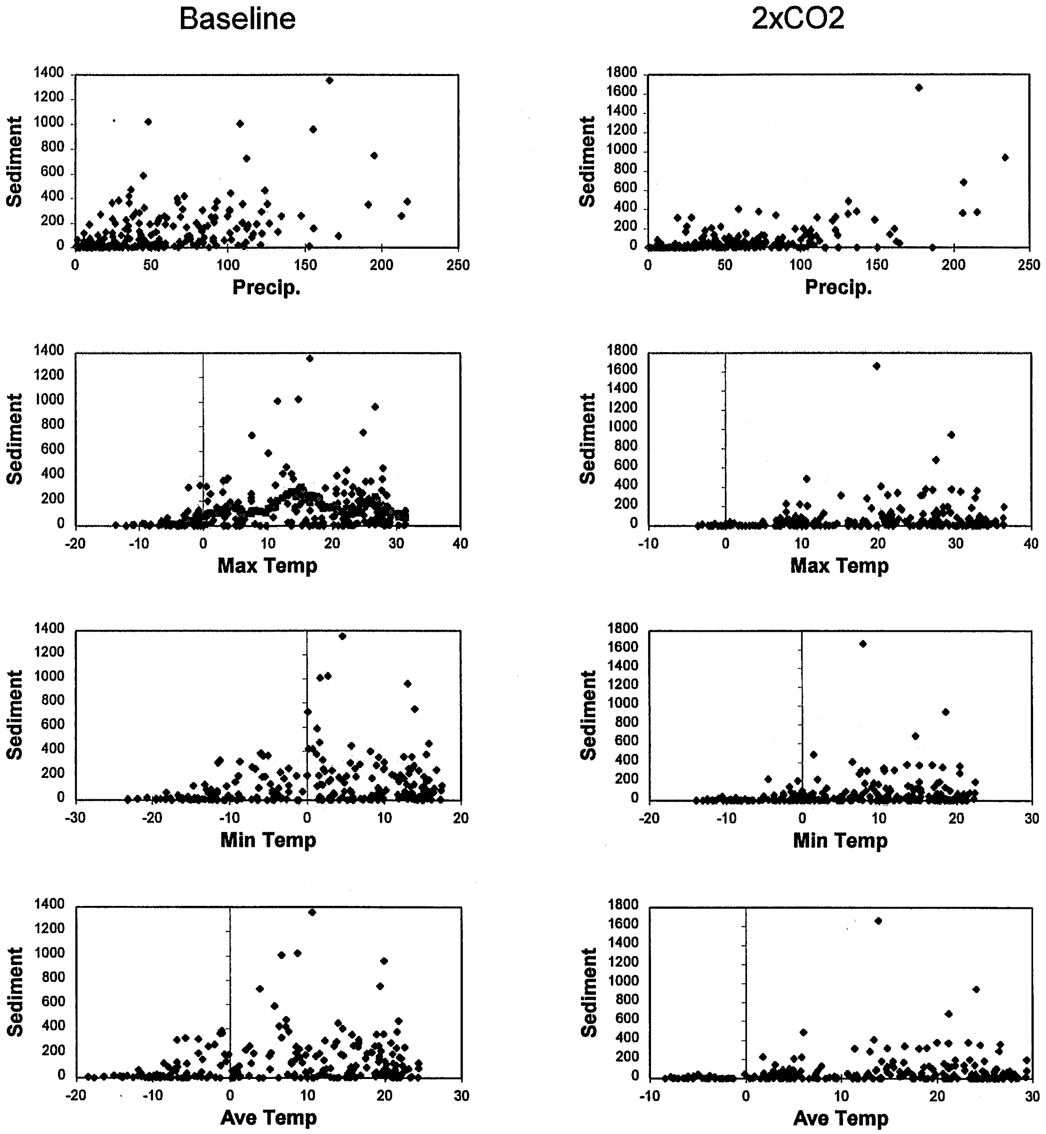

Figure 2d Simulated monthly sediment yield vs. monthly climate input parameters for the Cottonwood River watershed. The non-linear relationship between the baseline sediment yield simulations and the measured maximum daily temperatures is represented by a gray curve.

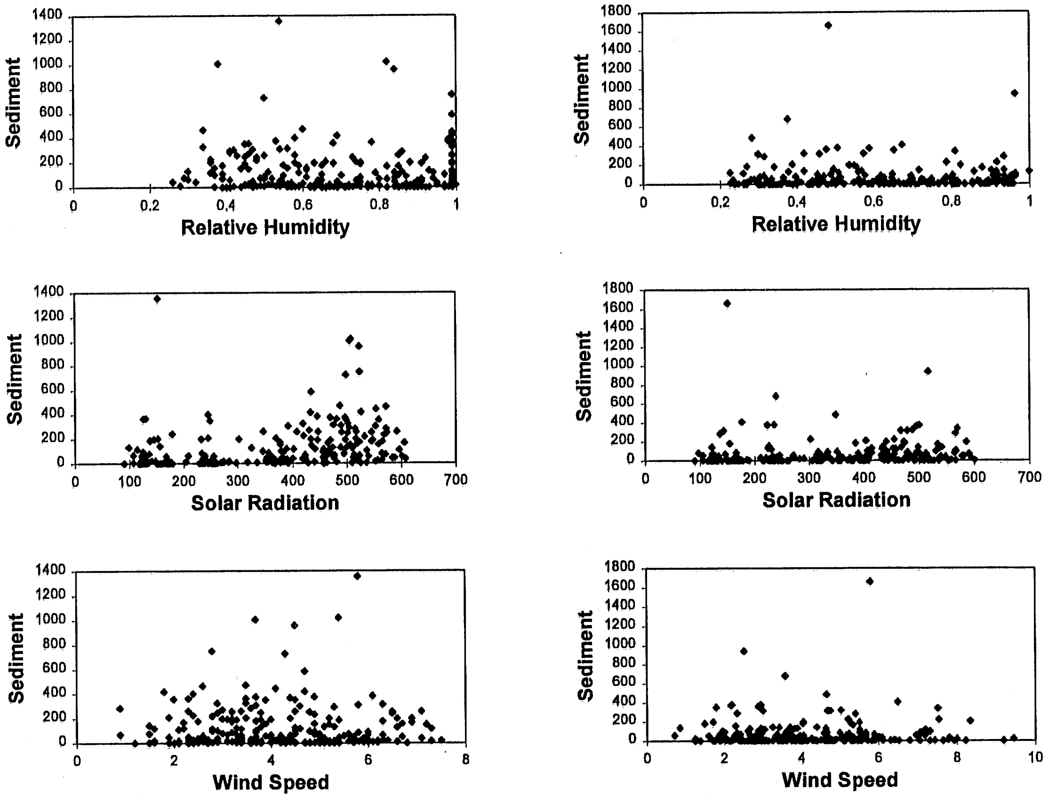

Figure 2d **(Cont'd.)** Simulated monthly sediment yield vs. monthly climate input parameters for the Cottonwood River watershed. The non-linear relationship between the baseline sediment yield simulations and the measured maximum daily temperatures is represented by a gray curve.

