Working Paper

Comparison of Models for Climate Change Assessment of River Basin Runoff

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WP-94-45
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Contents

Abstract

Two lumped-integral conceptual models, a non-parametric regression model and two annual "screening" models are used to compare the impact of climate variability on 5 basins at varying spatial scale and climactic characteristics around the world. Where data were available, different time steps were used to address the influence of the temporal scale on climate impact assessment of river runoff. The purpose of this exercise is to gain insight into the general applicability of these models and assess the impact of spatial and temporal scale on model results derived from changes in two key climate variables: precipitation and temperature. For two of the basins, the East River in Colorado USA and the Mulberry River in Arkansas USA., a comparison is made between these models and results taken from past research on basins using distributed integral models on a 6 hour time step. An additional objective of this study was the selection of a robust model that can be used to assess regional vulnerability of water resources to climate change where data availability is limited.

Introduction

In the last few decades it has been postulated that the definite increases in atmospheric gases (predominately CO_2) caused by human industrial development could lead to significant increases in temperature as well as global and regional variations in precipitation events. Apart from other key socio-economic problems facing today's modern societies, these changes in the hydrologic process could lead to potential long term variations in stream flow which could have profound implications on people and their environment. As we look to the future of water resource development and management around the world, the possible effects of a changing environment should not be neglected. Zaslavsky (1994) states that in the region of the Middle East, water availability could become the next major source of political conflict. In the western US., where water rights have been a continual source of dispute, changes in climatological patterns could greatly influence who has access to this increasingly precious commodity, water (Nash and Gleick, 1993). And in regions throughout Europe, where water availability is already a constraint, planners are wondering if now is the time to make investments in irrigation systems to offset the affects of climate change (Stanislawski 1994). If climate change is realized, these types of problems could potentially occur more quickly and could be repeated in many locations throughout the world.

Issues such as those described above have motivated many to investigate how changes in the climate might alter the hydrologic process and the propagation of these hydro-climatic changes through water resource systems. These studies have been conducted on a range of scales, from the microscopic interaction of CO_2 impacts on plant biomass and the subsequent implications of these changes on the hydrologic cycle to macroscale studies of water resource availability and national vulnerability assessment (Lettenmaier and Burges, 1978; Nemec and Shaake, 1982; Flaschka, I., et. al, 1987; Riebsame, W., 1988; Mimikou, M. and Kouvopoulos, Y., 1991; Vehviläinen, B. and Lohvansuu, J., 1991; Kaczmarek, 1993; Kulshreshtha, 1993, Skiles and Hanson, 1994;*)*. Among the myriad of work done in the area of climate change impacts on water resources have been studies concerning the impact of (primarily) temperature and precipitation changes on river basin runoff (Nemec and

Shaake, 1982, Gleick, 1987, Lettenmaier and Gan, 1990, Chang et. al, 1992, Nash and Gleick, 1993; Reibsame et al., 1994). Often these studies have used mathematical models to perform sensitivity analysis on basin discharge by transferring hydro-climatic variables (precipitation, temperature, humidity, land cover, etc.) to catchment runoff. And while much has been done to understand how well these models represent a basins response to climate variability, there appears to be no consensus on the most appropriate model or the best techniques to use when assessing basin vulnerability to climate change due to the large number of uncertainties.

Kundzewicz and Somlyódy (1993) comment on hydrologic modeling and the need to verify transferability, i.e. the likelihood that a model will work well under changed conditions. They state several issues that relate to transferability of models, which give insight into some of the uncertainties involved.

- Climatic Transferability: If a model can give a true representation of climate variability.
- Spatial Transferability: Model used and verified at site A will be verifiable at site B.
- Temporal Transferability: Model used in period T_1 will apply to a different period, T_2 (generally a more remote period)
- Land-Use-Change Transferability: Model may be applied for a different land use scenario than that in which it was developed for.

Although listed independently above, the issues of transferability are complicated by the fact that they undoubtedly interact. Of these four transferability issues, three have been addressed here (Land-Use-Change transferability is not investigated). Within each of these transferability topics comes a large number of uncertainties with regards to climate change impact assessment;

- Data; Historic data includes likely uncertainties due to instrument bias and/or human error and neglect (Conway and Hulme, 1993, Niemann, et. al, 1994).
- Physical Processes; Dynamic physical processes are not completely understood, especially under climate change conditions: i.e., Temperature, precipitation, evapotranspiration, soil-water-vegetation interaction, snowmelt processes, etc.
- Models; Definition of the mathematical relationships that attempt to describe the various physical processes like infiltration (Horton, Green Ampt), potential and actual evapotranspiration (Penman-Montieth, Priestly Taylor, Hargraves, etc.), runoff (SCS, conceptual, stochastic), etc. Also appropriate methodology is difficult to define such as the role of spatial and temporal distributions (scale).

The key issued addressed in this paper is how different modeling approaches and methodologies impact the assessment of climate change on basin discharge, while emphasizing the importance of transferability of hydrologic models. In regards to each transferability concept: Climate transferability is addressed with regards to the historic record of precipitation, temperature, and basin discharge and compared to model predictions. It is hoped that the historic records will give insight into a basin's response to variations in climate variables and into model performance. Spatial transferability is addressed by investigating how the different models perform in distinctively different basins and temporal transferability will be examined in a similar fashion to climate transferability.

In order to assess the vulnerability of regional water resource availability under climate change, details of regional-scale variability in climate variables such as precipitation, temperature, humidity, wind speed, etc. are necessary. Models are developed to assess the impact of climate change on water resources, with the common goal of transferring the changed climate into a response in catchment runoff. This response is usually derived by applying changes in precipitation and temperature over the basin. General Circulation models (GCM's) are one method used in transferring climate variables to changes in runoff. Dümenil and Todini (1992) present a rainfall-runoff scheme within the Hamburg climate model which partitions rainfall between infiltration and surface runoff and takes the heterogeneous distribution of soil water capacity into account. Even with the implementation of a detailed soil moisture model such as this within the GCM, historical discharges were often found in disagreement with model predictions. Generally speaking, GCM's are not yet able to provide the kind of detailed spatial resolution that is necessary in analyzing surface runoff. Also, GCM's representation of climatological parameters such as precipitation, temperature, evaporation, etc., at a sub-grid or regional scale has been criticized (Robock, 1993). GCM resolution is usually on the order of hundreds to thousands of kilometers, while small and medium catchments are hundreds of meters to tens of kilometers. So until the GCM's improve both their spatial resolution and their representation of hydrologic processes, there will be the need to use detailed, basin specific hydrologic models (Nash and Gleick, 1993; Lettenmaier and Gan, 1990).

Kundzewicz and Somlyódy (1993) have observed a recent trend towards simpler, classical modeling approaches especially with the new challenges which climate change brings. More sophisticated rainfall-runoff models have been developed over the past thirty years, but these are usually aimed at short-term flood forecasting on time scales of days or even hours. These distributed models have been used for analyzing climate impacts (Lettenmaier and Gan, 1990; Nash and Gleick, 1993). Yet Franchini and Pacciani (1991) comment on event scale models such as the STANFORD IV and SACRAMENTO models. They state that the interaction of the various phases of rainfall-runoff transformation within the soil is not advantageous for computational purposes, resulting in over-paramaterization which leads to difficulty in the calibration procedure. Beven (1989) states that three to five parameters should be sufficient to reproduce most of the information in a hydrological record. So with these issues in mind, the model comparison performed here has constrained itself to using lumped conceptual models which make use of a small number of parameters, although comparisons are made to distributed models where results were available.

A range of models and basins have been selected to determine the applicability of these different approaches to basin modeling. The basins selected for this work span a wide range of spatial resolution, from 10's to 100's of linear kilometers (approximately 1000 to 300,000 km^2). For smaller catchments, a short time step might be necessary in order to capture the storage dynamics within a basin. For extremely large basins (those greater than 100000 km^2), basin concentration time might exceed the time step and bias the results. So the spatial and temporal scale motivate the investigation of the "range" of basins that can be applied to these models. By looking at different modeling methods and applying them to different basins, a better understanding of how models influence the assessments of climate change impacts on basin discharge is possible.

Hydrologic Models and Climate Change

Todini (1988) states that mathematical models generally consist of one of two components (or a combination of the two): a physical component that uses a priori knowledge of the physical system and a stochastic component which uses statistical terms to represent what can not be explained by the physical element. Hydrologic models are a class of mathematical models used to describe the response of watersheds to climatic inputs. Four classifications or methodologies for modeling hydrologic process have been identified by Todini (1988). In increasing order of data needs these approaches can be identified as: stochastic models, lumped integral models, distributed integral models, and distributed differential models.

The stochastic model: The stochastic modeling approach centers around developing relationships that describe an output variable like runoff in terms of input variables such as precipitation and temperature without a prescription of the physical processes that occur.

The lumped integral model is the next class of models. The lumped integral approach normally makes use of the fewest number of parameters that can describe the basins response to climatological events. These models are designed to look at medium - large watershed areas and are often referred to as "water balance models". These models are not usually applicable to event scale processes (daily or hourly precipitation events), but are normally used after uniformly lumping a sequence of events (precipitation and runoff), to monthly mean values. The catchment or sub-catchment is modeled as a single, homogenous unit subject to uniform events and parameters. Parameters for this model type usually are not meant to represent physical catchment characteristics.

Attention to spatial and temporal variations is undoubtedly important and applicability of the lumped model can be questioned for this reason. Over a large catchment saturated and unsaturated conditions exist simultaneously; near rivers and streams saturation conditions prevail while slopes and areas with certain soil types could never reach saturation. Most conceptual models, whether lumped or distributed usually operate on the assumption that soil water is evenly distributed over the whole area. This means that runoff will only occur when the entire catchment reaches a certain level of saturation (Dümenil and Todini, 1993).

The distributed integral model is the third model class. A catctcment is Sub-divided into sub-basins and spatial heterogenities are taken into account, giving a more realistic representation of the actual catchment. In this approach, all phenomena are represented at a subcatchment scale using empirical formulas or impulse responses of the subsystem. These models attempt to maintain physical meaning to model parameters. This type of model is really an elaboration of the lumped integral model. In all catchments, daily or time event based processes are undoubtedly very important, and the distributed integral model is an attempt to characterize these processes. This type of model includes the STANFORD, SACRAMENTO, and National Weather Service models. However, accurate characterization of the parameters in these models is difficult (Todini, 1988).

The fourth and final model type is known as the distributed differential model. This is the most sophisticated of the modeling methods and generally is limited to the laboratory. Here catchment behavior is represented in differential form in both space and time. Mass and momentum equations are developed for each sub-system and are linked together by matching boundary conditions at each time step (Todini, 1988).

The author knows of no application of this model type to assess the impact of climate change on basin discharge.

Time Scale

The last issue addressed in the hydrologic modeling efforts is the selection of the time step. For most of the work here, data has been lumped on a monthly basis. For the two smaller basins (East and Mulberry), where event scale processes are undoubtedly important, the WatBal lumped integral model was run on a daily time step. Monthly models might not capture the true response of the basin to precipitation events distributed throughout the month, so it is important to understand what kind of error is introduced when lumping temporally. As an example, if data is given daily and then lumped uniformly over the month, information can be lost which gives insight into basin response to storm events. The total monthly precipitation could occur during one storm, and when applied uniformly over the month true soil moisture dynamics might not be captured when using the monthly time step.

For the East river in Colorado, climate change impact results were available from the US. National Weather Service 6 hour model (Nash and Gleick, 1993). For the Mulberry River, an analogous comparison is drawn from work by Nemec and Shaake (1982) who analyzed the Leaf River in Mississippi, USA. The lumped-integral model (WatBal) was also used in a daily mode to tests its applicability to modeling daily events for the East and Mulberry Rivers.

Annual Approaches

Dooge (1992) suggests a fundamental theorem in hydrologic theory, the lumped form of the continuity equation (1). When looking at the long term water balance of a large catchment or region, an appropriate assumption is that the change in storage can be assumed to be zero. Therefore the water balance equation can be written as;

$$P_a = Et_a + Q_a \qquad (1)$$

Given as annual long-term averages, P_a is the precipitation, Et_a is the evapotranspiration, and Q_a is basin runoff. Dooge (1992) points out that, "any estimate of the effect of climate change on water resources depend on the ability to relate change in actual evapotranspiration to the predicted changes in precipitation and potential evapotranspiration."

Here, annual average statistical values of a watershed were taken and annual changes in temperature and precipitation were applied. The first annual model uses an expression developed by Turc (Kaczmarek, 1990 and 1991), who attempted to relate precipitation and temperature to runoff. A second annual model was developed by E.M. Ol'dekop in 1911 which relates precipitation, evapotranspiration, and potential evapotranspiration to runoff (Dooge, 1992). So the two annual models used here attempt to use this "fundamental theorem" by applying their simple assumptions regarding runoff response to climate variation.

