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Effects of climatic variability on the hydrologic response of a freshwater watershed

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ABSTRACT

A generalized watershed model was used to evaluate the effects of global climate changes on the hydrologic responses of freshwater ecosystems. The Enhanced Trickle Down (ETD) model was applied to W-3 watershed located near Danville, Vermont. Eight years of field data was used to perform model calibration and verification and the results were presented in Nikolaidis et al., (1993). Results from the Goddard Institute for Space Studies (GISS) and the Geophysical Fluid Dynamics Laboratory (GFDL) general circulation models which simulated the doubling of present day atmospheric CO_2 scenarios were used to perform the hydrologic simulations for the W-3 watershed. The results indicate that the W-3 watershed will experience increases in annual evapotranspiration and decreases in annual outflow and soil moisture. Stochastic models that simulate collective statistical properties of meteorological time series were developed to generate data to drive the ETD model in a Monte-Carlo fashion for quantification of the uncertainty in the model predictions due to input time series. This coupled deterministic and stochastic model was used to generate probable scenarios of future hydrology of the W-3 watershed. The predicted evapotranspiration and soil moisture under doubling present day atmospheric CO_2 scenarios exceed the present day uncertainty due to input time series by a factor greater than 2. The results indicate that the hydrologic response of the W-3 watershed will be significantly different than its present day response. The Enhanced Trickle Down model can be used to evaluate land surface feedbacks and assessing water quantity management in the event of climate change.

Introduction

In the past few years, a number of studies have attempted to evaluate the impacts of climate change to regional hydrologic regimes (McCabe et al., 1989; Lettenmaier and Gan, 1990; and Lettenmaier and Sheer, 1991) and terrestrial ecosystems (Gleick, 1990). These studies have used simulation results from the general circulation models (GCMs) to obtain quantitative estimates of the climate changes by doubling present day atmospheric CO_2 concentration. The results of these studies indicate that climate changes could alter the timing and magnitude of runoff, soil moisture, lake water storage, groundwater availability, and water quality (Gleick, 1989; Lettermain and Gan, 1990; and Mitchell, 1989). These changes may also have severe implications for agricultural and other economic activities (Kohlmaier et al., 1989; and Smit et al., 1988).

The main objective of this research was to conduct a rigorous assessment of the impacts of climate change on freshwater watersheds. The following questions relating to the impacts of climate change on water resources were addressed.

1. How does global climate change affect the hydrologic response of watersheds in the northeastern U.S.?
2. What is the role of input uncertainty on the hydrologic response of watersheds?

The methodology used in evaluating hydrologic impacts of climate change is directly related to the parameterization of the hydrologic models that are being used and the way the simulation results from the GCM models are used. Simplified parameterization schemes of atmosphere and lithosphere interactions have been presented by McCabe and Wolock (1989) and Lettenmaier and Sheer (1991). These methods include the Thornthwaite Moisture Index (McCabe et al., 1990) which is an indicator of precipitation relative to evapotranspiration. Nikolaidis et al. (1993) presented a modified version of the Enhanced Trickle Down (ETD) model (Nikolaidis et al., 1988 and 1989) that treats the atmosphere and lithosphere as a single continuum. The model was modified to include an energy budget. The ETD model is driven through time series data of precipitation, air temperature, cloud cover, solar radiation, humidity and wind speed. Such a parameterization is compatible with the formulation of the GCM models and thus it provides a mathematically rigorous treatment of the coupling of GCM results with hydrologic models.

The second question deals with the uncertainty of the GCM model predictions regarding climate changes under a scenario which doubles the present day CO_2 concentration scenario and the interpretation of the hydrologic modeling results due to the propagation of uncertainty. In this study, the interpretation of the results was conducted in conjunction with the time series input uncertainties incorporated in the simulations of the model. The approach used, quantified the present day time series input uncertainty introduced into the model predictions. This uncertainty provides a measure of present day variability in the prediction of flow in a watershed. A comparison of the model simulation results created by doubling present day CO_2 concentration with the present day uncertainty in the estimates for the prediction of flow provides insight into the severity of climate change impacts to the hydrologic and biogeochemical response of freshwater watersheds.

The aim of this research is to gain an understanding of the hydrologic response of the W-3 watershed to climate changes. The W-3 watershed is located near Danville, Vermont at latitude 44.5 °N and longitude 72.2 °W. The watershed has a drainage area of 8.42 km^2 and ranges in elevation from 346 to 695 m with a mean elevation of 490 m. The average slope of the watershed is 8% (Anderson et al., 1979). The climate of the W-3 watershed can be characterized by long, cold winters, and moist summers. The mean annual temperature for the W-3 watershed is 4 °C. The long term precipitation record shows a fairly uniform distribution of precipitation throughout the year. The mean annual precipitation is 1215 mm. Snowfall is averaging about 300 mm (Anderson et al., 1979). The vegetation cover for the W-3 watershed has remained relatively unchanged over the past years. Approximately one-third of the watershed area is open land and includes grassland, roads, and farms. The remaining two-thirds of the area is covered by forest, generally second and third growth deciduous and coniferous species (Anderson et al., 1979). Soils on the W-3 watershed range from coarse-textured sandy loams at higher elevations to fine-textured silty loams at lower elevation areas. Seismic studies showed that the depth-to-bedrock varies greatly in the watershed. Bedrock was found at relatively shallow depths, with some surface outcropping. In a few scattered places, the depth of unconsolidated material is 30 feet or deeper. Pope Brook and the north fork of Pope Brook form the major channel that drains the W-3 watershed. The channels do not store water for appreciable periods of time because of the topography and geology of the area (Anderson et al., 1979). There are two reasons why W-3 watershed was selected.