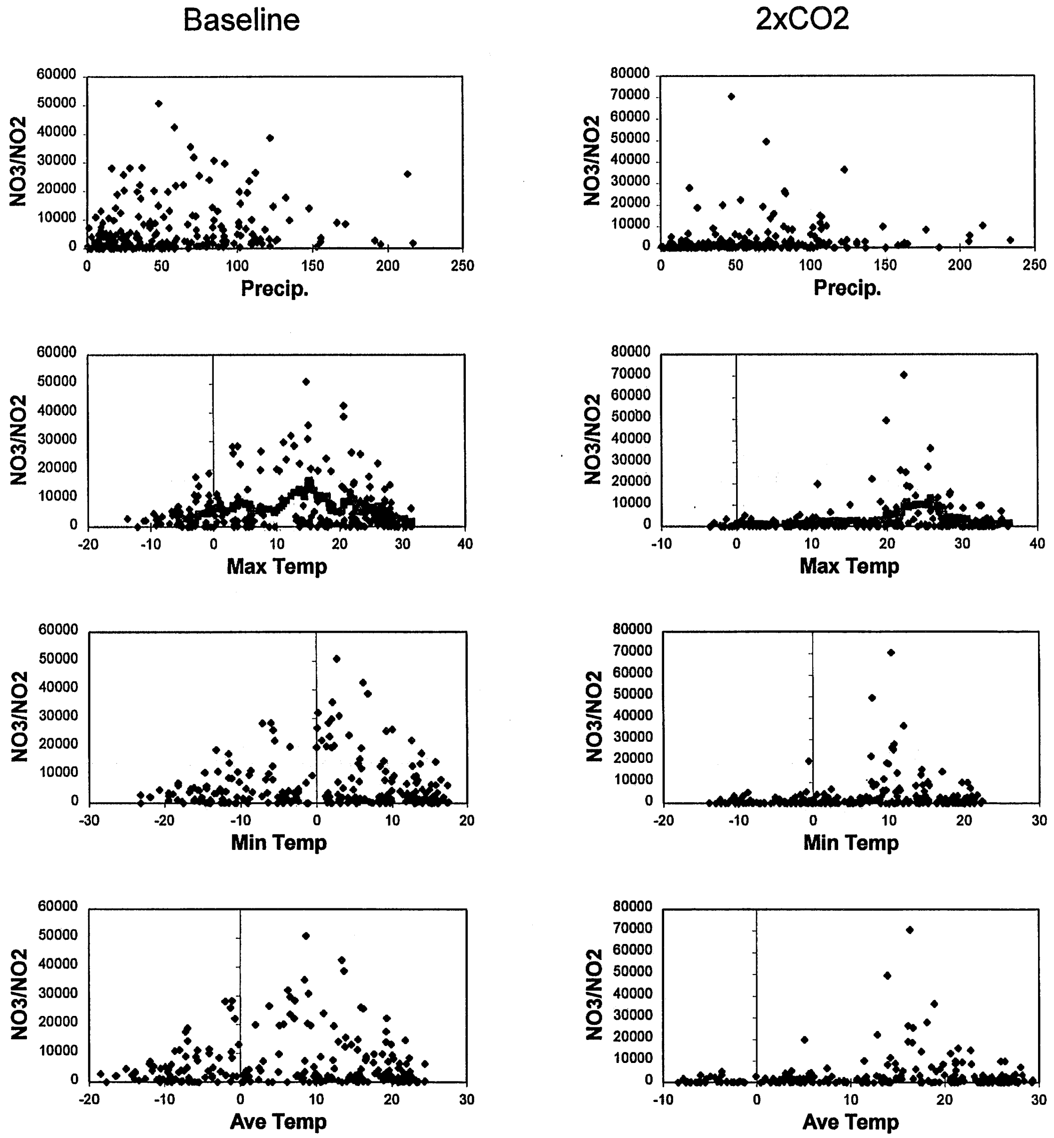

Figure 2e Simulated monthly nitrate/nitrite yield vs. monthly climate input parameters for the Cottonwood River watershed. The non-linear relationships between the nitrate/nitrite simulations and the measured and projected maximum daily temperatures are represented by gray curves.

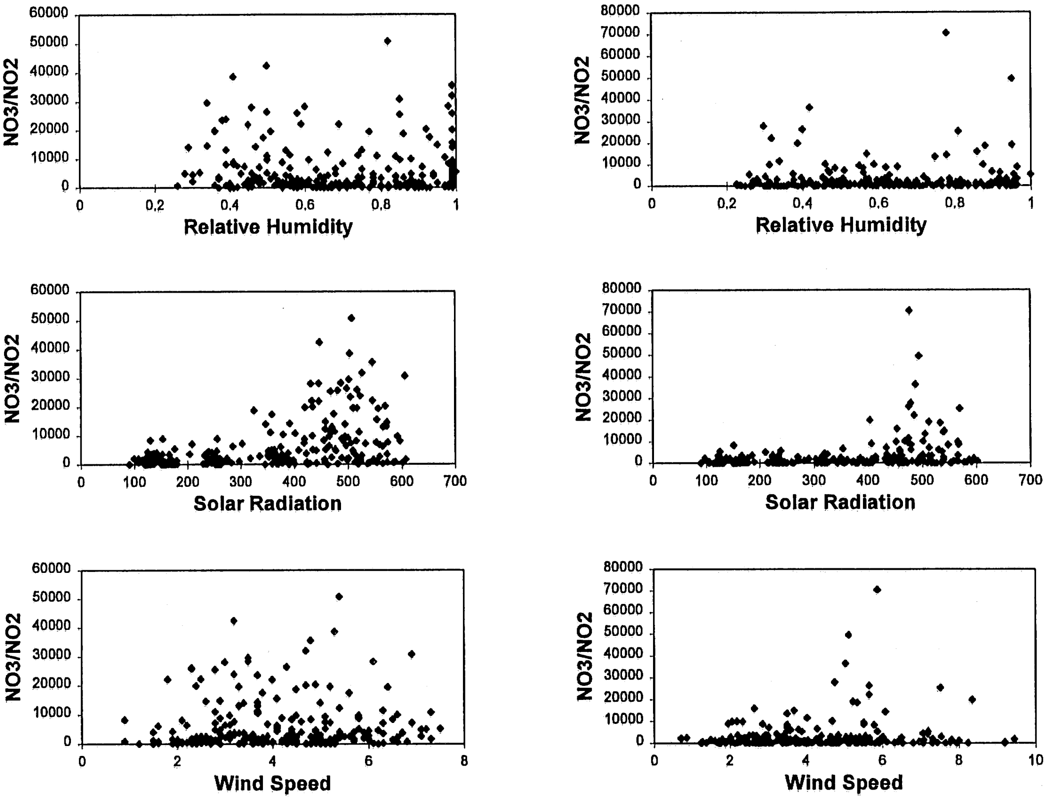

Figure 2e **(Cont'd.)** Simulated monthly nitrate/nitrite yield vs. monthly climate input parameters for the Cottonwood River watershed. The non-linear relationships between the nitrate/nitrite simulations and the measured and projected maximum daily temperatures are represented by gray curves.