Annual - Turc

Turc (Kaczmark, 1990 and 1991) has defined a relationship between annual runoff and precipitation and temperature, R=f(P,T). Although developed within the context of specific hydroclimatic regions, the model does contain a calibration coefficient and can therefore be applied, with caution, to different basins on an annual basis. The relationships between runoff and precipitation and temperature are given below.

$$Q_a = P_a\left[1 - \frac{L_a}{\sqrt{cL_a^2 + P_a^2}}\right] \tag{2}$$

$$L_a = 300 + 25T_a + 0.05T_a^3 \tag{3}$$

$$\text{if } P_a > (1-c)^{0.5}\, L_a \tag{4}$$

where,

L_a = regression relationship to describe runoff response to temperature
T_a = mean annual temperature (°C)
c = calibration coefficient

The other terms are defined above. The sensitivity of runoff to changes in temperature and precipitation are then given as partial derivatives.

$$dQ_a = \frac{\partial Q_a}{\partial T_a} dT_a + \frac{\partial Q_a}{\partial P_a} dP_a \tag{5}$$

Annual - Hyperbolic Tangent

An expressions that links actual evapotranspiration to precipitation and potential evapotranspiration on an annual basis is given by the hyperbolic tangent equation (6). Unlike the Turc model which is really an annual regression relationship, the hyperbolic tangent can be considered a "physically based" annual model since it uses precipitation and, actual and potential evapotranspiration. The model makes use of ratios of actual to potential evapotranspiration as a function of the ratio of precipitation to potential evapotranspiration.

$$\frac{\mathrm{Et_a}}{\mathrm{PET_a}} = \tanh\left(\frac{\mathrm{P_a}}{\mathrm{PET_a}}\right) \tag{6}$$

Figure 1 is a plot of this function along with the position of five basins plotted as P_a/PET_a vs. Et_a/PET_a. If it is assumed that long term storage is zero, a substitution is made for the expression for Et_a into the water balance, the annual water balance may be written as,

$$Q_a = P_a - Et_a$$

$$Q_a = P_a - \alpha\, PET_a \tanh\left((\frac{P_a}{PET_a})\right) \tag{7}$$

where,

PET_a = Annual Potential Evapotranspiration from Penman (mm)
α = annual calibration coefficient

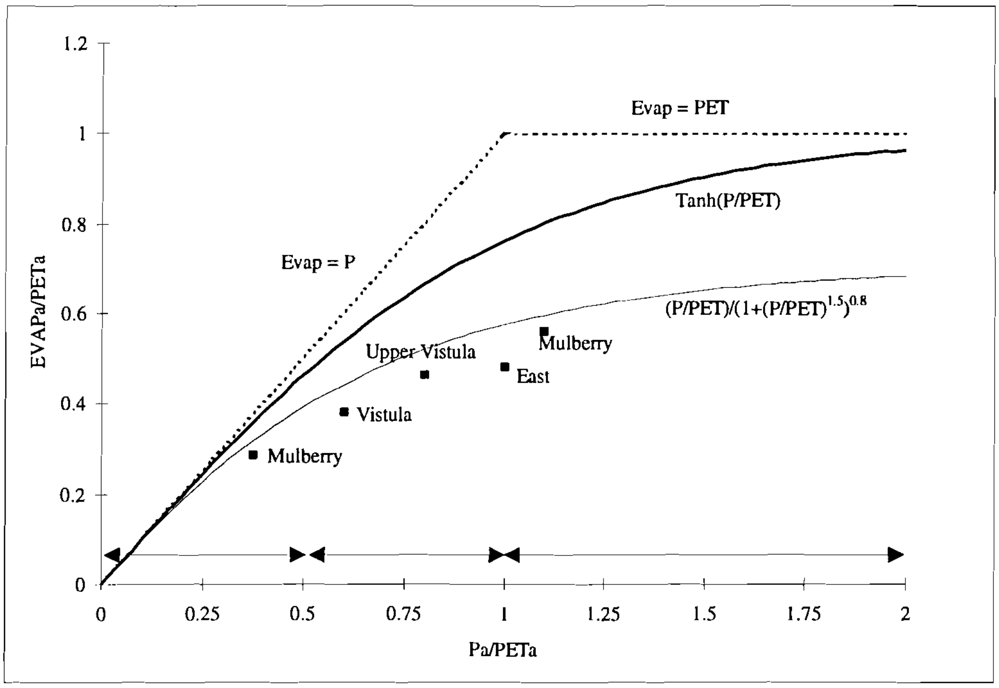


Figure 1. A plot of the observed annual values for the five different basins and the hyperbolic tangent model (Dooge, 1992). Basin points are plotted as the ratios of annual average observed evapotranspiration, potential evapotranspiration (by modified Penman) and precipitation. Hotter, more arid regions plot on the left of Figure 1 because potential evapotranspiration dominates (Blue Nile). Moving right the ratio of Pa/PET grows. Colder and/or more humid climates will plot further to the right, as potential evapotranspiration becomes small in comparison to precipitation. The function $(P/PE)/(1+P/PE^{1.5})^{0.8}$, closely fits the plot of these basins.

Water Balance Approaches

The second method for the impact of climate on basin discharge incorporates interannual variability by accounting for changes in catchment storage. These are physically based approaches and two different models are investigated here. The common link in most water balance approaches is the computation of a mass balance within the soil moisture zone. There are many ways of representing the infiltration, discharge and storage behavior of the soil moisture zone (Rawls et. al, 1993; Chow, et. al, 1988; Shaw, 1983). The two lumped integral models use different approaches to model soil moisture, yet each makes use of potential evapotranspiration to drive its extraction (actual evapotranspiration). A modified Penman equation was used to compute potential evapotranspiration (Leemans and Cramer, 1991; Shuttelworth, 1993). Only temperature was altered within the Penman equation, while the other input parameters; wind speed, relative humidity, and sunshine hours, were applied uniformly over the month. Mean monthly values were taken from the IIASA database (Leemans and Cramer, 1991). It has been shown that some basins are quite sensitive to the estimation of PET, so an accurate representation is important (Yates and Strzepek, 1994; Dooge, 1992).

Water Balance Model (WatBal)

Kaczmarek (1991) developed the framework for the first conceptual models that was used for this study. The approach was adapted and integrated into a climate impact assessment tool for studying river basin response to climate change (Yates, 1994). The uniqueness of this lumped conceptual model to represent the water balance is the use of continuous functions of relative storage to represent surface outflow, sub-surface outflow, and evapotranspiration. In this approach the mass balance is written as a differential equation and storage is lumped as a single, conceptualized "bucket" (Figure 2) with the components of discharge and infiltration being dependent upon the state variable, relative storage (10) The model contains five parameters: 1) β, direct runoff; 2) ε, surface runoff; 3) α, subsurface runoff; 4) S_{max}, maximum catchment water-holding capacity and 5) base flow.

For the computation of effective precipitation in regions where snowmelt makes up a substantial portion of the runoff water, a temperature index model similar to that described below was used with the upper and lower temperature bounds defined by trial and error (Ozga-Zielinska, 1994). This water balance model is described below.

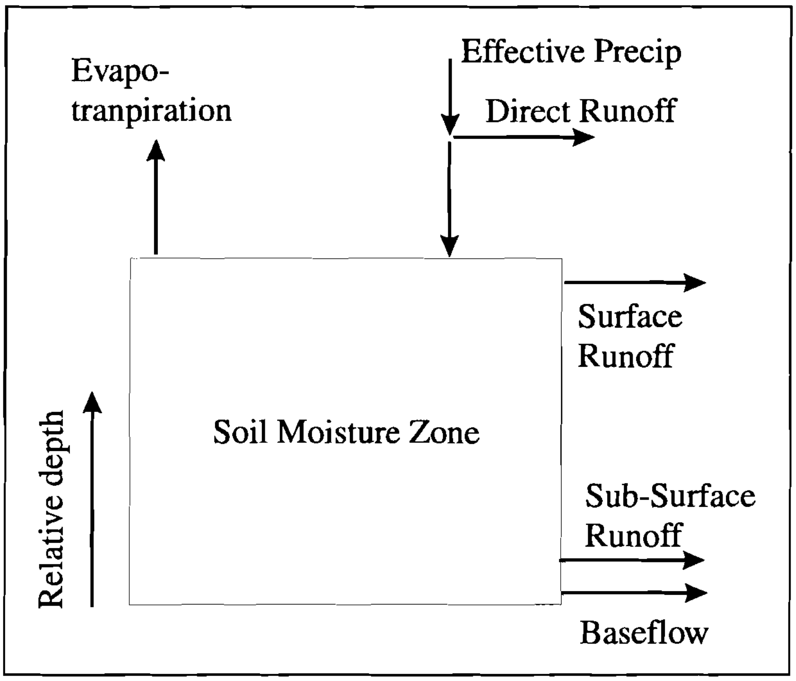


Figure 2. Conceptualization the water balance for the WatBal model

Direct runoff (R_d) is given as:

$$R_d = \beta P_{eff} \tag{8}$$

The soil moisture balance is written as:

$$S_{\max}\frac{dz}{dt} = \left(P_{peff}(t)(1-\beta)\right) - R_s(z,t) - R_{ss}(z,t) - Ev(z,t) - R_b \tag{9}$$

P_{eff} = Effective Preciptation (length / time)

R_s = Surface runoff (length / time)

R_{ss} = Sub - Surface runoff (length / time)

Ev = Evaporation (length / time)

R_b = baseflow (length / time)

S_{max} = Maximum storage capacity (length)

z = relative storage ($0 \le z \le 1$)

The Continuous functional forms that are used in equation 9 are:

1. Evapotranspiration - E_V:

Evapotranspiration is a function of Potential Evapotranspiration (PET) and the relative catchment storage. A non-linear relationship has been used to describe evpotranspiration (Kaczmarek, 1993).

$$Ev(z, PET, t) = PET\left(\frac{5z - 2z^2}{3}\right) \tag{10}$$

2. Surface Runoff - R_S:

The first parameter of the model, ε, is introduced here in the surface runoff term, R_S. Surface runoff is described in terms of the storage state, z, the effective precipitation, P_{eff}, and the baseflow.

$$R_s(z, P, t) = \begin{cases} z^{\varepsilon}(P_{eff} - R_b) & \text{for } P_{eff} > R_b \\ 0 & \text{for } P_{eff} \le R_b \end{cases} \tag{11}$$

3. Sub-Surface Runoff - R_{SS}:

Sub-surface discharge is a function of the relative storage state times a coefficient, α. In most cases, the value of γ is 2.0, however it was observed that for some basins (East) a value γ smaller than 2.0 greatly improved calibration. As γ approaches 1.0 the sub-surface discharge responds more linearly with relative storage, indicating a decrease in the holding or retention capacity of the soil. A value of γ less than 2.0 might be for gravel dominated basins such as that found in the East River.

$$R_{ss} = \alpha z^{\gamma} \tag{12}$$

The 4th model parameter is the maximum catchment holding capacity, S_{max}. The storage variable, Z, is given as the relative storage state: $0 \le Z \le 1$. Referring to figure 2, S_{max} is defined as the maximum storage volume, so when S_{max} is multiplied by z, the current storage volume for the period is given. Baseflow is given as the flow that is exceeded 95% of the time. Total runoff, for each time step, is the sum of the four components:

$$R_t = R_s + R_{ss} + R_b + R_d \tag{13}$$

Watbal uses a predictor-corrector method to solve the differential equation (Carnale and Chapra, 1988). The model is calibrated using a unconstrained heuristic algorithm which finds an optimal set of model parameters while meeting the criteria of minimizing the root mean square error between the observed and predicted monthly runoff value.

Basin Conceptual Model (BCM)

A second lumped integral model was also used that incorporates a simple mass balance in conjunction with a temperature-index snowmelt model (Ozga-Zielinska, et al, 1994). This is a monthly water balance model which uses multiannual monthly mean values of precipitation, temperature, potential evapotranspiration, and runoff. It uses a modification of the SCS method by taking into account an initial abstraction value based on the storage state of the soil in the previous month. It uses previous month storage to compute infiltration, evapotranspiration and runoff; therefore it does not need to be solved using a numerical method. It contains six parameters, with two of the parameters being the upper and lower temperature bounds on the freezing and melting process. An automated calibration routine minimizes the residual error between the observed and computed runoff.

Storage is written as:

$$S_{i-1} = Peff_i - S_i - Ev_i - R_i \tag{14}$$

effective precipitation is given by

$$Peff_i = \alpha_i(A_{i-1} + Pm_i) \tag{15}$$

where,

$$\alpha_i = \begin{cases} 0 & \text{for} \quad T_i \le T_s \\ 1 & \text{for} \quad T_i \ge T_l \\ \dfrac{(T_i - T_s)}{(T_l - T_s)} & \text{for} \quad T_s < T_i < T_l \end{cases} \tag{16}$$

and snow accumulation is written as,

$$A_i = (1-\alpha_i)(A_{i-1} + Pm_i) \tag{17}$$

Evapotranspiration, Ev_i, is given as;

$$Ev_i = PET_i\left(1 - \exp(-K_e\, S_{i-1})\right) \tag{18}$$

Runoff, R_i, is given in the winter season by (winter runoff condition prevails when $A_{i-1} > 0$ and $T_i < T_l$);

$$R_i = K_g S_{i-1} + K_w Peff_i \tag{19}$$

for the summer season, runoff is given by

$$R_i = \begin{cases} K_g S_{i-1} + \dfrac{(P_i - I_i)^2}{P_i - 4I_i} & for \ (P_i - I_i) > 0 \\ K_g S_{i-1} & for \ (P_i - I_i) \le 0 \end{cases} \tag{20}$$

where I_i - monthly total initial abstraction

$$I_i = \begin{cases} 0.2\left(\frac{1}{K_s} - S_{i-1}\right) & for \quad \left(\frac{1}{K_s} - S_{i-1}\right) > 0 \\ 0 & for \quad \left(\frac{1}{K_s} - S_{i-1}\right) \leq 0 \end{cases} \tag{21}$$

Model input data and state variables consist of:

$Peff_i$ = effective precipitation at time i (mm)
Pm_i = measured precipitation at time i (mm)
PET_i = Potential Evapotranspiration (mm)
S_i = Active basin storage in month i (mm)
R_i = Basin runoff in month i (mm)
A_i = Accumulation at time step i (mm)
α_i = Accumulation index $(0 \leq \alpha_i \leq 1)$
T_i = Temperature at time interval i (°C)

Model parameters consist of,

T_s = Solid snow threshold, completely frozen (≅ -3°C)
T_l = Upper temperature threshold, liquid above this value (≅ 3°C)
K_e = Evapotranspiration parameter
K_g = Active basin storage parameter
K_w= Winter basin runoff parameter
K_s = Inverse of the maximum river basin storage capacity (1/mm)

Regression Model (REG)

This model is a non-parametric regression relationship between precipitation, temperature and previous month runoff on a monthly time step (Ozga-Zielinska, 1994). This model falls within the first category of hydrologic models referred to as a stochastic method. In summary, the model develops a relationship between runoff in month ***i*** and temperature and precipitation in month ***i*** and the previous month runoff (*i-1*), where i is a multivariate random sample of size n.

$$\text{Reg}(R_i) = f(T_i, P_i, R_{i-1}) \tag{22}$$

The regression model assumes that the random variable R_i is related to a random vector of dimension k, here given as $\mathbf{X} = \{T_i, P_i, R_{i-1}\}$ (in the present case k = 3).