1. It has a long record (complete eight years) of hydrologic and meteorological time series data that can be used to calibrate and verify the ETD model.
2. The W-3 watershed is a representative sub-watershed of the Sleeper River watershed (they have similar geomorphologic, land use, soils, and climatic characteristics) that has a drainage area of 11,000 ha (Anderson et al., 1979), so the simulation results for the W-3 watershed can be representative of larger scale areas.

Methodology

A modified version of the Enhanced Trickle-Down (ETD) model (Nikolaidis et al., 1993) was adapted to evaluate the hydrologic response of W-3 watershed to climate change. The ETD hydrologic model is a generalized, energy-driven, lumped parameter conceptual model that is capable of simulating the hydrologic behavior of watersheds. A vertical discretization is used to resolve the vertical heterogeneity which includes overland flow, unsaturated zone, and groundwater zone. Major hydrological processes included in this model are: infiltration, overland flow, lateral unsaturated flow, vertical percolation, snow accumulation, melting and sublimation, groundwater flow and seepage. Evaporation, transpiration, and soil temperature are based on the energy balance of a bulk canopy layer superimposed on a uniform soil layer, and the energy balance of a bare ground extending down to the depth of the annual thermal boundary layer. Soil temperatures are calculated using the force-restore method (Nikolaidis et al., 1993; Lin and Sun, 1986). Both evaporation from the ground surface and evapotranspiration from the canopy are modeled based on a scaling concept. The potential ground surface evaporation and canopy evapotranspiration are adjusted according to the availability of the soil moisture and plant physiological stage.

The unique features of the ETD model include: 1) a hydrologic structure that has been proven to correctly simulate small to medium sized watersheds in a lumped parameter fashion, 2) a detailed energy submodel that can simulate the dynamics of evaporation, plant transpiration and snow melt processes, and 3) its relatively small size that makes it possible to perform sensitivity and uncertainty analyses.

Climate change simulation methodology

Deterministic, steady state simulations were performed using simulation results from two GCM models. Results from the Goddard Institute for Space Studies (GISS) and the Geophysical Fluid Dynamics Laboratory (GFDL) models simulating doubling present day atmospheric CO_2 scenarios were used to perform the hydrologic simulations for the W-3 watershed. Figure 1 presents the locations of the GISS and GFDL grids compared to W-3 watershed. The GCM results from four grids were interpolated using the inverse distance squared method (Isaaks, 1989) to generate the input scenario of doubling present day CO_2 concentration for the W-3 watershed. Monthly output changes between present day and double the present

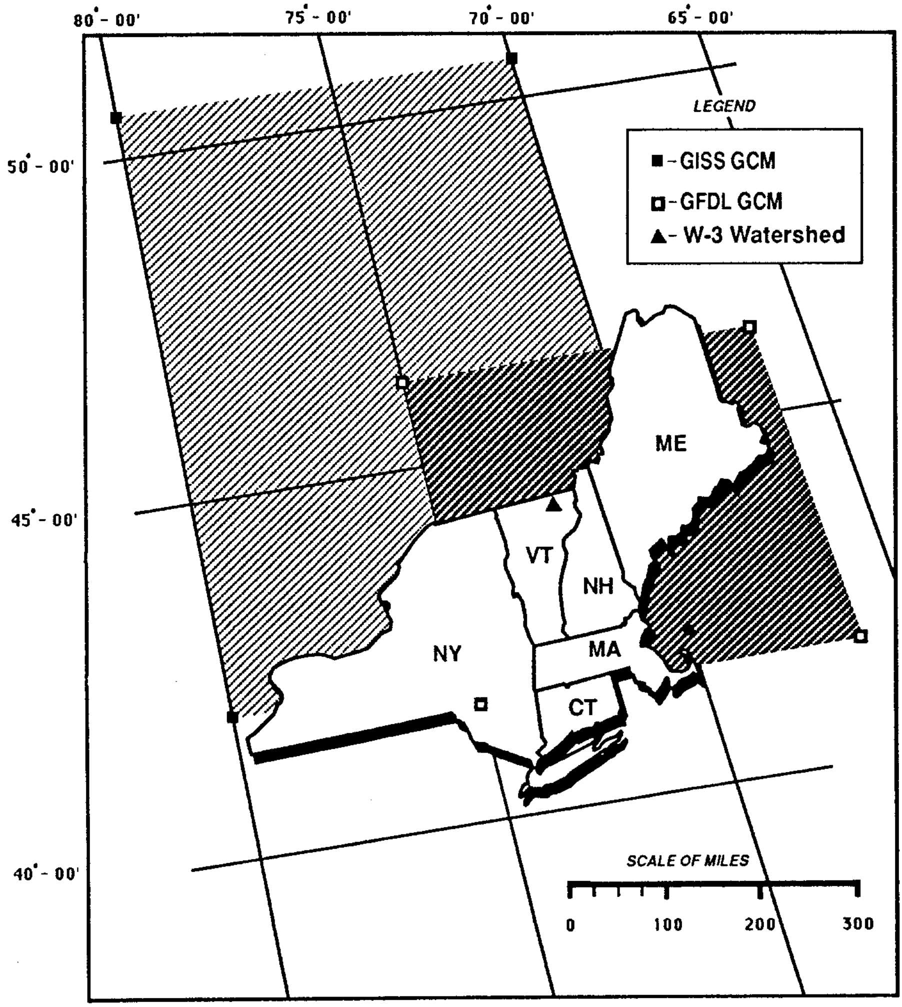

Figure 1. Location of the W-3 watershed and the global circulation model grid points