Little Washita River Watershed

The statistics comparing monthly input parameters and monthly output variables for the Little Washita River watershed are shown in Table 11 and the correlations between climate parameters are shown in Table 12. Since snowmelt is not a major portion of the hydrologic budget in the Little Washita River, temperature did not play a direct role in explaining the variation in the simulated streamflow and water quality. The non-linear relationships used to calculate the coefficients of determination in the northern watersheds did not apply to the Little Washita watershed (Fig. 3). Precipitation was the best predictor of monthly streamflow, total phosphorus yield, ammonia/organic nitrogen yield, sediment yield, and nitrate/nitrite yield (Table 11). Linear relationships between the variation in precipitation and the variation in streamflow and water quality yielded CoDs between 0.45 and 0.61. The CoDs of all of the other climate parameters were less than 0.10. Soil water, however, was a significant predictor of streamflow and water quality as well. Linear relationships between the variation in precipitation and the variation in streamflow and water quality yielded CoDs between 0.13 and 0.35. Therefore, the most important input variable to measure and project accurately for the Little Washita River watershed is precipitation. It is also be important to accurately simulate the retention and percolation of water through the soil.

Table 11 Sensitivity statistics for the SWAT simulation of the Little Washita River watershed. The coefficient of determination (CoD) from a linear relationship is given for each pair of input and output variables for the baseline and $2xCO_2$ climate scenarios.

Scenario	Parameter	Streamflow	Total P	NH3/Org N	Sediment	NO3/NO2
Baseline	Rainfall	0.46	0.48	0.45	0.54	0.52
	Max Temp	0.04	0.04	0.03	0.04	0.00
	Min Temp	0.06	0.05	0.05	0.05	0.01
	Mean Temp	0.05	0.04	0.04	0.04	0.00
	Humidity	0.00	0.00	0.00	0.00	0.00
	Solar Rad	0.06	0.09	0.10	0.08	0.07
	Wind Speed	0.01	0.01	0.01	0.01	0.00
	Soil Water	0.13	0.15	0.14	0.15	0.35
2xCO2	Rainfall	0.56	0.52	0.51	0.51	0.61
	Max Temp	0.00	0.00	0.00	0.00	0.00
	Min Temp	0.00	0.00	0.00	0.00	0.00
	Mean Temp	0.00	0.00	0.00	0.00	0.00
	Humidity	0.01	0.01	0.01	0.01	0.00
	Solar Rad	0.02	0.02	0.02	0.02	0.00
	Wind Speed	0.00	0.01	0.01	0.00	0.00
	Soil Water	0.33	0.17	0.16	0.19	0.31

Table 12 Pearson correlation coefficients for the relationships between the monthly climate parameters for the Little Washita River watershed. Precipitation and air temperature data were measured in the watershed. Humidity, solar radiation, and wind speed were generated by SWAT based on historical monthly means and the precipitation and temperature data.

Scenario	**Parameter**	**Max Temp**	**Min Temp**	**Mean Temp**	**Humidity**	**Solar Radiation**	**Wind Speed**
Baseline	Rainfall	0.31	0.36	0.34	-0.03	0.33	-0.08
	Max Temp		0.98	1.00	-0.06	0.61	-0.29
	Min Temp			1.00	-0.07	0.63	-0.29
	Mean Temp				-0.07	0.62	-0.29
	Humidity					-0.15	-0.05
	Solar Rad						-0.07
2xCO2	Rainfall	0.18	0.21	0.19	0.02	0.10	-0.06
	Max Temp		0.98	1.00	-0.22	0.65	-0.20
	Min Temp			1.00	-0.23	0.67	-0.20
	Mean Temp				-0.23	0.66	-0.20
	Humidity					-0.29	-0.12
	Solar Rad						-0.08

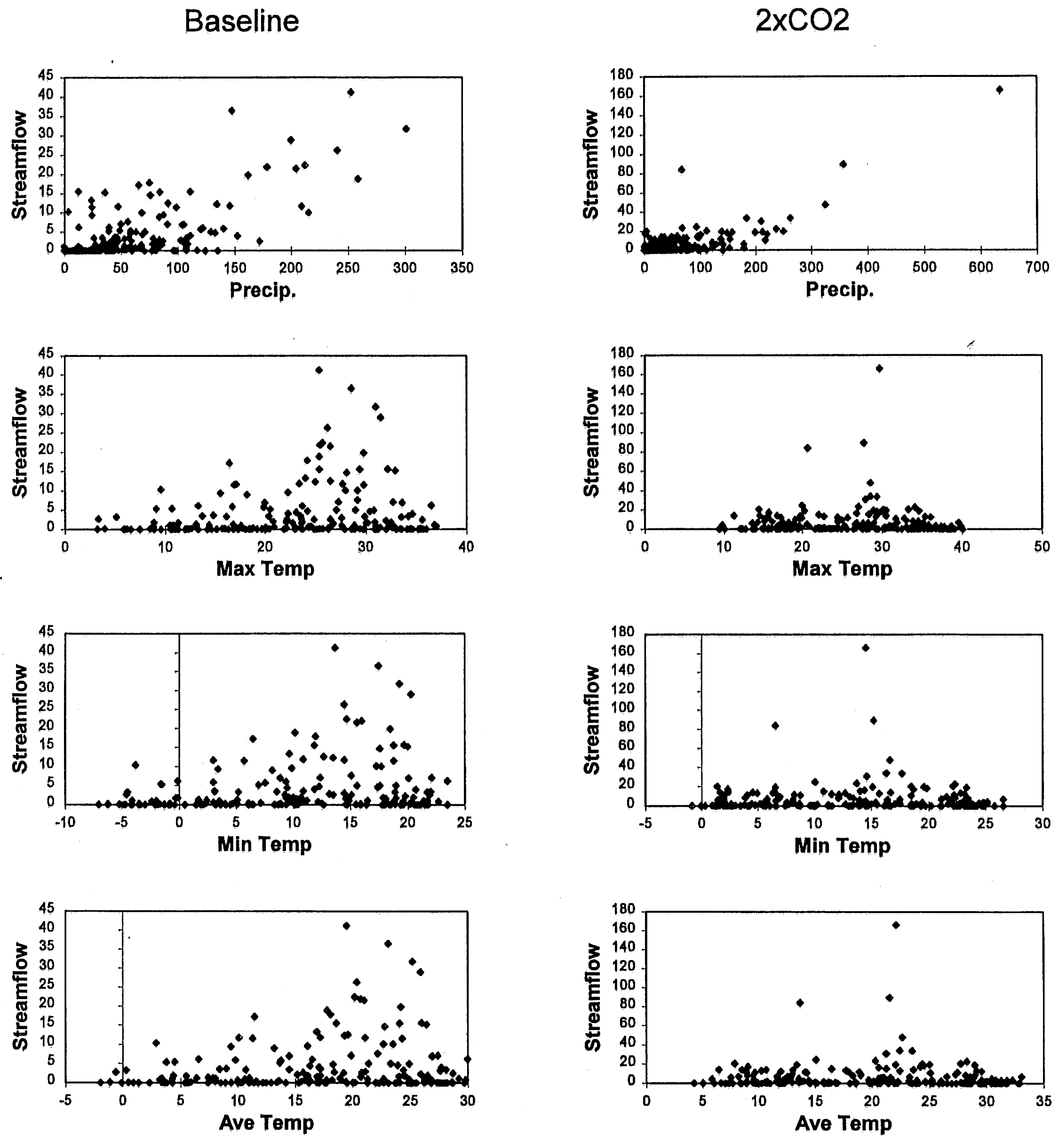

Figure 3a Simulated monthly streamflow vs. monthly climate input parameters for the Little Washita River watershed.