$$\{\mathbf{x_i}, R_i\} = \{T_i, P_i, R_{i-1}, R_i)$$

The conditional mean or regression of R on **X,** given **X=x** is:

$$\begin{aligned} &\text{reg}(\mathbf{x}) = E(R|\mathbf{X} = \mathbf{x}) \\ &or \\ &\text{reg}(\mathbf{x}) = \frac{1}{g(\mathbf{x})}\int_{-\infty}^{\infty} R\, f(\mathbf{x}, R)dR \end{aligned} \tag{23}$$

where g(**x**) is the marginal density of **X** given by;

$$g(\mathbf{x}) = \int_{-\infty}^{\infty} f(\mathbf{x},r)dr \tag{24}$$

and the conditional density of R given **X=x** is

$$f(r|\mathbf{x}) = \frac{f(\mathbf{x},r)}{g(\mathbf{x})} \tag{25}$$

The estimator of the unknown joint density is given by f$'$(**x**,r)

$$\hat{\mathrm{f}}(\mathbf{x},\mathrm{r}) = \frac{1}{\mathrm{n}}\sum_{i=1}^{n}\frac{1}{h_r}K\left(\frac{r-r_i}{h_r}\right)\prod_{j=1}^{k}\frac{1}{h_{x_j}}K\left(\frac{x_j - x_{ji}}{h_{x_j}}\right) \tag{26}$$

and the estimator of the marginal density g$'$(**x**) is given by;

$$\hat{\mathrm{g}}(\mathbf{x}) = \frac{1}{\mathrm{n}}\sum_{i=1}^{n}\prod_{j=1}^{k}\frac{1}{h_{x_j}}K\left(\frac{x_j - x_{ji}}{h_{x_j}}\right) \tag{27}$$

where K() is the gauss kernal function and $h_{\mathbf{r}}$ and $h_{\mathbf{x}}$ are smoothing factors,

$$K(z) = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{y}{2}\right)^2 \qquad \text{for} \quad -\infty < z < \infty \tag{28}$$

The non-parametric estimator of the regression function is given by,

$$\mathrm{r\hat{e}g}(\mathbf{x}) = \frac{\sum_{i=1}^{n} r_i \prod_{j=1}^{k}\frac{1}{h_{x_j}}K\left(\frac{x_j - x_{ji}}{h_{x_j}}\right)}{\sum_{i=1}^{n}\prod_{j=1}^{k}\frac{1}{h_{x_j}}K\left(\frac{x_j - x_{ji}}{h_{x_j}}\right)} \tag{29}$$

Impact of Models on Climate Change Assessments

To test the various modeling approaches, several river basins were selected with a range of climatic and geographic variability. Selecting basins with diverse characteristics will help to determine how robust is a particular model.

Basin Descriptions

Five basins of different scale and climatological characteristics were selected. These included the Blue Nile river basin of Africa , the Vistula river basin in Poland, the Upper Vistula sub-basin in Poland, the East River, a tributary of the Colorado River, in Colorado, USA, and the Mulberry River, a tributary of the Arkansas River, in Arkansas, USA. These basins were selected because of their range of variability both geographically and climatologically (Figure 3). Selection criteria included basin size, varying climatic and basin characteristics, as well as time series data availability. Table 1 is a summary of a selected set of basin hydroclimatic variables. Precipitation, temperature and runoff are given as annual means. The runoff coefficient is given as; $\Phi = R_a/P_a$. A brief description of each basin is given below

Blue Nile

The Blue Nile Basin (Lat 12°N Long 36°E) is in a temperate, semi-arid region with little variation in temperature. The mean monthly precipitation record reveals that precipitation comes during a three month "rainy season", while the remaining portion of the year is quite dry (figure 4.a). The Blue Nile Basin covers an area of approximately 325,000 km^2 (Shahin, 1985). Although the annual precipitation is quite high, in some places probably reaching 1500 mm year, the average annual runoff for this basin is approximately 165 mm, giving a runoff coefficient of approximately 0.2. This can be attributed to very high evapotranspiration within the basin (Table 1; Figure 3 & 4a.). The assumption that a catchment area of 325,000 km^2 can be represented as a single, lumped basin is worthy of question, but Beven (1989) points out that the prediction of discharge response of a real world catchment to rainfall is not difficult, for all that is needed are a loss and a routing function. How the model responds to a variety of different events within the catchment is a better criteria for judgment. So although it appears ambitious to model an area this large, it will provide insight into the range of applicability of these models.

Table 1. Basin Characteristics: Summary Hydro-Climatic Data. *PET derived from modifed Penam

	Area (KM^2 x000)	T_a (°C)	P_a (mm)	R_a (mm)	PET* (mm)	Φ Roff
Blue Nile	325	24.2	782	162	2151	0.20
Vistula	194	7.3	482	182	784	0.38
Upper Vistula	51	7.7	670	287	827	0.43
Mulberry	9.7	16.2	1039	464	1636	0.45
East	7.5	-2.2	817	427	789	0.52

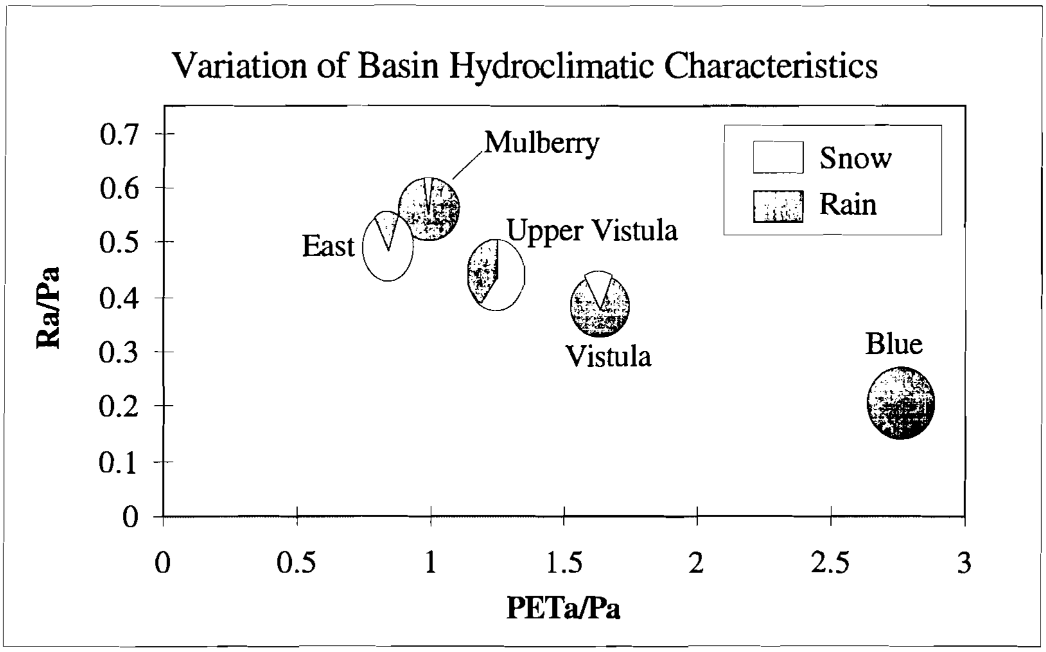


Figure 3. Basin Hydro-climatic Characteristics. The "arid" Blue Nile and East basins are the furthest outliers on Figure 3 from right to left; while the "humid" Mulberry basin plots the furthest to the top. An arid region has been defined by Shuttelworth (1993) as an area whose relative humidity during peak evapotranspiration is less than 60%, while a humid region has a relative humidity greater than 60% during peak evapotranspiration. Three basins that reside in more temperate zones (Vistula, Upper Vistula, and Mulberry) group more closely together as can be seen in Figure 3.

Vistula and Upper Vistula

The Vistula basin (Lat 52°N, Long 20°E), covers an area of 194,376, km^2 (87% within the boundaries of Poland). The area can be divided into main water sheds; with the southern portion of the basin residing in a mountainous area and the northern portion of the basin characterized by high and low lands and numerous lakes (annual precipitation ranging from 500 to 600 mm and mean annual air temperature 7.5°C). The entire Vistula basin has a runoff coefficient of approximately 0.30. The monthly mean discharge (Figure 4.b) reveals the rather constant discharge of this basin. This is also true of the Upper Vistula sub-basin, which is described below.

The Upper Vistula basin is one of the four sub-basins of the Vistula with an area of 50,732 km^2 (Table 1). This area is the southern most portion of the basin with the most climatological diversity due to variations in elevation (maximum altitude of 2500 m, annual precipitation ranging from 600 to 1600 mm, mean annual air temperatures from -0.8 to 8.0° C). The entire Vistula Basin has a runoff coefficient of 0.30, while the Upper Vistula coefficient is approximately 0.43, (attributable, most likely, to the fact that the Upper Vistula is located in a mountainous region).

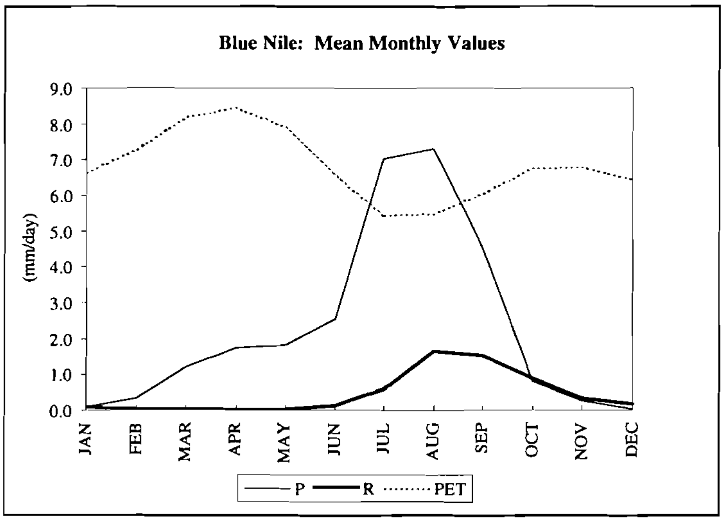
Mulberry

The Mulberry basin in Arkansas USA. is a substantially smaller catchment than those described above and is found at Lat 35°N Long 94°W. This is a moderately temperate climate, with a mean annual air temperature of approximately 16°C and only a few incidents of winter mean monthly air temperatures dropping below 0°C. The region is characterized by dense ground cover and has little variation in elevation, with the gauging station located at

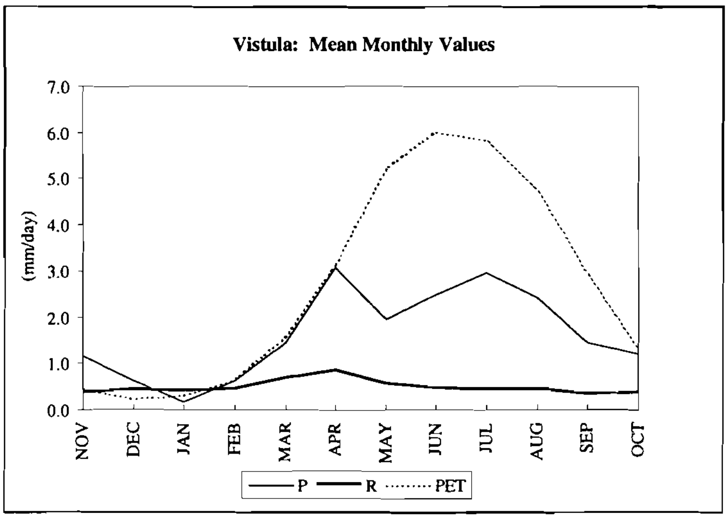
342 m above sea level. The basin area is a little less than 1000 km^2, making it a relatively "small" catchment. Although Nemec and Shaake (1982) state that modeling such basins should produce minimum error, the climate of this basin produces an interesting runoff characteristic that can be observed in Figure 4.d. Although the overall runoff coefficient is approximately 0.44; the winter season coefficient is as high as 0.70, while the summer season's runoff coefficient drops to below 0.20. This large seasonal change is difficult to model when using models with a limited number of parameters.

East

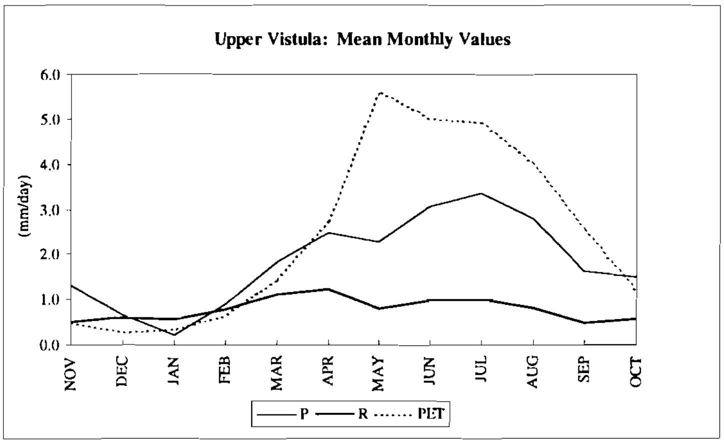
The East river in Colorado (Lat 40°N Long 105°W) USA. is a tributary of the Gunnison River basin and was the smallest catchment modeled. This basin resides within the Rocky Mountain Range, with most of the basin above 3000m. Although considered a semi-arid region, the runoff coefficient for this basin is highest of those selected because most of the basin runoff comes in the form of spring snowmelt. This can be seen from Figure 3, as this basins plots to the extreme left in this figure. The climate station for this basin is located in the Gunnison Valley (elevation 2500m), and so the precipitation records were adjusted to reflect the effect of elevation on precipitation by multiplying the precipitation record by 1.33 in the winter months, November to March (Gray and Prowse, 1993).