Table 1. Present day conditions and interpolated output of GCMs simulations were used as input of ETD model for W-3 watershed

a) Present Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Temperature (°C)	-9.7	-8.6	-4.1	1.5	9.0	13.2	15.2	14.3	10.0	5.5	-0.2	-6.9
Precipitation (cm)	102	67.4	96.2	89.9	86.9	125	118	126	98.4	96.6	118	115
Wind speed (cm/sec)	1.17	1.28	1.60	1.54	1.24	1.05	0.92	0.85	0.81	0.89	1.02	1.11
Relative Humidity (%)	67.7	64.4	61.7	58.3	54.3	61.8	62.9	66.1	67.1	66.4	73.2	69.7
b) GISS Scenario	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Temperature (2x-1x)	6.06	4.35	3.99	4.18	4.21	3.12	3.22	3.30	3.69	3.88	3.72	4.65
Precipitation (2x/1x)	1.20	1.11	1.05	0.95	1.43	0.87	1.01	1.16	0.85	0.80	0.74	1.04
Wind speed (2x/1x)	0.98	1.62	1.19	1.52	1.35	0.81	0.83	1.15	1.09	1.05	1.18	1.35
Specific Humidity (2x/1x)	1.43	1.40	1.17	1.37	1.32	1.20	1.20	1.23	1.28	1.13	1.23	1.27
c) GFDL Scenario	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Temperature (2x-1x)	7.96	6.23	5.88	5.33	4.34	5.21	7.71	6.44	5.65	6.16	6.01	6.97
Precipitation (2x/1x)	1.19	1.13	1.15	0.87	1.38	0.92	0.71	0.86	0.82	1.42	1.16	1.24
Wind sped (2x/1x)	0.91	1.01	1.05	0.89	0.81	7.08	7.02	0.81	1.68	0.50	0.86	0.83
Mixing Ratio (2x/1x)	2.11	1.63	1.50	1.42	1.30	1.39	1.26	1.15	1.24	1.45	1.50	1.85

day CO_2 concentrations for precipitation, air temperature, wind speed, and specific humidity are presented in Table 1. These data constitute steady state climate conditions under the doubling of present day atmospheric CO_2 concentration scenario. The deterministic, steady state simulations of the ETD model were performed in the following manner.

1. The present day, eight year long record of meteorological time series was repeated to generate a 24 year long record. A simulation having as input this 24 year long record was assumed to simulate the steady state climate conditions of present day atmospheric CO_2 concentrations.

2. The monthly output results from the GISS and GFDL GCM models presented in Table 1 were used to generate doubling the present day CO_2 scenarios by adjusting the daily present day time series record for the meteorological parameters listed in Table 1. Two 24 year long simulations were performed, one using the GISS results and the other the GFDL results.

3. The last eight years of the 24 year simulation were averaged to calculate annual and seasonal hydrologic budgets under present day and doubling present day CO_2 scenarios. The results from these simulations were used to quantify the effects of climate change on W-3 watershed.

Uncertainty analysis methodology

The second type of simulations performed were the stochastic simulations. They were used to evaluate the degree of variability in the hydrologic response of W-3 watershed due to present day interannual and intraannual variability in climate conditions. These simulations were used in the interpretation of severity of the effects of climate change to the hydrologic response.

Imperfect knowledge of future meteorological conditions cause uncertainty of the long-term projections of hydrologic models. Uncertainty due to input comprises a major fraction of the total uncertainty of model predictions. Stochastic models that can simulate collective statistical properties of meteorological time series can be used to generate data that drive hydrologic models in a Monte-Carlo fashion to quantify the uncertainty in the model predictions due to input time series. Eight years of daily meteorological data from the W-3 watershed (Anderson et al., 1979) were used to develop stochastic models for precipitation, air temperature, dew point, wind speed and insolation. These stochastic models were then coupled with the ETD model. This coupled deterministic and stochastic model was used to generate 24 year long hydrologic simulations of the W-3 watershed using the Monte-Carlo method. It was determined that 50 simulations were adequate to minimize the sampling error of the method.

Stochastic models for meteorological time series

Precipitation time series

The stochastic structure of daily precipitation time series has been extensively studied during the past three decades. Many models have been developed to model the precipitation process (Clark, 1977, Eagleson, 1978, Foufoula-Georgiou and Lettenmaier, 1986, Marien and Vandewiele, 1986, and Waymire and Gupta, 1981). This study adapted a point precipitation model developed by Eagleson (1978). Eagleson's precipitation model attempts to model the statistics of the critical components of a precipitation event, namely the storm interarrival time, t_a, the duration of the storm, t_r, and the storm intensity, i.