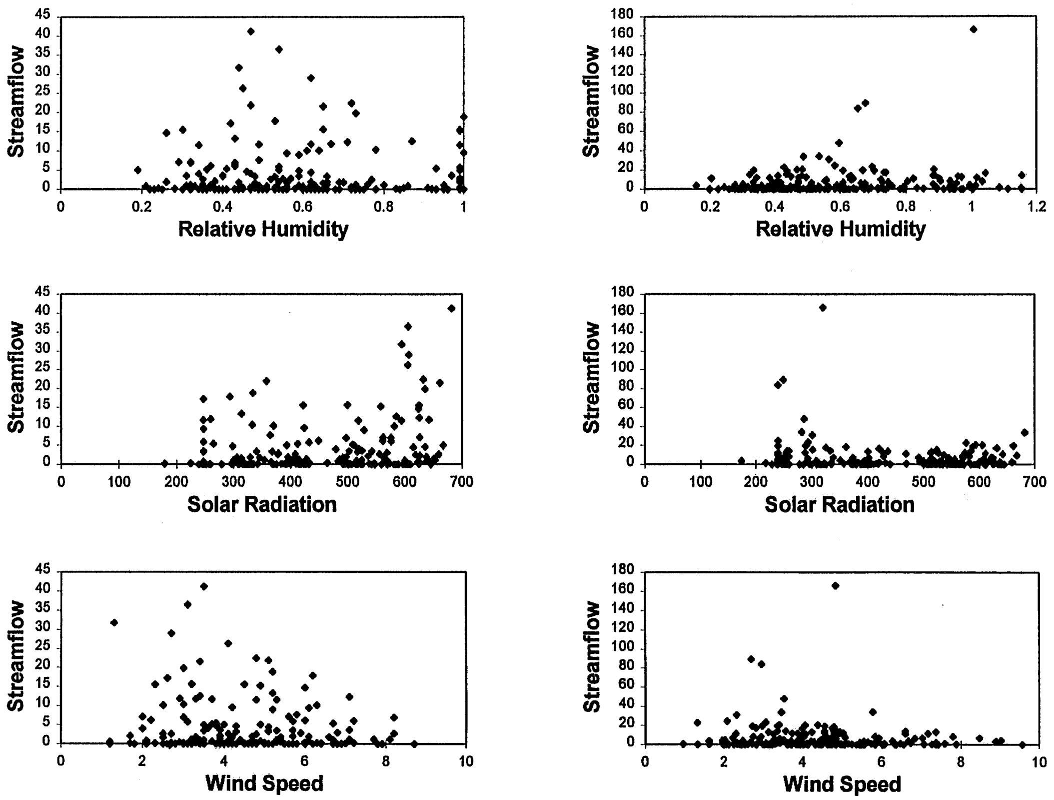

Figure 3a **(Cont'd.)** Simulated monthly streamflow vs. monthly climate input parameters for the Little Washita River watershed.

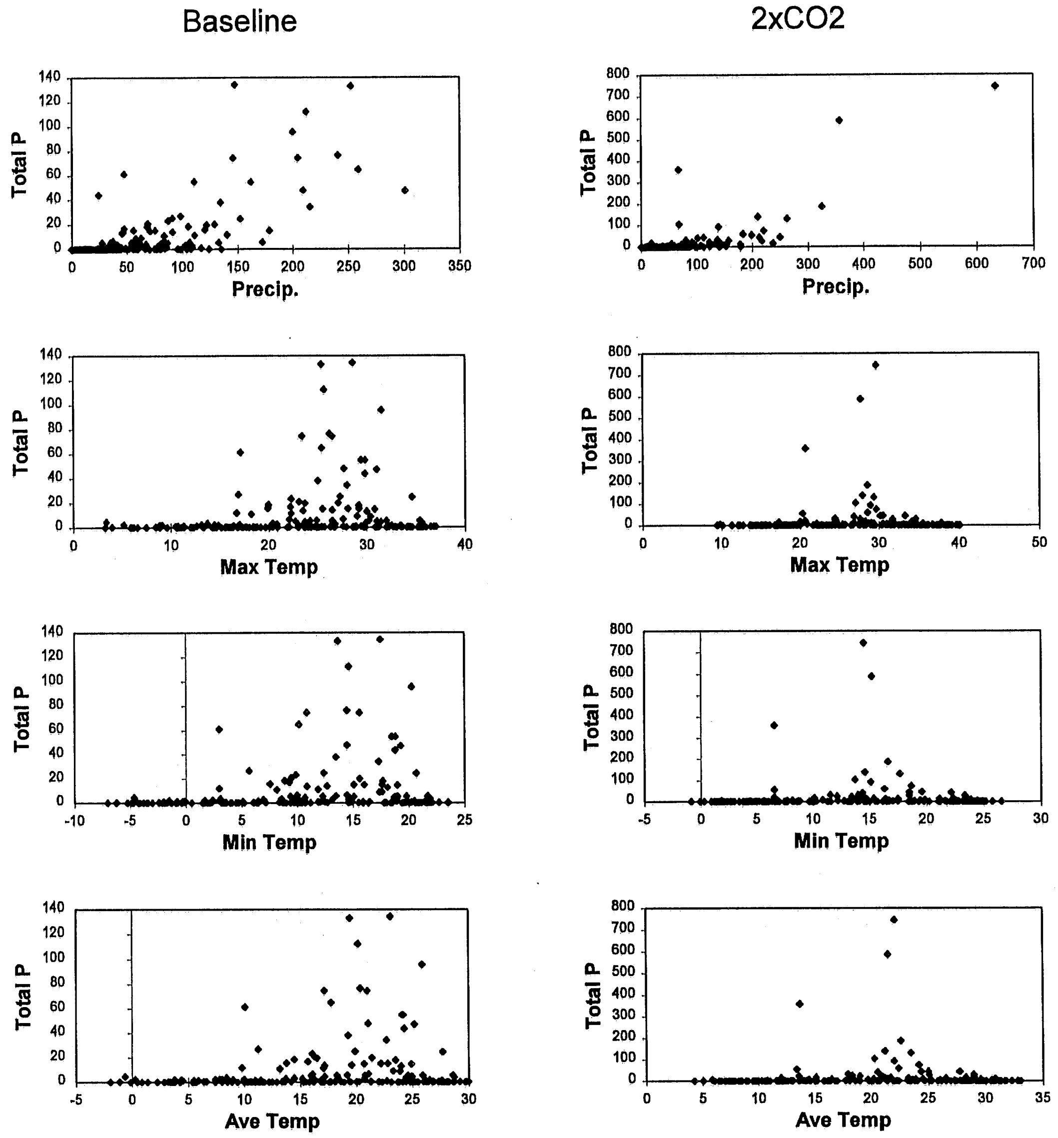

Figure 3b Simulated monthly total phosphorus yield vs. monthly climate input parameters for the Little Washita River watershed.