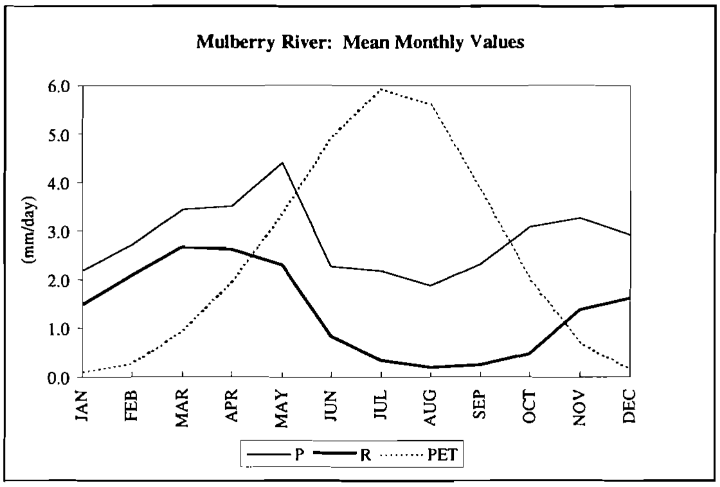
a. Blue Nile



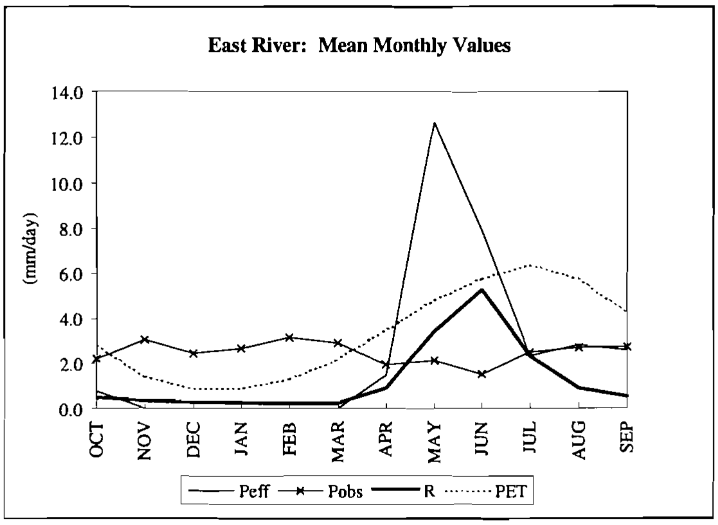
b. Vistula



c. Upper Vistula



d. Mulberry River



e. East River

Figure 4.a-e. Monthly mean values, computed from the time series used for both calibration and validation, for all five basins. The plots include observed discharge, potential evapotranspiration (using modified Penman) and effective precipitation. The East River includes the observed precipitation and the effective precipitation to show the strong influence of snowmelt in this basin.

Calibration and Validation

For all five models, a calibration and validation procedure was used to test the validity of each model. Gleick (1987) points out that the water balance model should 1) reproduce reasonably well the historic streamflow and 2) simulate the streamflow under climatic variability. So we look to how well the model performs with the calibration data set and then look to the validation data set to see if the model can capture varying hydrologic conditions. Gleick (1987) identifies two tests for model evaluation. The first is the split sample test which splits the hydrologic record into two segments, one used for calibration and the other for validation. If the statistical values derived from the calibration and validation procedure are similar (correlation coefficient and monthly error) then the model is deemed acceptable. The second test is the differential split sample test. This test is applied when base conditions are to be changed. For example if the model is to be used to assess a "warmer and wetter" climate, then the model should be calibrated for a "dry, cool" period of the historic record and then validated for other events in the record. Also, the split sample test could calibrate on average conditions (the entire record) and then verified by evaluating the errors in dry and wet periods, thus using the entire record for calibration.

For the calibration process used here, the split sample test was used for all basins. Because of the short record for the East river, the first 7 years were used for calibration and the reaming three year were used for validation (calibration: 1979-1985; validation 1986-1988). For both the Blue Nile, Vistula, and Upper Vistula, 26 years of data were selected. The first 13 years of data were used for calibration and the next 13 years were used for validation. For the Mulberry river, 40 years of data were available from 1948 to 1987; the first 20 years were used for calibration and the second 20 for validation. Table 2 gives the results from this calibration/validation procedure for the 5 models and for the five basins. For the two annual models a calibration procedure was also performed, but because annual values are used the criteria for calibration was only checking the mass balance.

The correlation coefficient and the average monthly error are used to describe model performance. The correlation coefficient is given by:

$$\rho_{Q_o,Q_p} = \frac{Cov(Q_o,Q_p)}{\sigma_{Q_o}\sigma_{Q_p}} \tag{30}$$

where, $Cov(Q_o, Q_p)$ is the covariance of the observed and modeled discharge and σ_{Qo} and $\sigma_{Q\mathrm{p}}$ are the standard deviation of the observed and modeled series. The average monthly error between the predicted and observed discharge is given by

$$E_{p,o} = \frac{\sum abs(Q_p - Q_o)}{n} \tag{31}$$

where;

Q_o = Observed monthly discharge
Q_p= Model prediction of monthly discharge

Table 2. Results of calibration and validation procedure for the 5 basins. Avg. Err is given in (mm/month). *Error for the annual models is given as the percent change in runoff over the validation period, where the percent change in the calibration period will always be 0%.

		WatBal		BCM		REG		*TRC	*HT
		Calib	Valid	Calib	Valid	Calib	Valid	%	%
Blue Nile	Correl	0.95	0.93	0.93	0.90	0.99	0.94	-4	-4
Africa	Avg. Err	3.6	3.8	4.9	5.1	1.3	2.8		
Vistula	Correl	0.76	0.76	0.87	0.75	0.92	0.59	-7	10
Poland	Avg. Err	4.2	4.1	2.8	3.8	2.3	4.4		
Upr Vistula	Correl	0.74	0.79	0.82	0.73	0.95	0.67	7	-7
Poland	Avg. Err	8.3	7.7	6.4	6.9	3.5	6.5		
East	Correl	0.98	0.95	0.90	0.85	0.99	0.87	-4	-16
CO. USA	Avg. Err	10.3	9.6	13.3	13.5	2.1	13.0		
Mulberry	Correl	0.85	0.82	0.85	0.84	0.97	0.36	-9	11
AR. USA	Avg. Err	23.0	26.0	21.0	23.0	12.2	36.0		

Table 3 shows the strength of the physically based approach, where the percent difference between the calibration and validation series for WatBal and BCM were 3.5 and 7.6 respectively. The regression model was superior under calibration, but performs poorly under validation with a 65 percent difference between the two; clearly pointing to the weakness of the regression model in performing climate sensitivity analysis. On average WatBal was the best in comparison to the other three models; although Table 2 shows that it performs better in the two semi-arid basins where there is a strong seasonal precipitation and runoff pattern (Blue Nile and East), while the BCM appears to perform better in the more humid basins (Vistula, Upper Vistula, and Mulberry). The percent difference between calibration and validation was lowest for the WatBal model, allowing it to be described as the "most robust" of the three time series based approaches. Of the two annual models (Turc and the hyperbolic tangent), the Turc model consistently produced the largest percent change in observed versus modeled outflow (Table 2). However, a better measure of these two approaches is to see how they performed under the climate change scenarios.

Table 3. Average error of all five basins for the 3 time series models along with the percent difference between the calibration and validation series.

WatBal			BCM			REG		
Calib	Valid	% Diff	Calib	Valid	% Diff	Calib	Valid	% Diff
9.9	10.2	3.5	9.7	10.5	7.6	4.3	12.5	65.0

Blue Nile

A 26 year portion of the Blue Nile historical record was used for this study. The model was calibrated against the first 13 years of the 26 year time series. Only monthly time series data were available so no results are reported using a daily model. Figure 5 is a plot of the annual precipitation, temperature and runoff for the Blue Basin. There is an interesting portion of the series which contains a series of higher temperature years, 1953-1957, which were preceded by a series of low precipitation years, 1950-1956, (Figure 5). The precipitation and temperature records are derived from three record points for the entire Blue Basin which is over 325,000 km^2. It is probable (Figure 5) that these three sparse records do not provide enough information for predicting basin discharge. This is most evident when examining the last portion of the record, where there appears to be a change between the correlation of precipitation and discharge. This behavior is difficult to explain, but the sparse precipitation record might not capture spatial variations in precipitation that probably occur over this basin. In this case, it would be beneficial to sub-divide the basin into sub-basins to increase the spatial resolution. However, detailed data for the Blue Nile on the subcatchment level is not available. Figure 5 reveals that with the scale of the Blue Nile, information has been lost in the aggregation of the precipitation record, as the monthly precipitation events and the corresponding temperature series can not explain the large decreases in Blue Nile flow for the period 1965-1969. Conway and Hulme (1993) observe that from 1965 onward there was a prolonged period of low flows. Surprisingly, they note, the magnitude of the temporal trends present in the runoff time series do not occur in the precipitation time series. They state, "The estimate of catchment precipitation for the Blue Nile is questionable. The vast area, poor density, quality and record length, combined with high spatial variability of precipitation all make it difficult to obtain an accurate estimate of true catchment precipitation."

The overall mass difference for the 26 year period is less than 5% for the lumped models, but from Figure 6 it appears that the lumped conceptual models, although definitely following the historical discharge trends, tend to over predict fluctuations in basin discharge. In spite of its large area, modeling at a monthly time-step for the Blue Basin can be justified. The basin is characterized by steep slopes and quick runoff response to the large precipitation events in the rainy season.

Inspite of some of the difficulties of scale in the Blue Nile, it is interesting to note that the statistical values derived during calibration and validation are good for this basin. This can be easily explained by examining the nature of the monthly mean runoff hydrograph (Figure 4a) which shows strong seasonality by the high flows during the short rainy season. Because of the nature of this basin, high correlation and low error are achieved because of the consistency of floods during this period.

The two physical models performed similarly in the Blue Nile Basin. Both tend to over exaggerate basin discharge response to changes in precipitation. The large decrease in discharge predicted by the models is related to the large decrease in precipitation in combination with an increase in basin temperature (Figure 5). The regression model gave superior results under calibration, but tends to overpredict discharge during validation. The regression model includes the temperature variable and temperature is not strongly correlated to runoff in the Blue

Nile, so the regression model tends to exaggerate the dependency of temperature on runoff. The calibration and validation statistics for the annual models are given in Table 2, where both produce an error of approximately -4% total discharge over the validation period. Because of the unique characteristics of the historical record, definitive conclusions regarding climate change impacts on the Blue Nile Basin are difficult to draw.

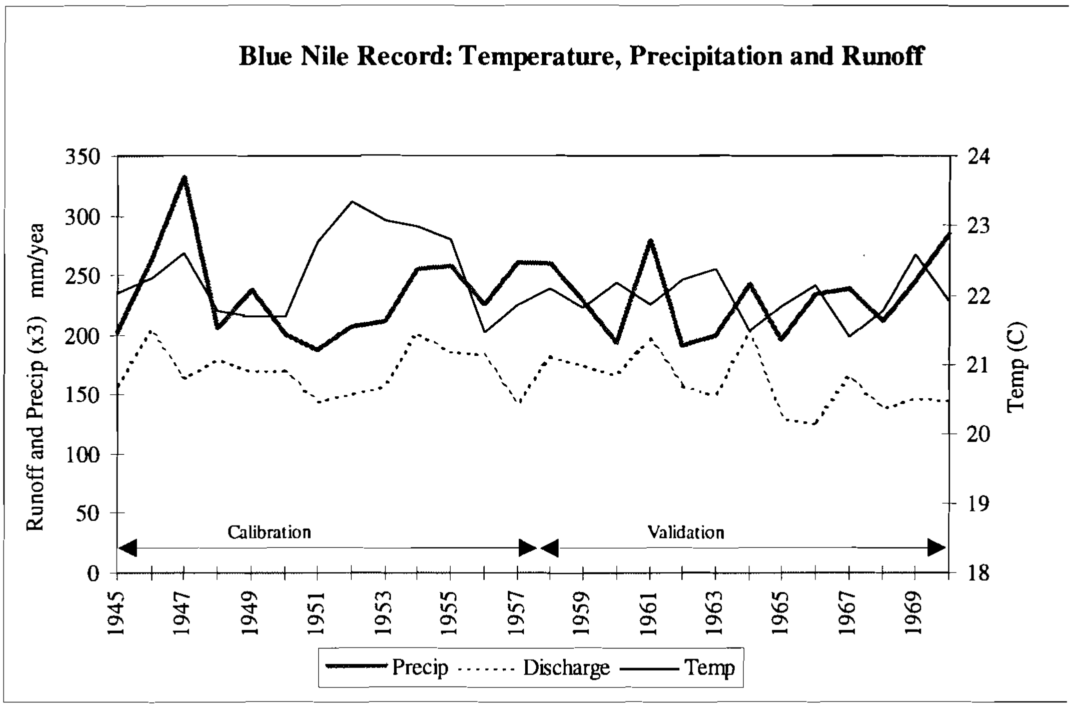


Figure 5. Blue Nile Record, annual runoff and precipitation (the precipitation is scaled by a factor of three) and mean annual temperature for the 26 year record used for the Blue Nile

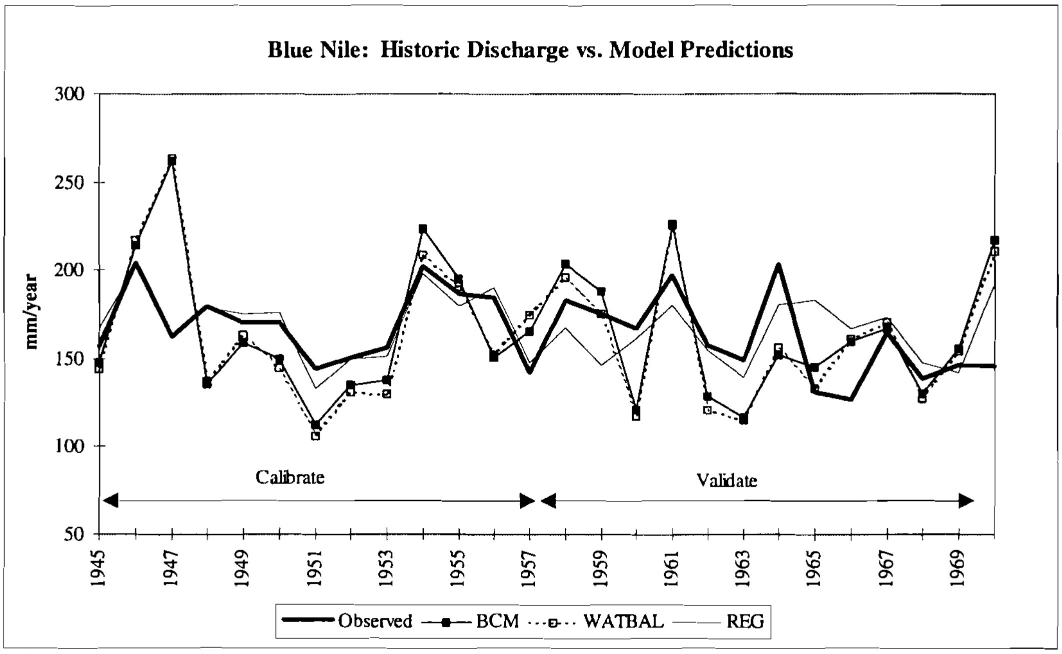


Figure 6. Blue Nile model predictions vs. observed discharge

Vistula and Upper Vistula

The climatological record for the Vistula and Upper Vistula basins covers the period 1955 - 1980. Because the Upper Vistula is a catchment within the Vistula basin, the calibration and validation results are combined. The hydrologic year begins in November, when it is assumed that snow accumulation is zero. Figures 7 and 9 are the annual temperature, precipitation, and runoff records for these basins. Interestingly, the precipitation and temperature records show strong correlation in both basins ($\approx$0.6). The precipitation record for the years 1958, 1959, and 1960 shows no significant increase while the temperature record shows a modest increase. However, for this period the discharge record shows a substantial increase in basin discharge. Since the lumped-physical models are only making use of two pieces of information, precipitation and temperature to compute runoff, these models will always have a difficult time capturing these types of discharge changes. A question arises out of this problem: Are these types of changes due to climatological variations, physical changes in the basin (land use), misrepresentation of the basin due to spatial and temporal aggregation, or are there historical errors in the data?