The probability density functions of the interarrival times, t_a, between storm events and storm duration times, t_r, were assumed following exponential distribution given by

$$f_{T_a}(t_a) = \omega e^{-\omega t_a}$$

with the mean and variance given by

$$m_{ta} = \omega^{-1}$$
$$\sigma^2_{ta} = \omega^{-2}$$

respectively, and the probability distribution of the storm duration

$$f_{T_r}(t_r) = \delta e^{-\delta t_r}$$

with the mean and variance given by

$$m_{t_r} = \delta^{-1}$$
$$\sigma^2_{t_r} = \delta^{-2}$$

respectively.

The probability density functions of the total storm depth, H, were assumed to be gamma distribution [*Eagleson*, 1978], and given by

$$f_H(h) = \frac{\lambda h^{k-\lambda}\ e^{-\lambda h}}{\Gamma(k)} \quad \text{for} \quad h \geq 0$$

The mean and variance of storm depth are given by

$$m_H = \frac{\kappa}{\lambda}$$

$$\sigma^2_H = \frac{k}{\lambda^2}$$

In the above equations m_{ta}, σ^2_{ta}, m_{t_r}, $\sigma^2_{t_r}$, m_H and σ^2_H are parameters that can be determined from observed time series. Further details of this model can be found in Georgakakos et al. (1989) and Hu (1991).

Once the duration of a storm and total amount of precipitation were evaluated, the total storm depth was distributed to daily rainfall using regional rainfall distribution curves (Huff, 1967). Huff's results indicate that a major portion of the total rainfall occurs during a short period regardless of the duration or the magnitude of the storm. Storms in a region were classified into four groups depending on whether the heaviest rainfall occur in the first, second, third or fourth quartiles of the storm period. For each type of storm, the time distributions were expressed in probability terms. Huff also showed that the first and second quartile storms are the most frequent ones. In this study, the second-quartile, 50% probability time distribution, was adopted.

Meteorological time series

Stochastic models were developed for the following meteorological parameters: air temperature, dew point, wind speed, insolation (incoming solar radiation) and cloud cover. Stochastic models of meteorological time series consist of two major components, the deterministic component, $\overline{T}_i$, and the stochastic component, T_i'.

$$T_i = \overline{T}_i + T_i'$$

Kothandarman (1971, 1972) pointed out that the first harmonic of a one year period could account for approximately 80% of the total variance in a meteorological parameters such as air temperature. Song (1974) verified Kothandarman's results using meteorological data from the Minnesota River Basin. After neglecting higher harmonics, Song expressed the deterministic component of an air temperature model as

$$\overline{T}_i = \mathrm{A} + \mathrm{B}\sin\frac{2\pi i}{365} + \mathrm{C}\cos\frac{2\pi i}{365}$$

where i is the Julian day, and A, B, and C are fitted parameters to the time series record.

This stochastic component, T_i' can be expressed as follows

$$T_i' = R_a T_{i+j} + C_f M_i + \delta_{ai}$$

where

T_i' = stochastic component of time series data at Julian day, i
T_{i+j} = time series data with lag j days
R_a = auto-correlation coefficient of time series with lag j days
C_f = cross-correlation coefficient of time series
M_i = time series of other meteorological variables, and
δ_{ai} = random residual variance of normal distribution $N(0,\delta_a)$.

Eight years long meteorological record from the W-3 watershed was used in this study. The time series included daily meteorological measurements of precipitation, temperature, dew point, wind speed and insolation, recorded between 10/01/70 and 09/30/78. In order to examine the effects of climate change, cloud cover data is necessary; however, cloud cover data was not available for the W-3 watershed. The same eight years period of cloud cover data from the Burlington weather station in Vermont, 53 miles from the W-3 watershed, was used.

Monte-Carlo simulations

The Monte-Carlo simulation technique was used to estimate the uncertainty in model predictions due to the variability of input time series data. As described earlier, stochastic models were developed for each parameter of the input time series. These stochastic models contain a deterministic component and a stochastic component. The stochastic component is comprised of components that describe the autocorelative nature of the time series, the cross correlation with other variables as well as a white noise component. The white noise, or random variation of the time series data, was estimated by performing random sampling from the distribution of the respective parameters. The stochastic models provided random time series sequences of the meteorological variables that were used to drive the ETD model. Fifty ETD simulations were performed and the simulation results were used to compute an expected simulation result and its standard deviation. The standard deviation of the Monte-Carlo simulation results was considered as a measure of the uncertainty due to input time series.

Results

A detailed description of the ETD model can be found in Nikolaidis et al. (1988) and Nikolaidis et al. (1989). The ETD model was modified to incorporate an energy budget of the watershed (Nikolaidis et al., 1993). The results of calibration, verification and sensitivity analysis simulations of the modified version of the ETD model using data for the W-3 watershed were presented in Nikolaidis et al. (1993). This paper presents the results of steady state climate change simulations and the Monte-Carlo simulations to quantify the uncertainty associated with the input-time series.