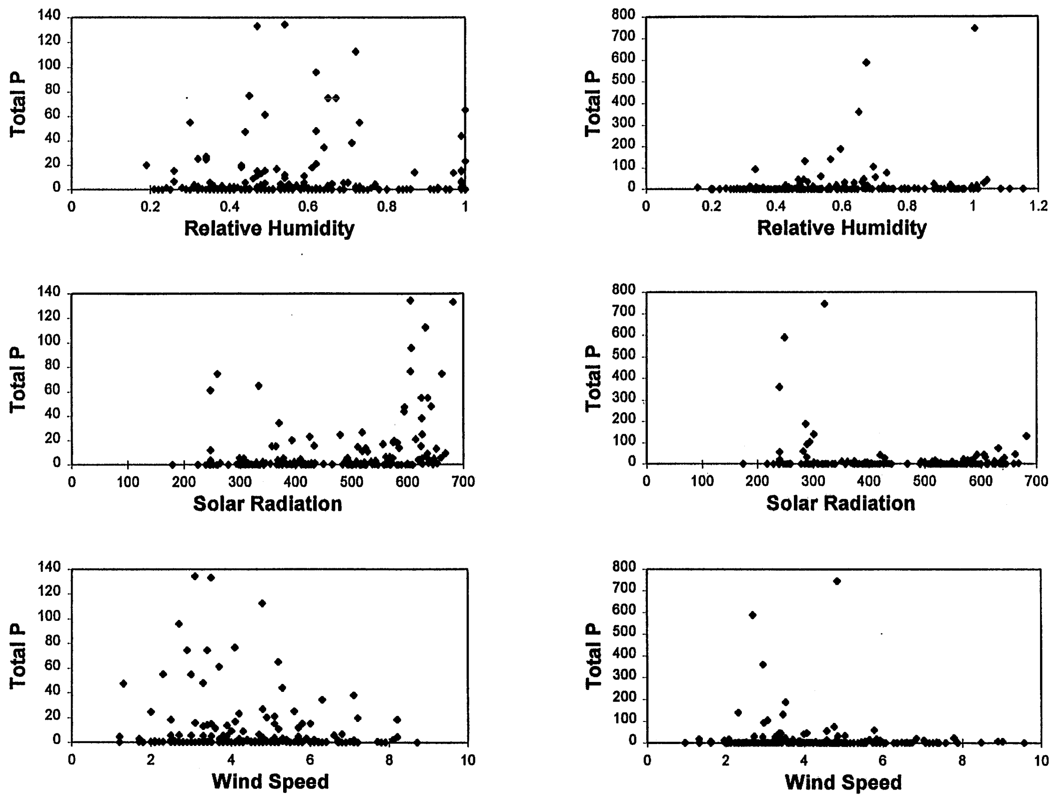

Figure 3b **(Cont'd.)** Simulated monthly total phosphorus yield vs. monthly climate input parameters for the Little Washita River watershed.

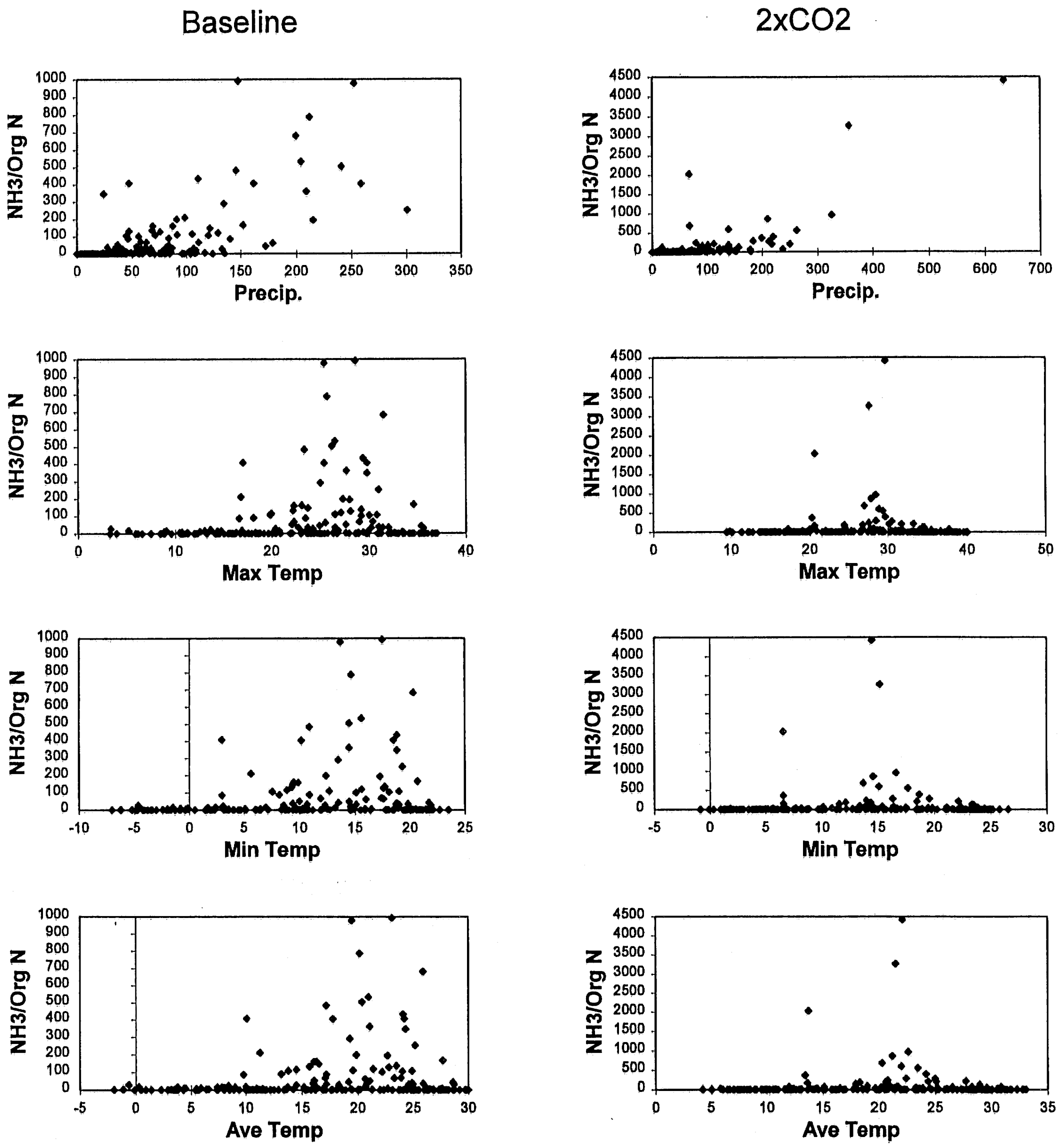

Figure 3c Simulated monthly ammonia/organic nitrogen yield vs. monthly climate input parameters for the Little Washita River watershed.