All models perform adequately during the calibration phase. The physical models matches closely with the observed discharge until 1975, after which models tend to underpredict basin discharge. For most of the record past 1975, there is a substantial increase in discharge without a substantial increase in precipitation or change in temperature. The regression model performs well under calibration but did perform well under validation.

From this record it appears that a large portion of the calibration period had a series of low flow years (1955-1966). In the first period of the validation sequence, a high flow was realized. A low flow period was observed beginning in 1973 and ending in 1975. After 1975 there appears to be a substantial increase in flows, where the average value from 1975 to 1980 was .51mm/day, compared with the entire sample average (1955-1980) of .48 mm/day. The precipitation record from 75-80 does not necessarily explain this increase in flow, as the mean precipitation from 1975 to 1980 was 1.70 mm/day as compared to 1.65 mm/day from 1955-1970. These values correspond to a 7.4% increase in basin discharge during the period 1975-1980 compared with only a 3.3% increase in precipitation (based upon the entire record), respectively. This discrepancies is very apparent when examining the model results for the validation period in Figures 8 and 10. The tail end of the discharge record reveals the large increase in basin flow and all three time series models fail to identify this large increase.

The WatBal and BCM model produce similar calibration and validation results for these basins (Figure 8, 10, and Table 2). From Figures 8 and 10, it is observed that WatBal tends to under predict while the BCM tends to over predict historic discharge. The regression model performed well under calibration for both basins, but for the validation series it tended to over predicted Vistula discharge and under predict Upper Vistula discharge. The calibration and validation results for the annual models are given in Table 2, where the error in the Vistula for the hyperbolic tangent model was slightly larger but with a sign change (-7% Turc, +10% hyperbolic tangent). In the Upper Vistula the situation was reversed with a +7% error in the Turc model and a -7% error in the hyperbolic tangent.

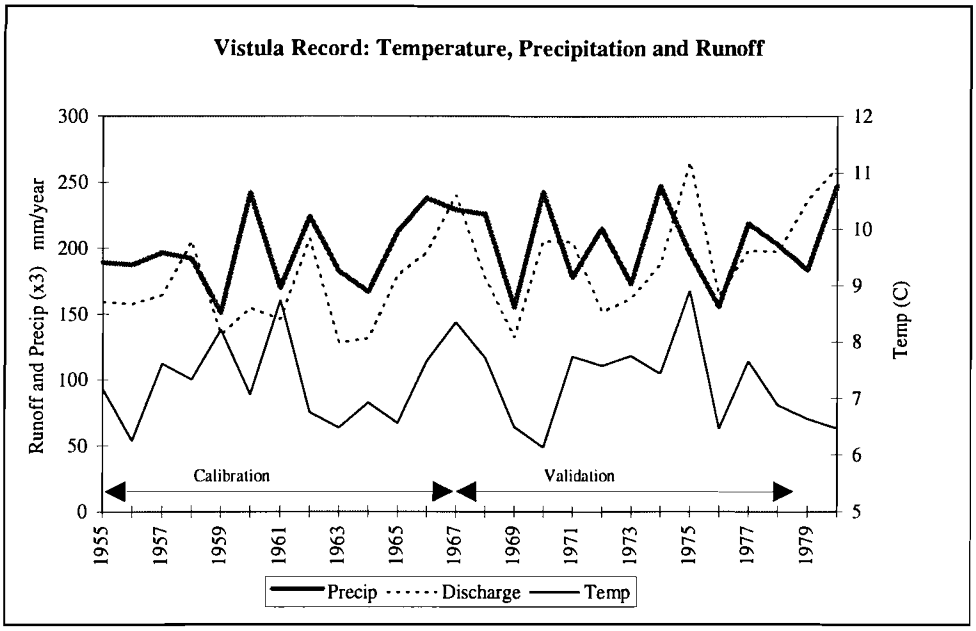


Figure 7. Vistula: Observed precipitation, discharge and temperature given as annual values

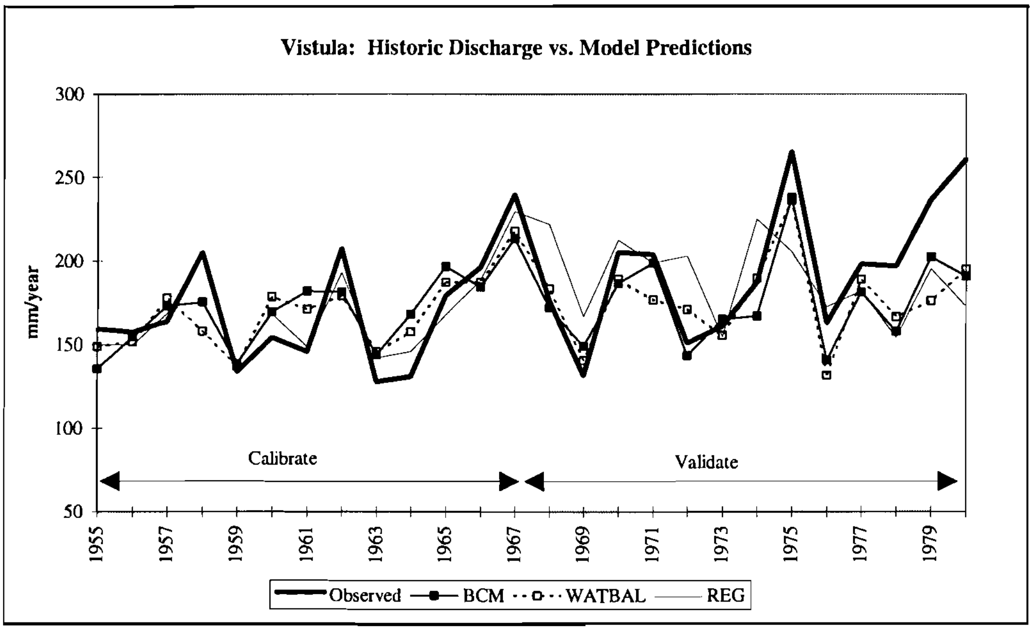


Figure 8. Vistula : Model Predictions vs. observed discharge of annual discharges

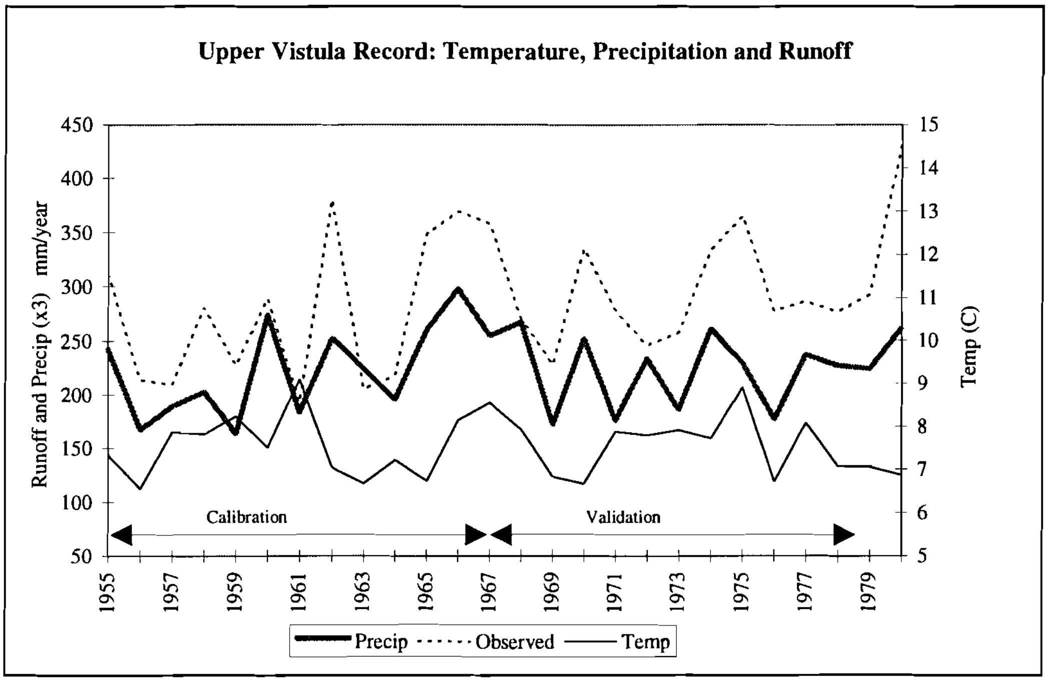


Figure 9. Upper Vistula: Climatological data given as 3-yr moving average

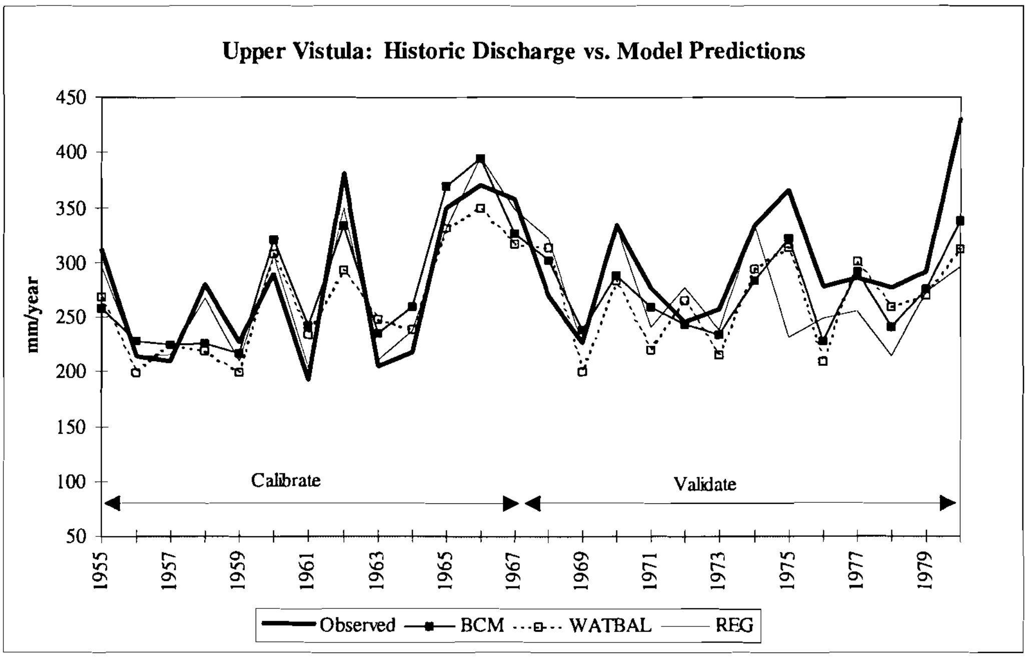


Figure 10. Upper Vistula: Model Predictions vs. observed discharge (3 yr. moving average)

Mulberry

The climatological record for the Mulberry River spans the years 1948 - 1987. Because of the availability of daily data, results for this basin are given for: 2 annual models, 2 lumped integral models on a monthly time step, 1 stochastic model on a monthly time step, and 1 lumped integral model on a daily time step. Additional conclusions are drawn using an analogous basin, the Leaf River in Mississippi USA (Nemec and Shaake, 1982). Figure 11 shows the annual values of temperature, precipitation, and runoff for this basin. The basin shows strong runoff response to moderate changes in precipitation and temperature. The period 1953 to 1958 shows a decrease in precipitation, an increase in temperature with a subsequently large decrease in discharge (Figure 11). Temperature is negatively correlated to runoff (-0.32), while precipitation, not surprisingly, is positively correlated (0.70). The annual precipitation, temperature and discharge record seems to indicate that the basin is possibly sensitive to even small temperature variations, as the two driest portions in the record are also the warmest (1954-1958 and 1964-1969). One portion of the record (1973 to 1977) has a large increase in basin discharge without a significant increase in precipitation or a substantial decrease in temperature and all models failed to reproduce this portion of the record (Figure 11).

A first modeling attempt of the Mulberry basin gave considerable error when attempting to match the historic runoff. It was assumed that the Mulberry precipitation record was given as gauge precipitation, therefore a interception value of 0.25 was used for the months, June, July, August, and September. This procedure produced an "effective precipitation" that was used for all model runs. After the derivation of effective precipitation, the model was again calibrated with a disturbing amount of error considering the use of monthly values. Figure 4d. is a plot of mean monthly values for the Mulberry River which displays the drastic reduction in discharge after the month of June. This is caused by high evapotranpsiration from water that was stored in the soil during the wet, winter months and high interception loses of summer precipitation due to forest canopy. As mentioned above, all models used the Penman method for estimating PET. The Penman method appears to over predict PET, particularly in the early spring when the soil moisture is near saturation. This can be observed from the monthly mean values shown in Figure 2d. In addition to over predicting the value of PET, it appears that the Penman method also over predicts the relative magnitude of PET in the spring period. This fact made calibration with the lumped models difficult. Because of the apparent sensitivity of this basin to temperature variation proper modeling of PET is critical (Yates and Strzepek, 1994).