Climatic scenarios simulation results

Figure 2 presents a comparison between present day and doubling present day atmospheric CO_2 concentration (using data generated by the GISS and GFDL GCM models) of annual average precipitation, outflow, evapotranspiration and percent change of soil moisture content. The annual averages were computed from the last 8 years of the 24 year long simulation period. Both GCM models predicted that the annual average precipitation will increase, by 1.3% and 7% for GISS and GFDL respectively. The ETD model simulations predicted that annual evapotranspiration will increase by 34.9% and 78.8% for the conditions provided by the GISS and GFDL models respectively. However, annual average outflow was predicted to decrease by 19.6% for the GISS scenario and 38.7% for the GFDL scenario and annual average soil moisture content will decrease by 17.9% and 37.5% for the GISS and GFDL scenarios respectively. Under present day climate conditions, the W-3 watershed receives approximately 1.2 m of precipitation, 60% of which is in the form of snow. Under both GCM model scenarios, the amount of snow accumulation and melting will decrease. The ETD model predicted that snowmelt will decrease by 33% for GISS and 50% for the GFDL scenarios, even though it has been

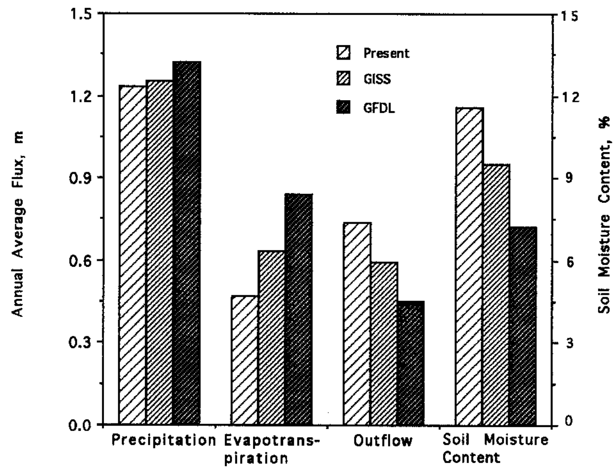

Figure 2. Comparison of the annual average predictions between the present day and double the present day atmospheric CO_2 climatic conditions

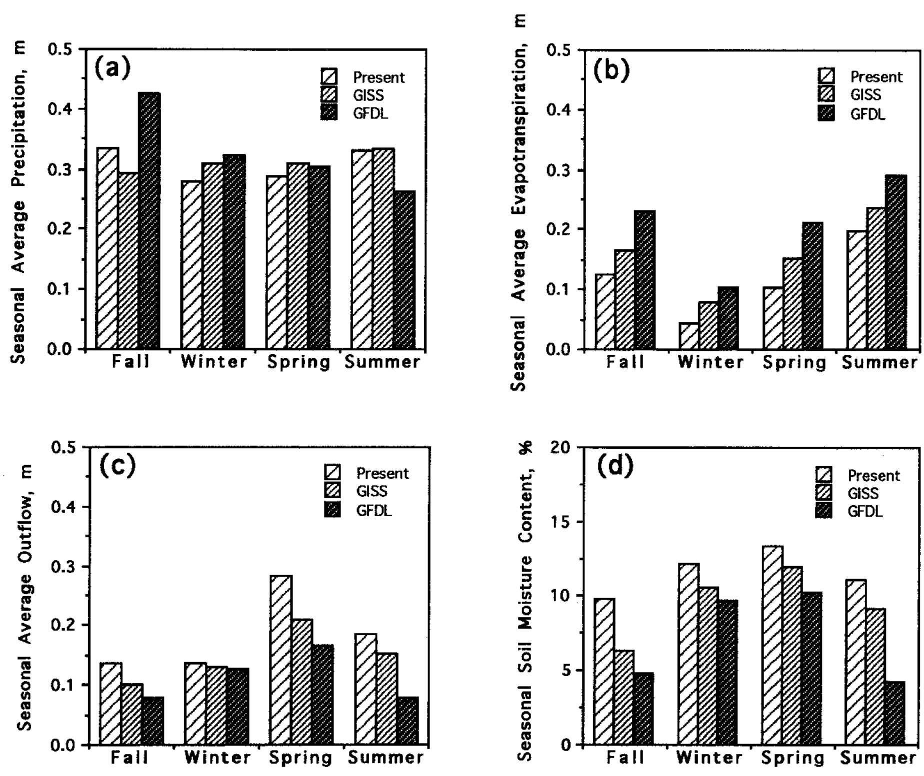

Figure 3. Comparison of the seasonal average predictions between the present day and double the present day atmospheric CO_2 climatic conditions