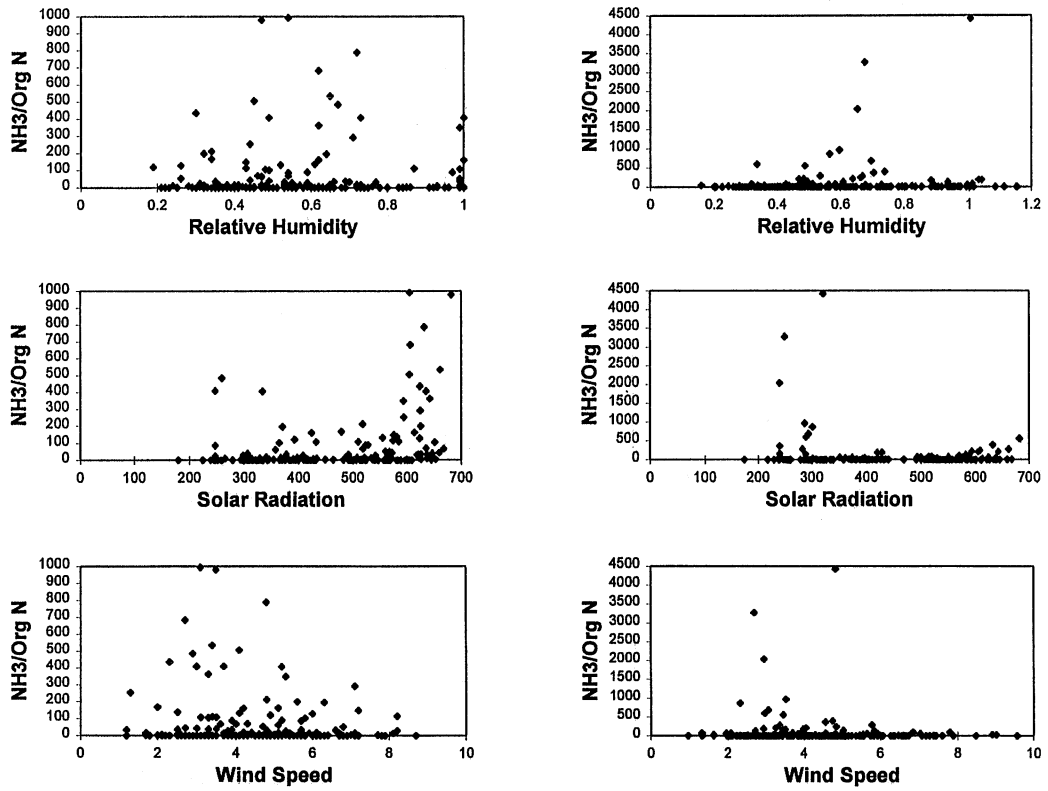

Figure 3c **(Cont'd.)** Simulated monthly ammonia/organic nitrogen yield vs. monthly climate input parameters for the Little Washita River watershed.

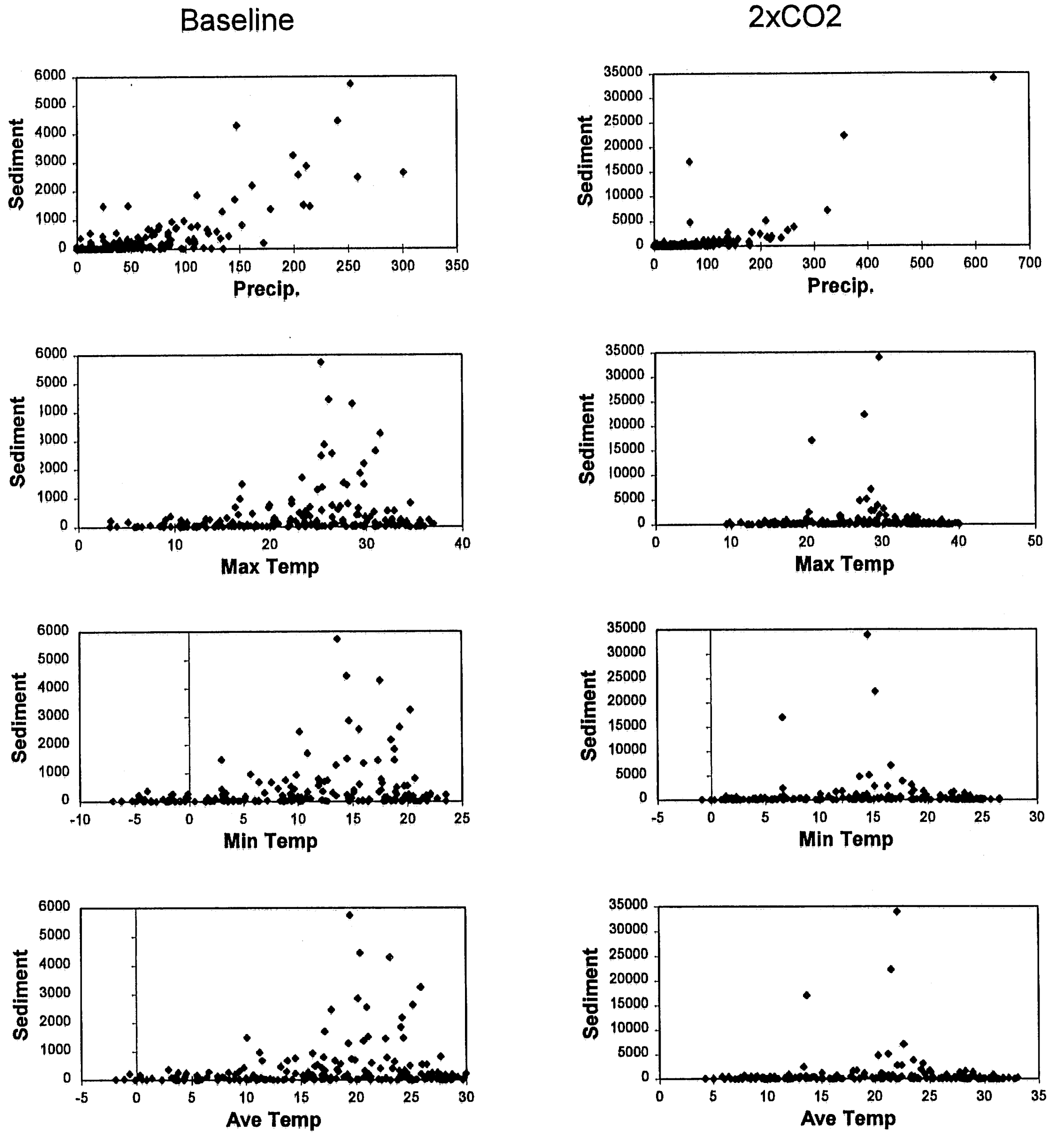

Figure 3d Simulated monthly sediment yield vs. monthly climate input parameters for the Little Washita River watershed.