The regression model for this basin returned good results for calibration but performed poorly under validation. In Figure 12 the calibration series for the regression model is hardly observable because it closely matches the historic discharge. However a large deviation is observed during the validation phase (Figure 12) and the error during validation is substantially larger than during calibration (Table 2). Error in the annual models was +11% for the hyperbolic tangent and -9% for the Turc relationship.

The WatBal model was also run using daily data in order to compare the difference between a monthly and daily time step. Nemec and Shaake (1982) point out that the shorter the time scale, the more significant the terms of storage become and it becomes harder to accomplish a mass balance. Ten years of daily data (1949-1958) were used - the first 5 for calibration and the second 5 for validation (Figure

13). Basin discharge during the period 1949-1953 was significantly higher than during the 1954-1958 period. The WatBal model generally overpredicts basin discharge during this dry perod. Although the calibration and validation statistics do not vary greatly, observation of figure 13 shows the poor performance of the model during the low flow period.

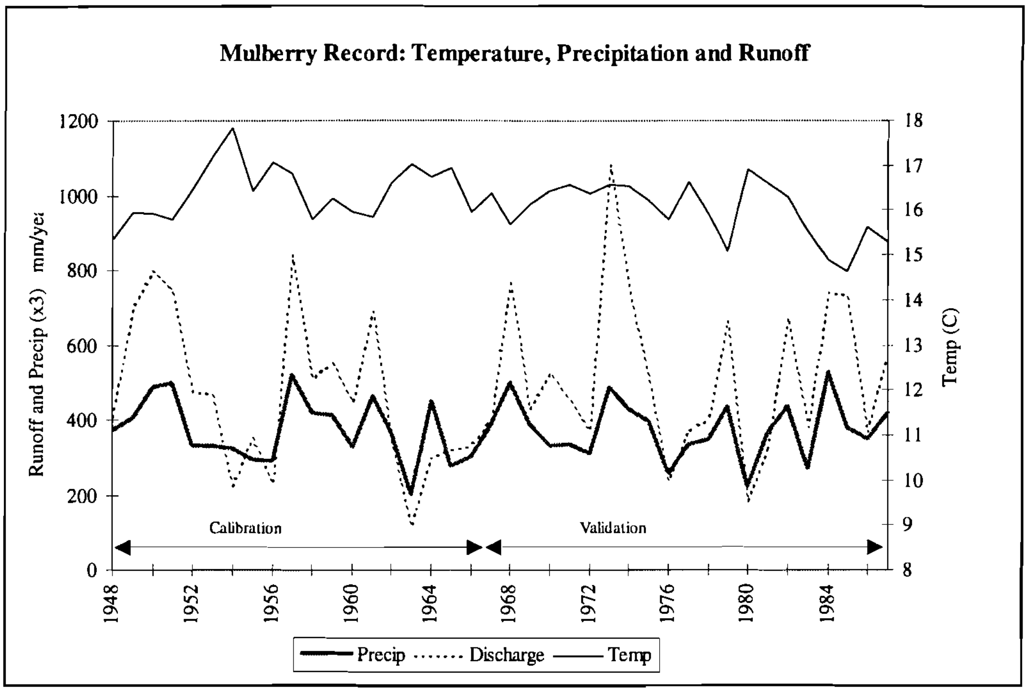


Figure 11. Mulberry: Climatological data given as annual values

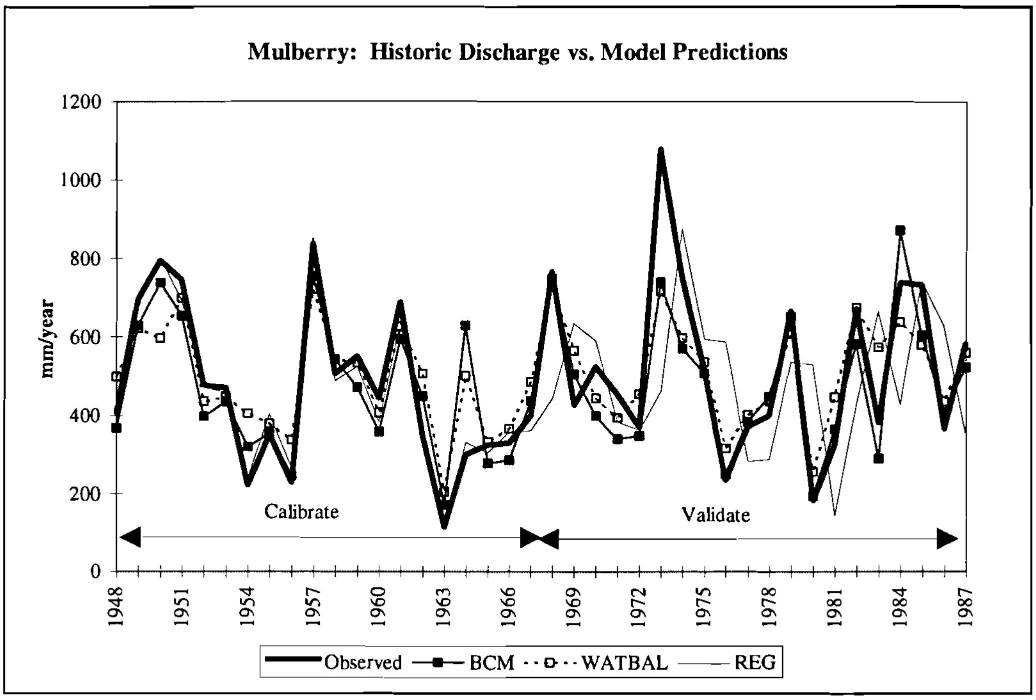


Figure 12. Mulberry: Model Predictions vs. observed discharge

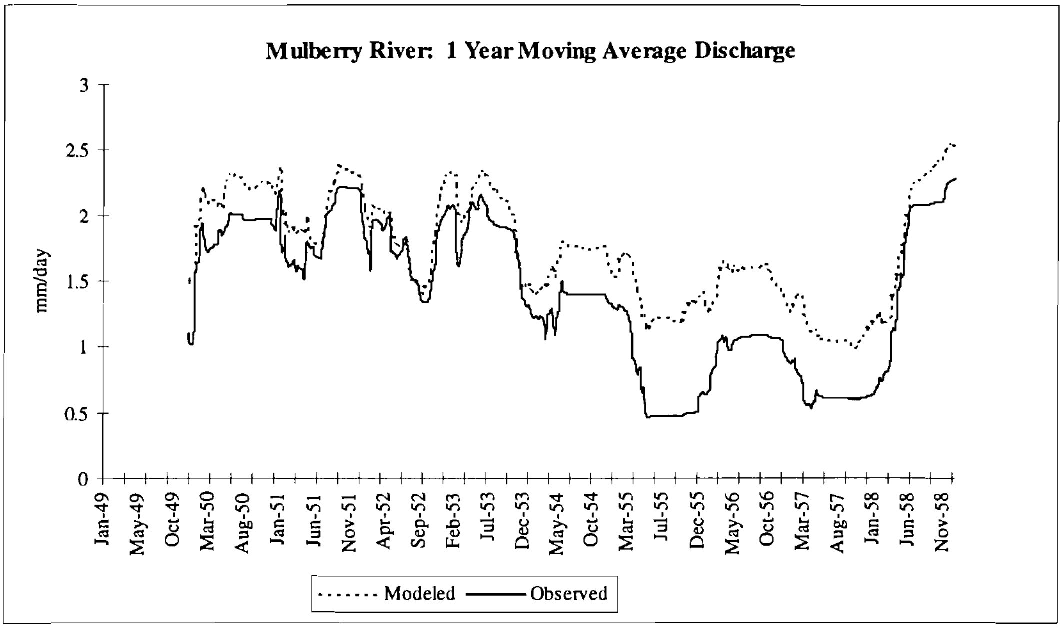


Figure 13. Mulberry river: 1 year moving average of daily discharge (observed) vs. model prediction. 1949-1953 is the calibration series (correlation coefficient = 0.81; average daily error = 1.0 mm/day). 1954-1958 is the validation series (correlation coefficient = 0.79; average daily error = 0.98 mm/day)

East

Data availability has made it possible to report results for the following models for the East River: 2 annual models, 2 lumped integral models on a monthly time step, 1 stochastic model on a monthly time step, 1 lumped integral model on a daily time step. Results from a distributed integral model with a 6 hour time step were also available (Nash and Glecik, 1993). Below is a discussion of the calibrations performed with the various models for this basin.

The climatological record for the East River spans the years 1979 - 1988. The hydrologic year begins in October, when it is assumed that snow accumulation is zero. Because the basin is located in mountinous regions, it is assumed that the guaging station underpridicts basin precipitation. For this reason winter precipitation values were increased by 60%. Figure 14 is the annual temperature, precipitation, and runoff for this basin. Figure 15 is a plot of the annual discharges for the three models and the observed discharge for the ten year calibration and validation series. Table 2 and Figure 15 reveal that the regression model performs well under calibration, but performs poorly under validation, as this model appears to exaggerate temperature fluctuations. This places into questions its applicability for climate change assessment. The validation error for the hypebolic tangent model was greatest in this basin (-16%), while the validation error with the Turc model was much smaller (-4%).

Although the calibration and validation statistics are reasonable for the BCM model, the models tended to be instable at low flows. Storage values would become negative with the BCM model producing negative runoffs. The WatBal model with a monthly timestep also produces reasonable calibration and validation statistics for this basin. Because the WatBal model uses the differential approach, the mass balance is inherently stable at low flows, as storage can not become negative.

The physically based monthly models were very sensitive to the definition of effective precipitation; a one or two degree variation can be significant in the representation of snow melt, which is used to derive the effective precipitation. Also, representation of the melting rate produces a significantly different runoff regime as represented by changes in model parameters. This was also seen when applying WatBal on a daily time step. In both instances, the main mechanism of runoff was subsurface discharge. One of the weaknesses of both the lumped models is their inadequate representation of seasonal variability in the soil moisture holding capacity. Spring runoff occurs over predominantly frozen soils, which has less holding capacity than the dryer summer soils. For the WatBal model, a single maximum holding capacity is specified, so in order to observe the high spring discharge, a smaller soil moisture capacity value must be given at the expense of high summer runoffs. Although the lumped models parameters loose some of their physical meaning, it is possible to achieve similar calibration results with significantly different calibration parameters. A large soil moisture holding capacity (S_{max}), combined with a large value for the sub-surface flow parameter, α, will give similar results to a smaller values of these parameters. When larger precipitaiton changes are prescribed, then the smaller values of S_{max} will give substantially more discharge due to the non-linearity. Therefore, understanding the mechanisms of runoff, even with a lumped model with automated calibration is important in a basin such as the East.

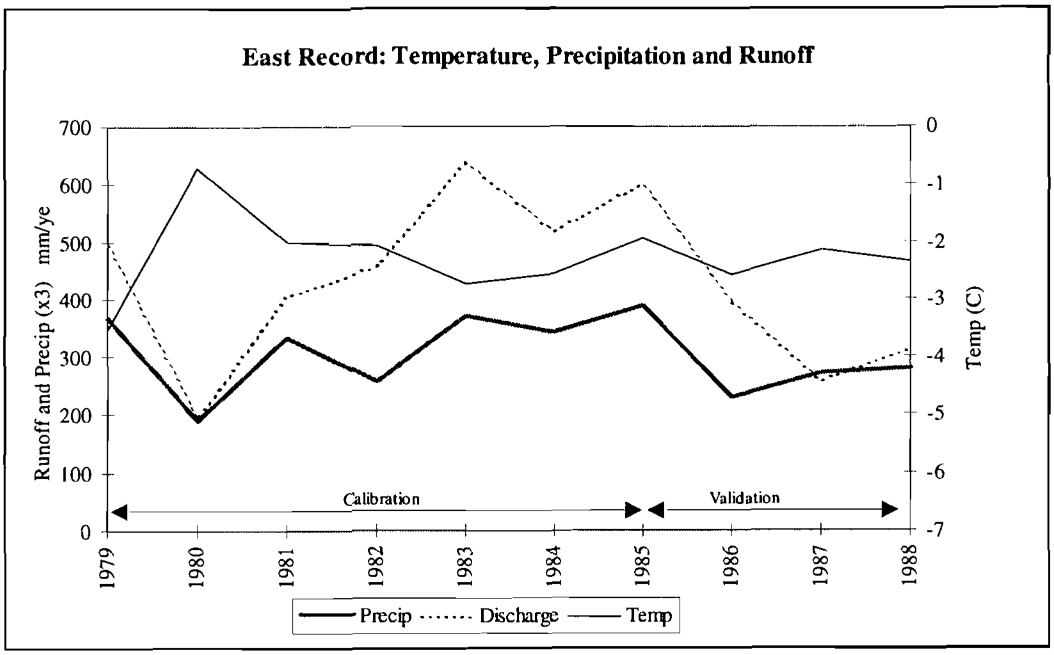


Figure 14. Annual values of runoff and precipitaiton (x3); and annual mean temperatures for the East River