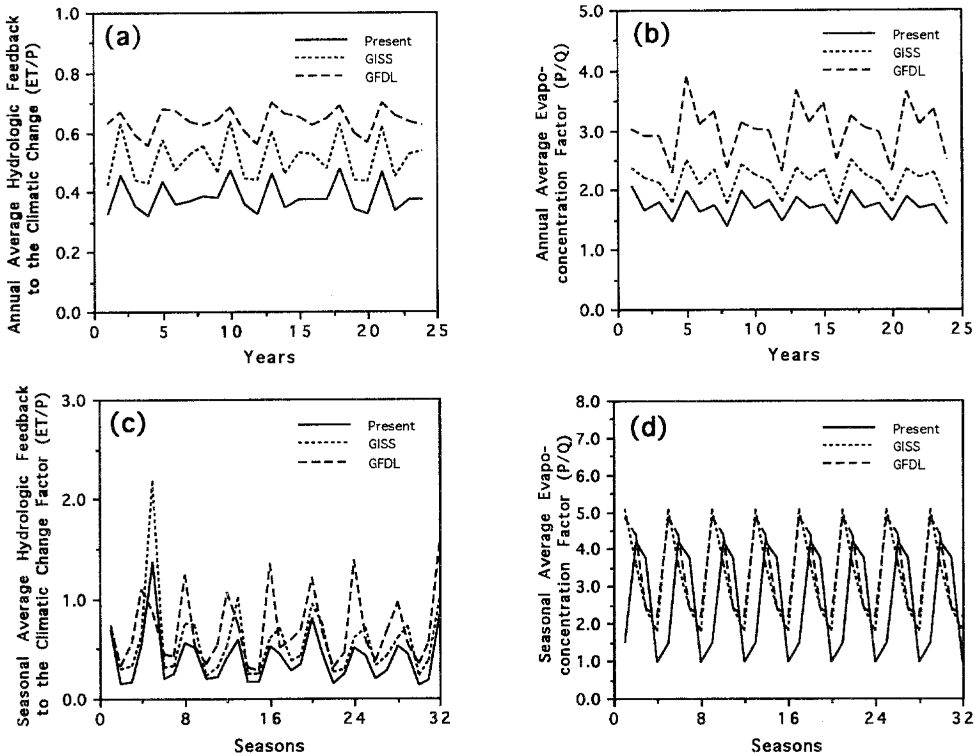

Figure 4. Comparison of the annual and seasonal average predictions between the present day and double the present day atmospheric CO_2 climatic conditions of the hydrologic feedback and the evapoconcentration factors

predicted by both models that the total winter precipitation will increase. Decreases in the lateral flow contribution of the watershed to the stream and overland flow were also predicted by the ETD model.

The seasonal variability of the various hydrologic processes of the W-3 watershed under the doubling of present day atmospheric CO_2 concentration scenario is depicted in Figure 3. Figure 3a presents the seasonal average precipitation for present day, GISS and GFDL scenarios climate conditions. Both GISS and GFDL scenarios predicted that seasonal precipitation will increase except in the fall season as predicted by GISS and in the summer as predicted by GFDL. The ETD model predicted that seasonal evapotranspiration (Figure 3b) will increase for all seasons except the fall for the GFDL scenario, seasonal outflow (Figure 3c) will decrease with the exception of winter for both GISS and GFDL scenarios and seasonal soil moisture content (Figure 3d) will decrease in all seasons and under both climate conditions..

In addition to the above analysis, there are two more important factors to analyze to obtain a better understanding of the effects of climate change on regional watersheds. These are the hydrologic feedback to climate change factor, ET/P and the evapoconcentration factor, P/Q (Schnoor et al., 1986). ET/P is the evapotranspiration intensity of the soil, ET, over the precipitation intensity, P, and is a measure of the feedback of the watershed to climatic perturbations. Changes in precipitation, air temperature and other meteorological variables will cause changes in the feedback mechanism from the watershed to atmosphere, the evapotranspiration process. On the other hand, P/Q (precipitation over outflow) is a measure of the waste assimilation capacity of freshwater bodies. It indicates the change in the degree of concentration of a waste due to evaporation. The principle of dilution has been used historically as a mean for disposal of pollutants. The waste assimilation capacity of a lake or a stream decreases due to the process of evaporation. Figure 4 presents the variability of these two factors. Figure 4a and 4b present the annual average changes of ET/P and P/Q for present day climatic conditions and the two climate scenarios generated by the GCM models. Figure 4c and 4d present the seasonal variability of these two factors for the last eight years of the simulation period. Under annual average conditions, it is expected that the hydrologic feedback of the W-3 watershed will increase by 60% for the GFDL scenario and by 35% for GISS. The evapoconcentration factor P/Q will increase by 75% for the GFDL and by 30% for the GISS. The greatest seasonal variability is predicted to occur during the winter and summer seasons.

Stochastic simulations and uncertainty analysis

The eight year long meteorological record obtained from the W-3 watershed (Anderson et al., 1979) was used to generate the stochastic models to drive the ETD model in a Monte-Carlo fashion. The stochastic models generate time series sequences with the same statistical characteristics as the observed data. Table 2 presents the statistical characteristics of the meteorological variables collected at the W-3 watershed. In order to develop the stochastic models of each meteorological variable, the autocorrelation structure of each time series and the cross correlation interaction among the time series were examined. The time series of air temperature, dew point, wind speed, insolation and cloud cover exhibited a strong autocorrelation behavior (with autocorrelation coefficients of about 0.91). The components of precipitation, t_a, t_r, and h, did not have any significant autocorrelation.

Table 2. Statistical characteristics of the observed time series of the W-3 watershed

Parameter	Mean	Standard Deviation
Precipitation, mm/d	3.39	7.12
Air Temperature, °C	3.90	12.25
Dew Point Temperature, °C	−0.62	11.0
Wind Speed, m/s	1.29	0.63
Insolation, Ly	4.90	3.41
Cloud Cover, %	71	27
Precipitation Components		
Interarrival Time, d	6.16	3.67
Storm Duration, d	3.84	3.75
Storm Intensity, mm	21.0	23.77