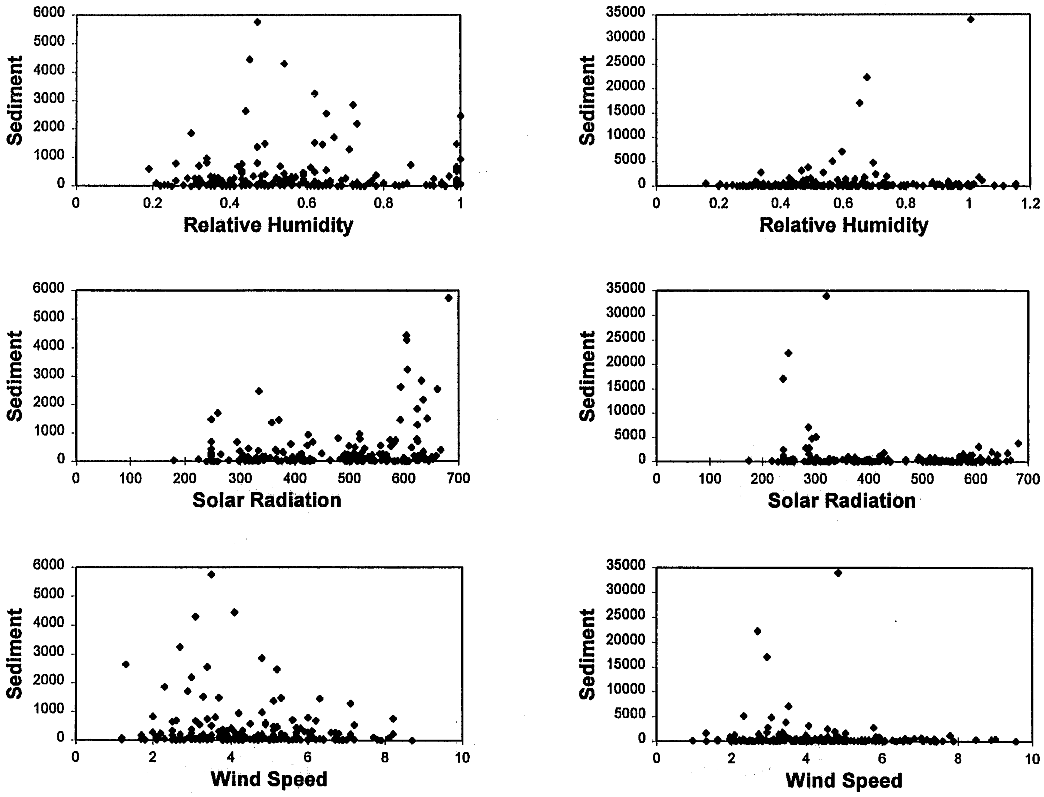

Figure 3d (Cont'd.) Simulated monthly sediment yield vs. monthly climate input parameters for the Little Washita River watershed.

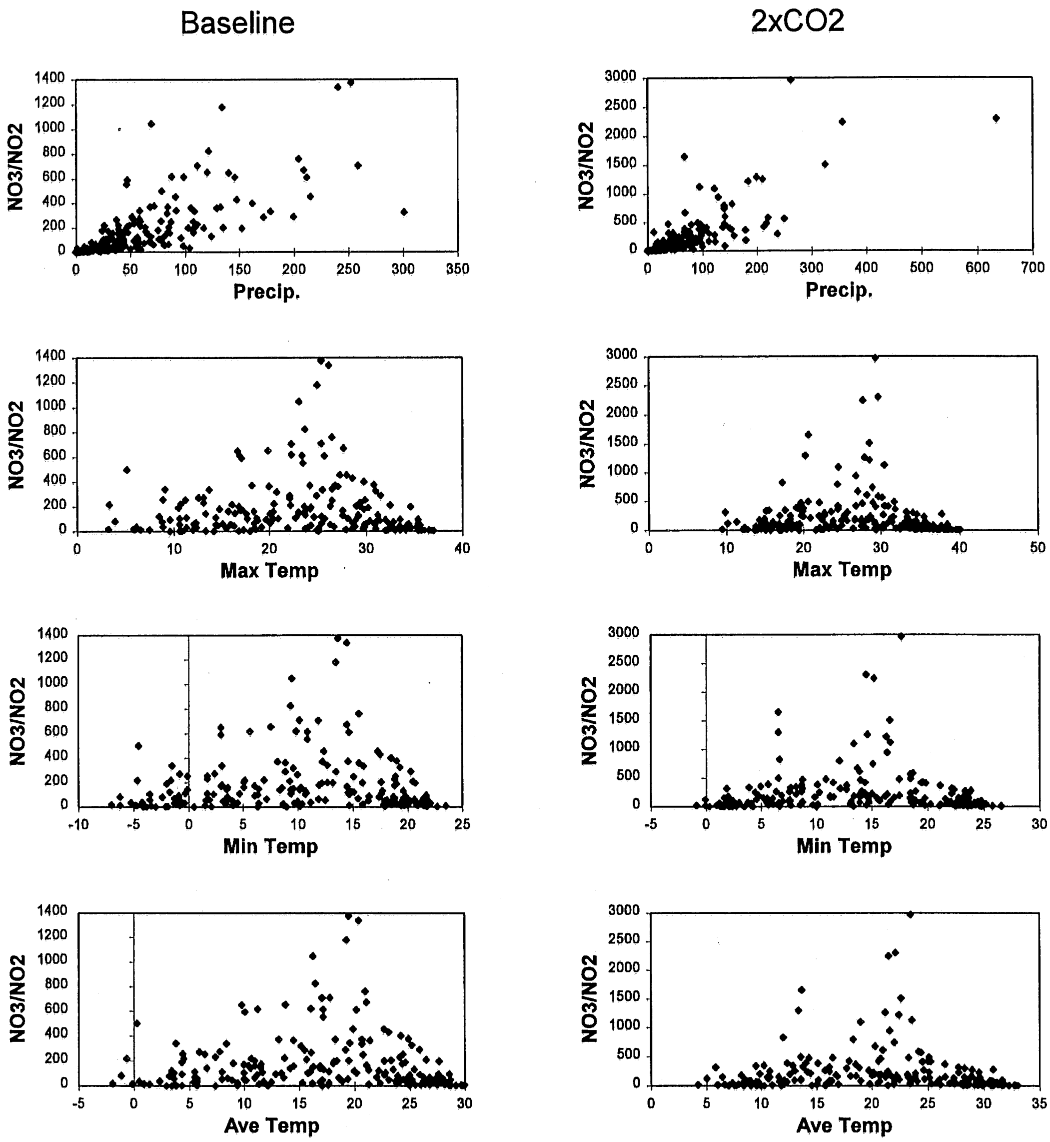

Figure 3e Simulated monthly nitrate/nitrite yield vs. monthly climate input parameters for the Little Washita River watershed.