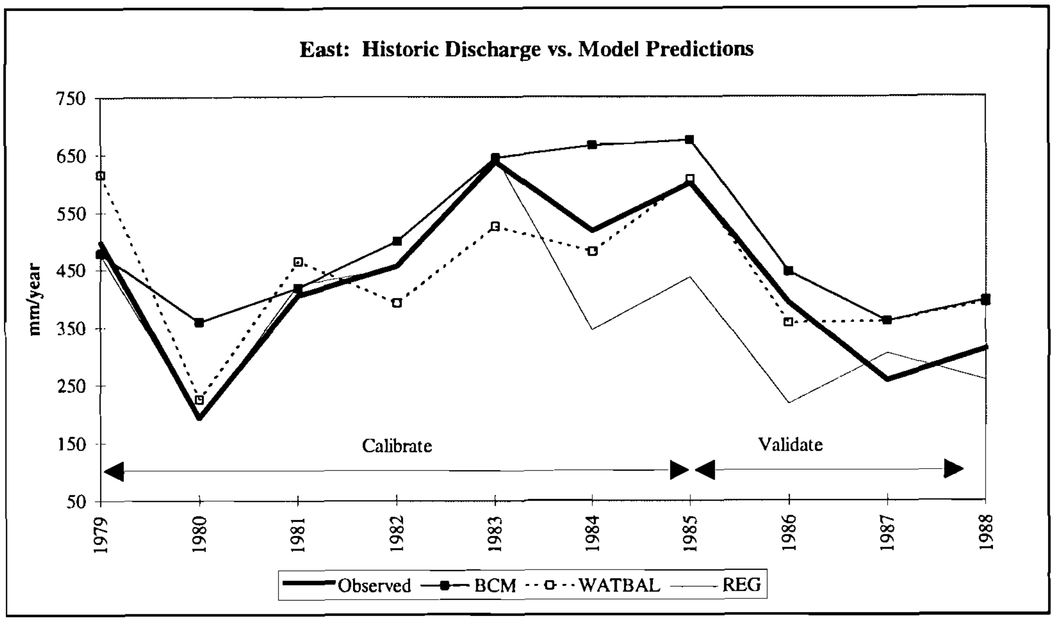


Figure 15. Model predictions vs. observed annual discharge using a monthly time step

The lumped integral model, WatBal, was used in daily mode to evaluate its applicability to smaller, snow melt driven basins (Figure 16). As previously mentioned, as the time step is shortened, the importance of properly modeling storage increases. This motivates the testing of the lumped model to see how well it will behave in this basin on a shorter time step. First it was necessary to calculate the effective precipitation based on snow melt. A modified daily snow melt function (32) was used, whose parameters proved to be very sensitive during the calibration procedure of the lumped model (Gray and Prowse, 1993). A shift of 1°C or 2°C in the value of T_b drastically shifts the runoff regime and requires recalibration to match the discharge record. This sensitivity pointed out the importance of properly representing the snow melt process, which is one of the keys to understanding climate change for a basin such as the East.

$$M_f = (A_{i-1} / A_{\max}) * M_r(T_i - T_b) \qquad (32)$$

where,
M_f = melting rate (mm/day)
M_r = melting rate constant (≈ 5.5 / °C day)
T_i = daily mean temperature °C
T_b = temperature threshold (≈ 0 °C)
A_i = accumulation (mm)

Observing the daily runoff hydrograph and the effective precipitation computed using the simple snow melt model, it is possible to "predict" the primary mechanisms of runoff with the lumped integral model. The basin is not an "event" driven basin, as the slower snow melt process produces an effective uniform precipitation that is discharged primarily as sub-surface flow (as defined by the model). The calibration procedure seems to indicate that this lumped model does not handle the storage mechanism in this basin well. The rapid decrease in discharge in June is followed by relatively large summer precipitation's that do not show up in the observed runoff hydrograph (this was one reason winter precipitations were assumed to be underestimated). This is possibly due to large interception by plants as well as changes in the soil moisture holding capacity when the soil matrix undergoes thawing. In order to account for this discrepancy the summer precipitation (June - Sept.) was reduced by 20%. Potential evapotranspiration was also reduced based on snow cover extent, where $PET_i = PET_i(1-(A_i/A_{max}))$

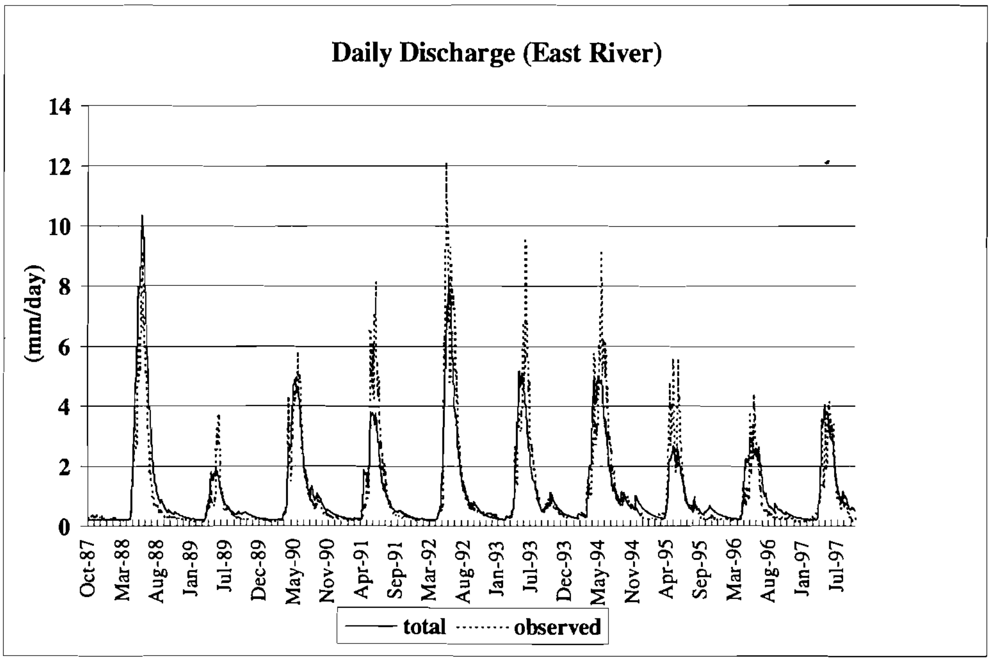


Figure 16. East River Daily runoff hydrograph (WatBal) vs. observed discharge.

Climate Change Scenarios

In order to arrive at plausible climate change scenarios when using a hydrologic model, the model should be capable of reproducing observed historical changes in runoff which can be explained by precipitation and/or temperature variations. This must be accomplished because precipitation and temperature are the primary climate variables that are used to assess the impact of climate change on basin runoff. Calibration and validation statistics might indicate that a model performed "satisfactorily", but it has been shown that it is difficult to explain historical variation in runoff due to precipitation and temperature changes. So climate change scenarios can only point to the possible sensitivity of the basin to marginal climate variations. Anthroprogenic variations in land use and/or land cover might dramatically change the runoff characteristics of the basin which would nullify models calibrated to the present climate, therefore results should be considered more qualitatively than quantitatively.

Scenario development for climate change impact assessment is usually performed in one of four ways (Niemann, et. at, 1994).

1. GCM based scenarios.	GCM derived adjustments to base climates.
2. Hypothetical scenarios.	Usually put in the framework of sensitivity analysis by applying an ensemble of potential climates.
3. Historical scenarios.	Data from historic periods that "mimic" a changed climate (if available)
4. Analog scenarios.	The changed climate in one location could be potentially similar to the climate in another location.

The first method above uses the gridded results from Global Circulation Models (GCM's) which give changes in climatological variables. Robock (1993) points out that the use of GCM results at the grid level is highly questionable, since most GCM's fail to even return plausible base case values, i.e. observed historical data does not match the GCM base results. Likewise, Lettenmaier and Gan (1990) state that GCM results are best interpreted as alternative climate scenarios and not predictions. A few generalized results of GCM's have been accepted in the scientific community. One of these generalizations is that greenhouse gasses will create a "warmer, wetter" environment in many places. This assumption generally leads to the second method of climate change analysis; an ensemble of scenarios. The ensemble of alternative, plausible climate scenarios can be used to examine the sensitivity of physical systems to climate change. In this spirit, the work here has chosen to look at 15 "plausible" climate scenarios. These scenarios will enable the generation of a family of tables that will give insight into the sensitivity of the basins and the models to climate variations. The scenarios chosen give uniform, annual changes in temperature (ΔT) and precipitation (%P) in the following combinations, with the expectation that they cover the range of plausible future climates (Table 4).

Table 4. Uniform Climate Scenarios Used

T +0 P+0 (base)	T +0 P+10	T +0 P+20	T +0 P-10	T +0 P-20
T +2 P+0	T +2 P+10	T +2 P+20	T +2 P-10	T +2 P-20
T +4 P+0	T +4 P+10	T +4 P+20	T +4 P-10	T +4 P-20

These scenarios were applied uniformly over the base data set for the entire record of each basin. It might be argued that it is possible to produce temporally disaggreated climate scenarios by investigating GCM results. However because of the uncertainty in GCM results, it was decided to apply uniform changes to the entire record for all simulations.

Blue Nile

Climate change results for the Blue Nile are given for the 2 monthly lumped models, the regression model and the two annual models. The lumped conceptual models produced very similar results, with basin discharge responding non-linearly to marginal changes in precipitation as low as +-10% (Table 5). As Nemec and Shaake (1982) pointed out for an arid basin in the U.S., the impact of precipitation changes is substantially greater than those caused by temperature fluctuations. This is relatively intuitive given the nature of the runoff hydrograph for the Blue Nile, where most of the runoff comes in a 3 or 4 month flood period, when soil moisture is high and runoff is large. The physical models, WatBal and BCM, indicated that a 20% drop in annual precipitation reduced flows by an average of 32% (ΔT=0° C). If a uniform temperature increase of C°2 and a C°4 are added to this precipitation change then there is an additional reduction in flow of 3% and 6% respectively. It appears for each ° C increase, there is a 3% decrease in annual flow (Table 5). In spite of the regression models good calibration, it was unable to produce reasonable results when climate scenarios were run. This is believed to be due to the lack of correlation between temperature and runoff in the Blue Nile, so the regression model overestimates the impact of temperature fluctuations while underestimating the impact of precipitation changes in this basin. The hyperbolic tangent model produces strong linear results and appears to under predict the impact of precipitation changes in the basin. The Turc model behaved similarly to the Turc model, although producing showing stronger impact under more extreme variability (Table 5). Gleick (1991) used a simple annual water balance model to determine the Nile's sensitivity to climate change and found for the Blue and Atbara region a 50% decrease in runoff under a 20% decrease in precipitation. Which from these results, seems to over estimate the impacts of precipitation changes on the Blue Nile.

BLUE	WATBAL	BCM	REG	HT	TURC
T+0 P+0	0%	0%	0%	0%	0%
T+0 P+10	19%	18%	4%	14%	11%
T+0 P+20	39%	39%	9%	28%	22%
T+0 P-10	-17%	-16%	-5%	-13%	-12%
T+0 P-20	-33%	-31%	-16%	-25%	-25%
T+2 P+0	-5%	-4%	-53%	-1%	-2%
T+2 P+10	13%	14%	-50%	11%	9%
T+2 P+20	33%	34%	-42%	26%	20%
T+2 P-10	-22%	-19%	-57%	-13%	-14%
T+2 P-20	-37%	-33%	-68%	-24%	-28%
T+4 P+0	-10%	-7%	-11%	-3%	-3%
T+4 P+10	8%	11%	3%	10%	8%
T+4 P+20	27%	30%	19%	23%	19%

Table 5. Annual climate change impacts on the Blue Nile Basin, Ethiopia: ΔT, %P

Vistula and Upper Vistula

Because of the seasonal uniformity of the basin discharge, and the spatial scale of the basin, these two basins were the least difficult to calibrate and perform climate sensitivity runs on. Only monthly data were available for the Vistula and the Upper Vistula Basin, so results are not reported for any model using daily data. WatBal and BCM produced similar results for the climate scenarios, although WatBal showed greater response to precipitation changes and BCM was slightly more sensitive to temperature fluctuations. The hyperbolic tangent model gave similar results to the water balance models. Surprisingly, the Turc model gave unrealistic results for climate change scenarios considering these basins seem to be close to the climatological environment in which the model was developed for. The regression model appears to underpredict the response of precipitation changes, while closely matching the results from the physically based models with respect to temperature fluctuations (Table 6 and Table 7). This can be explained by a stronger correlation between temperature and runoff for these basins (Figures 4.b&c).

VIST	WATBAL	BCM	REG	HT	TURC
T+0 P+0	0%	0%	0%	0%	0%
T+0 P+10	18%	14%	7%	16%	28%
T+0 P+20	37%	30%	13%	33%	58%
T+0 P-10	-15%	-13%	-10%	-15%	-27%
T+0 P-20	-29%	-25%	-10%	-28%	-52%
T+2 P+0	-4%	-5%	-5%	-3%	-23%
T+2 P+10	12%	8%	-1%	12%	5%
T+2 P+20	31%	23%	5%	29%	34%
T+2 P-10	-19%	-17%	-11%	-17%	-50%
T+2 P-20	-31%	-28%	-16%	-30%	-75%
T+4 P+0	-8%	-9%	-10%	-5%	-47%
T+4 P+10	7%	3%	-6%	9%	-19%
T+4 P+20	25%	16%	-1%	25%	11%
T+4 P-10	-22%	-21%	-15%	-19%	-74%
T+4 P-20	-33%	-31%	-20%	-31%	-99%

Table 6. Annual climate change impacts on the Vistula Basin, Poland: ΔT, %P

UPR VIST	WATBAL	BCM	REG	HT	TURC
T+0 P+0	0%	0%	0%	0%	0%
T+0 P+10	15%	15%	10%	13%	17%
T+0 P+20	31%	32%	23%	27%	35%
T+0 P-10	-14%	-14%	-6%	-13%	-16%
T+0 P-20	-26%	-27%	-18%	-24%	-31%
T+2 P+0	-4%	-6%	-5%	-2%	-9%
T+2 P+10	10%	9%	4%	11%	9%
T+2 P+20	25%	24%	16%	25%	26%
T+2 P-10	-17%	-19%	-14%	-14%	-25%
T+2 P-20	-29%	-31%	-25%	-25%	-40%
T+4 P+0	-8%	-11%	-13%	-3%	-17%
T+4 P+10	5%	2%	-6%	10%	1%
T+4 P+20	20%	20%	3%	23%	18%
T+4 P-10	-21%	-24%	-22%	-15%	-33%
T+4 P-20	-32%	-35%	-31%	-26%	-48%

Table 7. Annual climate change impacts on the Upper Vistula sub-basin, Poland: ΔT, %P

Mulberry

Climate change results for the Mulberry basin are given in Table 8. Of the five basins, the modeling results for this basin show the smallest variability. Interestingly, the annual model results compare closely to those of the physical models. Of the five basins modeled with Turc, the Mulberry basin returned the most reasonable results when compared to the physical models. This is not surprising considering that the relationship was developed for the climate of this basin type. The hyperbolic tangent model also produced similar results as compared to the physical models. The regression model produces similar results as compared with the other models except for the extreme ΔT4,%+20 case where it is substantially higher. Observation of Figure 11 shows a strong correlation between temperature, precipitation and runoff in this basin, so the regression model should perform best in this type of basin where correlation relationships are strong. The WatBal and BCM models produce interesting results, as WatBal showed greater sensitivity to temperature changes than did the BCM model. This points to the importance of properly representing soil moisture and the mechanism of runoff, even for simplified lumped models.