Table 3. Summary of stochastic meteorological models

a) Precipitation

Component	Model
Interarrival Time, t_a	$f_{T_a}(t_a) = \omega e^{-\omega t_a}, \quad \omega = 0.25$
Duration Time, t_r	$f_{T_r}(t_r) = \delta e^{-\delta t_r}, \quad \delta = 0.431$
Total Storm Depth, h	$fH(h) = \frac{\lambda h^{\kappa-1} e^{-\lambda h}}{\Gamma(\kappa)}, \quad \lambda = 0.0476, \quad \kappa = 1$

b) Meteorological Parameters

Parameter	Model
Air Temperature (T_i)	$T_i = 1.37 - 1.697 \sin \frac{2\pi i}{365} - 4.75 \cos \frac{2\pi i}{365} + 0.649\, T_{i+1} + \sigma_a(0,15.65)$
Dewpoint (D_i)	$D_i = -4.1 - 0.431 \sin \frac{2\pi i}{365} + 2.087 \cos \frac{2\pi i}{365} + 0.155\, D_{i+1} + 0.915\, T_i + \sigma_a(0,3.84)$
Wind Speed (W_i)	$W_i = 0.919 + 0.248 \sin \frac{2\pi i}{365} + 0.0693 \cos \frac{2\pi i}{365} + 0.285\, W_{i+1} + \sigma_a(0,0.023)$
Insolation (I_i)	$I_i = 16.1 - 0.193 \sin \frac{2\pi i}{365} - 2.7 \cos \frac{2\pi i}{365} + 0.029\, I_{i+1} - 0.15\, H_i + \sigma_a(0,1.905)$
Cloud Cover, % (C_i)	$C_i = 102.65 + 4.762 \sin \frac{2\pi i}{365} - 17.956 \cos \frac{2\pi i}{365} + 0.0705\, C_{i+1} - 7.56\, I_i + \sigma_a(0,233.25)$

Note: H_i = Relative humidity calculated from Bosen's formula (Viessman, 1989)

$$= 100\left(\frac{112 - 0.1\,\mathrm{Ti} + \mathrm{Di}}{112 + 0.9\,\mathrm{Ti}}\right)^8$$

Air temperature and dew point time series exhibited a strong cross-correlation of 0.96. Insolation and cloud cover time series exhibited a negative correlation of 0.61. The remaining of the time series did not have significant cross-correlation.

Table 3 presents the stochastic models generated in this study and summary statistics of the white noise. It was decided that the air temperature model should not have any cross-correlation component in its structure, since it is an independent variable provided by the GCM models. The model was capable of capturing the mean variability of the observed time series and it had a standard deviation of the residuals of 4.8 °C. The dew point temperature model has an autocorrelation component and a cross-correlation component with air temperature. The white noise of the dew point model had a zero mean and a standard deviation of 2.4 °C. The white noise mean and standard deviation of the wind speed model was 0 and 0.57 m/s respectively. Insolation did not exhibit any significant cross-correlation with other meteorological measured time series, but it had a high cross corelation coefficient with humidity. Humidity time series were calculated from the air temperature and dew point time series using Bosen's equation (Viessman et al., 1989). The statistical characteristics of the insolation, cloud cover and precipitation models are presented in Table 3. Detailed procedures for the estimation of the parameters of these models can be found in Georgakakos et al. (1989) and Hu (1991).

Fifty, 24 year long Monte-Carlo simulations were performed randomly driven by the stochastic models. Based on the sample standard deviations (σ) of 0.206 m/yr for annual average precipitation, 0.063 m/yr for annual average evapotranspiration, and 0.179 m/yr for annual average outflow, the 50-runs sampling erros for the mean value of the annual average precipitation, evapotranspiration, and outflow have the standard deviations (σ_s) equal to 0.0291 m/yr, 0.0089 m/yr and 0.0253 m/yr ($\sigma_s = \sigma/\sqrt{50}$) respectively. This means that $\pm$0.063 m/yr of annual evapotranspiration and $\pm$0.179 m/yr of annual outflow is the range of input uncertainty. Figure 5a, 5b, 5c, and 5d present the deterministic simulation and the Monte-Carlo expected averages (and standard deviation) simulations of annual average precipitation, evapotranspiration, outflow and soil moisture content for the W-3 watershed. The deterministic prediction of precipitation and outflow is within $\pm$ one standard deviation from the Monte-Carlo results. The deterministic simulation results for evapotranspiration fall below the expected average by approximately one standard deviation. The opposite occurs with the soil moisture content results. The results