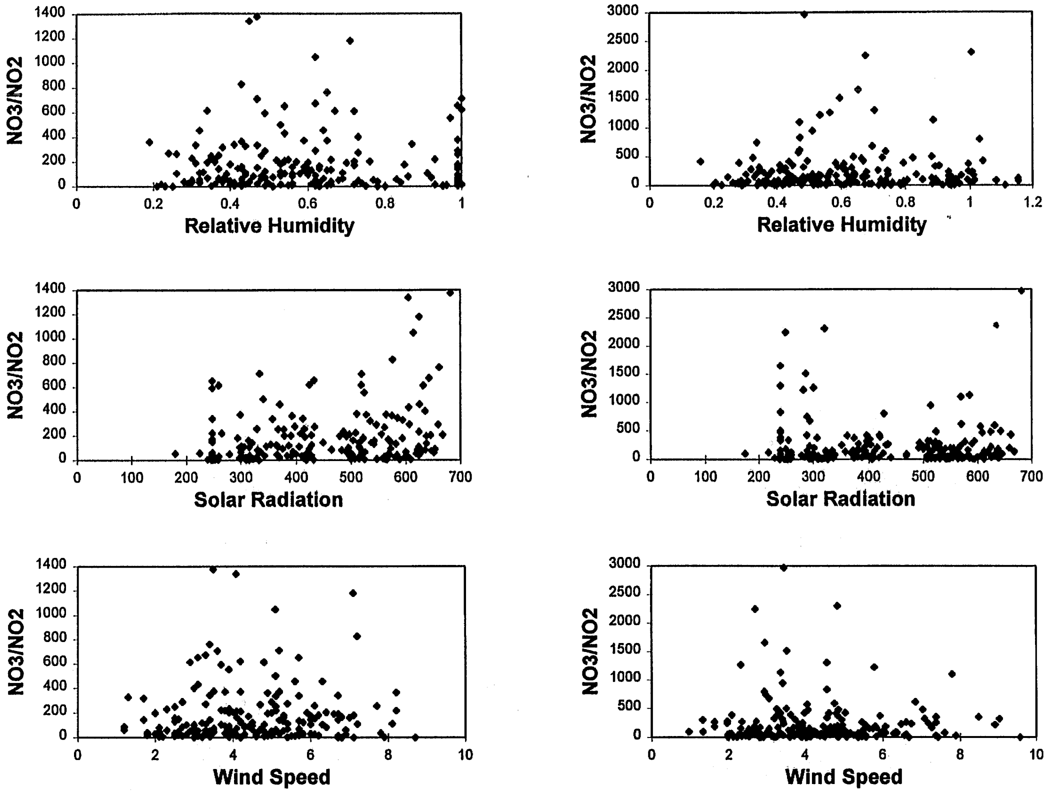

Figure 3e **(Cont'd.)** Simulated monthly nitrate/nitrite yield vs. monthly climate input parameters for the Little Washita River watershed.

6. IMPLICATIONS FOR MODEL CALIBRATION AND APPLICATION

These sensitivity analyses of SWAT served two purposes. (1) They provided guidance for calibrating the SWAT input parameters and (2) they delineated the most important climate parameters for simulating the effects of climate change on the water quantity and quality of three very diverse rural watersheds.

Calibration

The best parameter for calibrating SWAT for monthly streamflow will usually be the SCS runoff curve number. In the case of a forested watershed, the parameters related to forest ET, maximum leaf area index and the initial soil concentration of the nutrients that limit forest growth, will be useful as well. The sensitivity of streamflow (and, therefore, of water quality) to land use implies that the simulated streamflow and water quality should be calibrated only after the dominant land use for each subbasin is determined as accurately as possible.

Calibration of SWAT for sediment yield can be done using the parameters that govern sediment routing (the routing channel MUSLE cover factor, routing channel erodibility, and potential stream bed degradation coefficient and/or exponent), provided that the "normal concentration" parameters for suspended sediment in lakes, wetlands, and groundwater return flow are in realistic ranges.

To calibrate the SWAT simulations of total phosphorus and ammonia/organic N, the initial concentrations of organic P and organic N in the surface layer and the land management practices, such as spring plowing or fertilizing with manure will be the most useful. Nitrate/nitrite yields, however, will not always be responsive to the same input parameters. In a watershed where no fertilizers are used, such as a forested watershed, the initial organic N concentration in the soil will be the most useful for calibration, but in an agricultural watershed, the amount of chemical fertilizer applied to the watershed will be the most useful.

Simulation of Climate Change Effects

Overall, the streamflow and water quality in the Baptism River (MN) watershed were most influenced by air temperature and precipitation. Precipitation was the best predictor for changes in streamflow and water quality in the Cottonwood River (MN) watershed. Temperature was also a good predictor for some of the water quality. Soil water, which reflects the precipitation and temperature input from past months was as good or better at predicting changes in streamflow and water quality as precipitation and temperature. For both the Baptism and Cottonwood River watersheds, the importance of air temperature was much lower in the $2xCO_2$ simulation because of the decrease in the importance of snowmelt.

It should be noted that the sensitivity of SWAT's output to temperature would have been missed in this error analysis if only linear relationships (*i.e.*, r^2) had been used to calculate the influence of the climate parameters. Non-linear relationships were required to measure the influence of air temperature on the SWAT simulations of streamflow and water quality.

The most important input variable for the Little Washita River (OK) watershed was precipitation. Temperature was not nearly as important for explaining variation in the water quality and quantity as it was in the two Minnesota watersheds, but soil water was as important for the Little Washita as it was for the Cottonwood River watershed. Therefore, when making projections of the impact of future climate scenarios on rural watersheds, it is most important to correctly project the change in precipitation. In watersheds where snowmelt plays a significant role in the hydrologic budget, it is also important that changes in temperature be projected correctly.

7. CONCLUSIONS

The SWAT simulations of streamflow and water quality can be calibrated to three very different watersheds with a small number of its input parameters (Tables 1, 2, and 3). Streamflow in the two agricultural watersheds can be calibrated with the runoff curve numbers and the effective hydraulic conductivity of the routing channels and streamflow in the forested watershed can be calibrated with the maximum leaf area index and nutrient concentrations in the soil. Sediment yield can be calibrated with the sediment routing parameters, provided that the parameters for the normal concentration in ponds, wetlands, and groundwater return flow are in realistic ranges. Nutrient yields can be calibrated with the initial concentrations in the top soil layer and with land management practices such as fertilization and plowing.

When using error analysis to measure the influence of the model input parameters on various model outputs, both linear and non-linear relationships must be taken into account. If only the square of the correlation coefficient, r^2, is used to measure influence, some important variables could easily be missed.

When using SWAT to project the impact of future climate scenarios on rural watersheds, it is most important to correctly project the change in precipitation. In watersheds where snowmelt plays a significant role in the hydrologic budget, it is also important that changes in temperature be projected correctly. Unfortunately, current GCM's are not very good at simulating precipitation distribution (Lau *et al.,* 1996). Therefore, the research being conducted to improve the GCM simulations should be continued until the models are able to accurately simulate both precipitation and temperature.

Finally, because the SWAT simulations of water quality were sometimes more sensitive to changes in land management than to changes in temperature or precipitation, projections of climate change effects must be interpreted carefully. The changes due to land management practices could surpass any anticipated change in water quality due to climate change. Therefore, it may be more important to achieve proper land management practices through education and/or regulation.

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