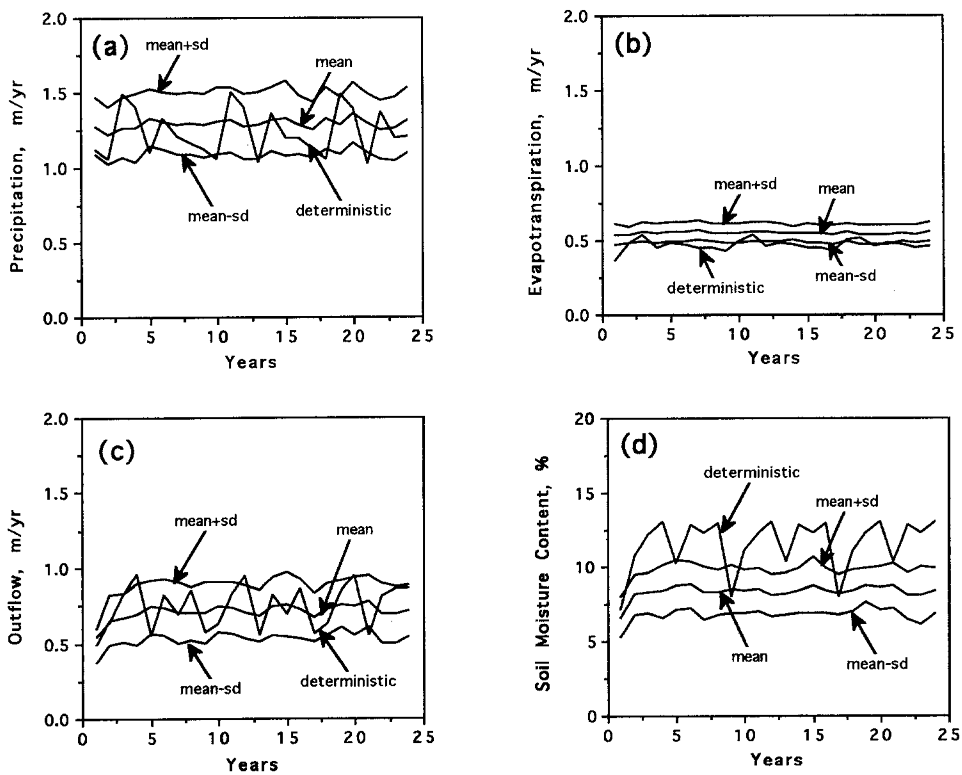

Figure 5. Monte-Carlo simulation results

Table 4. Comparison of the results of deterministic simulations and stochastic simulations

Annual Results:

Parameter	Deterministic	Monte Carlo Simulations		
	mean	mean-sd	mean	mean + sd
Precipitation, m	1.231	1.083	1.289	1.495
Evapotranspiration, m	0.465	0.482	0.545	0.607
Outflow, m	0.741	0.524	0.703	0.882
Soil Moisture Content (%)	11.52	6.76	8.29	9.82

Seasonal Results:

Parameter	Deterministic	Monte Carlo Simulations		
	mean	mean-sd	mean	mean + sd
Precipitation, m				
Fall	0.334	0.296	0.332	0.368
Winter	0.280	0.287	0.324	0.361
Spring	0.287	0.275	0.313	0.351
Summer	0.331	0.282	0.320	0.358
Evapotranspiration, m				
Fall	0.125	0.068	0.095	0.122
Winter	0.044	0.012	0.016	0.020
Spring	0.102	0.142	0.155	0.169
Summer	0.198	0.263	0.278	0.293
Outflow, m				
Fall	0.135	0.057	0.101	0.145
Winter	0.135	0.066	0.079	0.091
Spring	0.283	0.348	0.413	0.479
Summer	0.185	0.086	0.127	0.168
Soil Moisture Content (%)				
Fall	9.76	4.62	6.37	8.12
Winter	12.17	5.94	7.54	9.14
Spring	13.35	8.96	11.4	13.9
Summer	11.06	5.0	6.92	8.84

indicate that evapotranspiration and soil moisture content are very sensitive and outflow is less sensitive to the intraannual and interannual variability of climatic change. The absolute average difference between the Monte Carlo runs and the deterministic predictions were 0.058 m/yr, 0.080 m/yr and 0.029 m/yr for precipitation, evapotranspiration, and outflow respectively. Table 4 summarizes the results of the deterministic simulation and the Monte Carlo simulations of annual and seasonal precipitation, outflow, evapotranspiration, and soil moisture content.

Comparing the standard deviation obtained from the Monte-Carlo simulations, with the deterministic climate changes simulations discussed earlier, it can be seen that the deterministic simulation results fall within the present day input time series uncertainty of the predictions.

Conclusions

Steady state deterministic simulations of the W-3 watershed with scenarios representing present day and doubling present day atmospheric CO_2 concentration climate conditions were performed to assess the effects of climate changes on the hydrologic response of the watershed. The results indicate that under the doubling of present day CO_2 concentration scenario, the W-3 watershed will experience small increases in precipitation (1.3% to 7%) that would be accompanied by large increases in evapotranspiration (35% to 79%), and significant decreases in soil moisture (18% to 38%) and stream runoff (20% to 39%). Examination of the seasonal variability of the response of the watershed revealed that climate pertubations will have adverse effects on the timing and magnitude of snowmelt and available soil moisture. The process of evapotranspiration and soil moisture content were shown to be very sensitive to climate pertubations. The hydrologic feedback to climate forcing factor will increase (35% to 60%) and the watershed will experience a decrease in its capacity to assimilate wastes.

The uncertainty of the long term deterministic simulations due to input time series was assessed using the Monte-Carlo simulation technique. Present day meteorological time series uncertainty accounts for ± 6.3 cm/yr of the variability of annual evapotranspiration, for ± 0.53% of the variability of soil moisture content, and for ± 17.9 cm/yr of the variability of annual outflow. This translates into 11%, 25% and 6% variability of the mean evapotranspiration, outflow and soil moisture respectively. The predicted evapotranspiration and soil moisture under doubling present day atmospheric CO_2 scenarios exceed the present day uncertainty due to input time series by a factor greater than 2. This leads to the conclusion that the hydrologic response of the W-3 watershed under global warming is going to be significantly different than its present day response. The water quality and natural resources of the watershed will be adversely impacted.

This study developed an elaborate framework for the assessment of the effects of climate change on a freshwater watershed. The ETD model can be used to address climate change problems, such as evaluating land surface feedbacks and assessing water quantity management problems.

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