A comparison between the monthly and daily impacts using the WatBal model reveals that for this basin, the daily time step does not produce drastically different results when compared to the monthly time step (Table 8). One exception is that higher precipitation changes produce more runoff on the daily step (+6%) than the monthly step. The mean monthly discharge of the Leaf River near Collins Mississippi, with a drainage area of 1949 km^2, a mean precipitation of 1314 mm and a mean runoff of 409 mm, is shown in Figure 17 (Nemec and Shaake, 1982). Nemec and Shaake used the NWSRFS (Sacramento) model on a 6 hour time step. They did not produce results for a 4°C temperature change, but the results for a 2°C temperature change are given in Table 8. Their results conclude that the affects of changes in potential evapotranspiration (derived from temperature variations) have relatively less influence on the change in runoff than have the changes in precipitation. Interestingly, if we assume that the results for the Leaf River are similar to those of the Mulberry River there is a substantial difference between the results from a distributed integral and the lumped integral models. Nemec and Shaake report that the Leaf River, with an increase of 20% in precipitation and a increase of 2°C increases runoff by approximately 40%, where the monthly water balance models produce an average increase of approximately 29%. Yates and Strzepek (1994) point out that the method to determine potential evapotranspiration is critical when using the lumped integral models.

For the Mulberry Basin, an addition test was performed due to the availability of daily precipitation, temperature, and runoff data. The WatBal model was then used to perform a sensitivity analysis using this daily data. A comparison was then made between the results derived from the monthly data and those found at the daily time step. Analysis of the impact on climate change is given as the change in annual water (Table 8). One conclusion drawn from this comparison is that when assessing the impact of annual water availability, the use of daily data and a lumped integral model did not give significantly different results from those found using the monthly time step (with the lumped integral model). The greatest difference for any given scenario was only 6% (Table 8). This conclusion might not hold for all basins, but was found to be true for the Mulberry.

Nemec and Shaake (1982) report the results of a modeling effort for a similar basin in Mississippi which also exhibits this reduction. Because of the relatively close geographic location of these two catchments, a comparison is made between the results drawn from Nemec and Shaake (using a distributed integral model) and the results found in the modeling work done for this paper. Their conclusions show a much stronger impact on runoff due to precipitation changes than do the results of the modeling work on the Mulberry river reported here (Table 8).

MUL	Leaf (6hr)**	WB DAY	WB MON	BCM	REG	HT	TURC
T+0 P+0	0%	0%	0%	0%	0%	0%	0%
T+0 P+10	28	16%	16%	17%	19%	17%	13%
T+0 P+20	50	31%	33%	35%	31%	35%	26%
T+0 P-10	-20	-15%	-15%	-16%	-7%	-16%	-14%
T+0 P-20	-40	-28%	-29%	-32%	-23%	-31%	-29%
T+2 P+0	-10	-4%	-2%	-3%	-4%	-3%	-5%
T+2 P+10	20	12%	14%	14%	7%	14%	9%
T+2 P+20	40	27%	31%	31%	18%	31%	22%
T+2 P-10	-30	-17%	-17%	-19%	-18%	-18%	-19%
T+2 P-20	-52	-31%	-31%	-34%	-34%	-32%	-33%
T+4 P+0	*	-7%	-5%	-6%	-17%	-5%	-8%
T+4 P+10	*	9%	11%	11%	-6%	11%	6%
T+4 P+20	*	23%	28%	28%	3%	28%	18%
T+4 P-10	*	-20%	-19%	-21%	-33%	-20%	-21%
T+4 P-20	*	-33%	-33%	-36%	-46%	-34%	-34%

Table 8. Annual climate change impacts on the Mulberry River, Arkansas USA: ΔT, %P Comparison to analogous Leaf River Mississippi (Nemec and Shaake, 1982; *scenarios not run; ** estimates taken from paper)

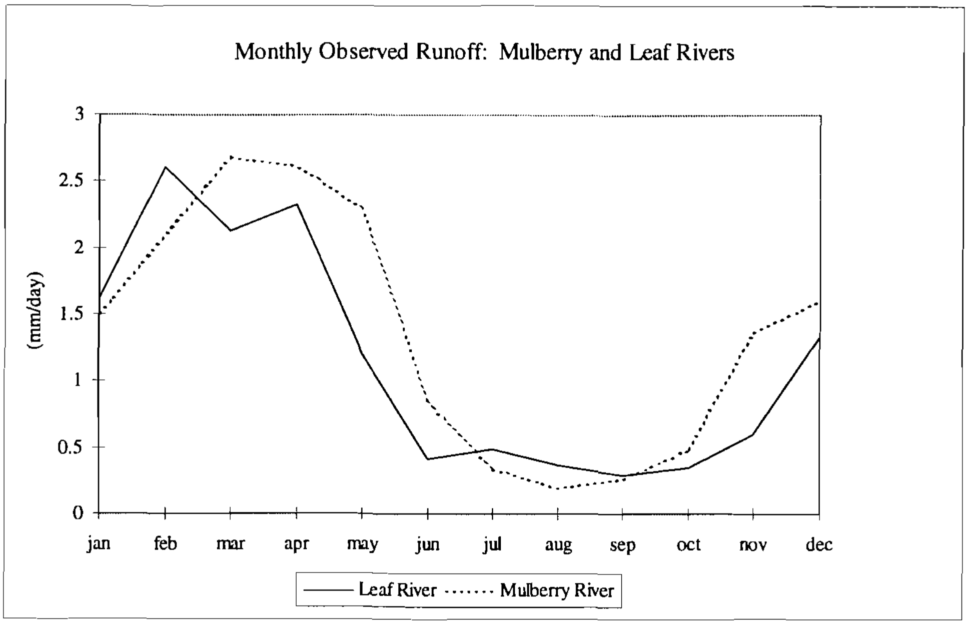


Figure 17. Comparison of monthly discharge of Leaf River and Mulberry River. *Estimates taken from Nemec and Shaake (1982)

East

The East basin is perhaps the most sensitive to model calibration since most of the runoff is produced from snowmelt. A monthly temperature index model was used to derive an effective precipitation; and this model appears to be as sensitive as the physical runoff models themselves. For the monthly model, an upper (melting) and lower (freezing) temperature computes an effective "melting" rate, the greater the difference between these two values the more distributed the melting process becomes. On the monthly scale and daily scale, a one or two degree shift greatly affects the distribution of the effective precipitation, thereby altering the mechanisms of runoff. There are several important questions that arise when looking at the response of a basin within a snowmelt dominated region. What is the mechanism by which runoff is produced? What is the impact of temperature change on evapotranspiration and/or soil moisture?

The BCM model became "unstable" when there were extreme changes in the runoff regime, actually producing negative surface runoff. Extreme scenarios revealed this instability; for example a 4°C increase with a 20% decrease in precipitation actually produced a 7% increase in discharge, a very inconsistent result. Moderate changes in the climate variables with BCM in this basin produced similar results to Water Balance model run on a daily time step (Table 9). The regression model did not perform satisfactorily under the climate change scenarios when temperature changes were applied. It produced similar results when compared to the other models for the precipitation changes only (temperature held constant). The annual hyperbolic tangent model again performed "predictively", showing strong linear relationships to temperature. A 2°C temperature increase causes a -2% decrease in discharge and a 4°C temperature increases causes a -4% decrease in discharge. Precipitation changes exhibit a more non-linear relationship, where a 10% increase (decrease) in precipitation returns a 13% increase (decrease) (Table 9). The simple hyperbolic tangent model again shows that it is a relatively good relationship between precipitation, potential evapotranspiration, and runoff. Surprisingly, Turc produced similar results to the hyperbolic tangent model as well as to the physical models. This is surprising considering the low temperatures of this basin.

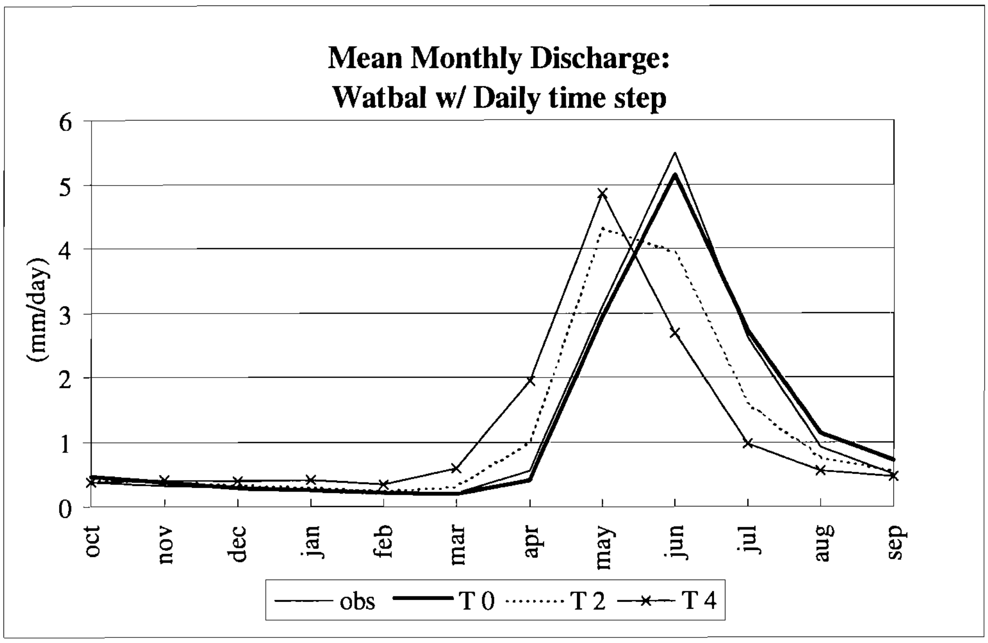
The monthly water balance model, WatBal, produces quite different results as that reported by Nash and Gleick (1993). They report the results of a study done on the East River for the US. Environmental Protection Agency, Figure 19. This study was the only one available for directly comparing the monthly time step to a shorter time step (6 hours in this case) for the same basin. In this work a 6 hour time step, distributed integral model (NWSFRS) was used to assess climate change impacts on the basin. Inputs to this model are areal temperature and precipitation and annual, uniform precipitation and temperature changes were applied over the basin. Figure 18.a-b and Figure 19 show that the data used by Nash and Gleick gave lower discharges from the basin (data sources were different), however the runoff distribution follows the same trend as that used in this work (Figure 18 a-b). Under climate change, Nash and Gleick point out that the peak discharge month moves from June to May under a uniform temperature increase of 4°C. A 2°C creates a double peak with June still being the dominant runoff month. However in their work, no mention is made to the mechanisms of runoff. Interestingly and somewhat surprisingly, Nash and Gleick report a 9 percent decrease in discharge with a 2°C increase in temperature and a 12 percent increase in discharge with a +2°C, +20%P climate scenario, revealing temperatures significant negative impact on runoff. This appears to be primarily due to the flattening of the runoff hydrograph over more months, giving rise to increase in soil moisture and evapotranspiration loses. The combination of these mechanisms reduces runoff. In a similar snowmelt driven basin in northern California, Lettenmaier and Gan (1989) state that a increase in temperature in a high elevation watershed did not greatly affect the distribution of evapotranspiration. Wet, early spring soils do not produce as much evapotranspiration as wet late spring soils. However, these results are very sensitive to the method of basin discharge. WatBal has two primary mechanisms for runoff, surface and subsurface flow. It was assumed that the primary mechanism for runoff was subsurface flow. Definition of the peak precipitation event is critical. If the peak "effective" precipitation is lagged compared to the peak discharge, then a large fraction of runoff is given as sub-surface flow. However, if the peak discharge shifts toward the peak "effective" precipitation, then a larger component of runoff is given as surface runoff. Table 9 gives the results of the WatBal simulation, where the impacts of the melting process are quickly seen. If precipitation is held constant (%Δ P = 0), then increases in temperature shift the spring runoff. The calibration parameters ($S_{max} \approx 400$mm) kept the soil moisture very low, indicating a mechanism of quick infiltration into the sub-surface and subsequent base flow runoff. This meant little water was available for evapotranspiration from the soil matrix. The ΔT=4 scenarios did produce less runoff than the ΔT=2, although the non-linearities are quite dramatic considering that the ΔT+2,%P-20 gives a decrease of 21% while the Δ T+4,%P-20 gives a decrease of only 15%; again revealing the sensitivity of the snow melt model to temperature changes. Figure 18 b. is a plot of the monthly mean discharge for the East basin with T+0 (base), T+2 and T+4. scenario using the monthly time step.

WatBal was also run on a daily time step, where T+2 P 0% and T+4 P 0% give overall decreases in runoff, similar to the findings of Gleick and Nash (1993). However, the T+4 P 0% scenario's annual discharge was the same as the T+2 P 0% scenario. This is undoubtedly due to the shift of the runoff to the spring months, where the value of potential evapotranspiration is smaller due to the decrease in available solar energy despite the increase in temperature. It is felt that this is a likely scenario under a temperature shift without any change in precipitation in a high mountain water shed such as the East River. The higher temperatures will increase the magnitude of the spring runoff which would mean increased risks due to flooding a reduced risk in total water availability. On a daily time step, WatBal also shows that temperature changes might simply shift the runoff hydrograph to the earlier spring months and not reduce the overall annual flow significantly. Figure 18 a. is a plot of the monthly mean discharge for the East basin with T+0 (base), T+2 and T+4. scenario using the daily time step.

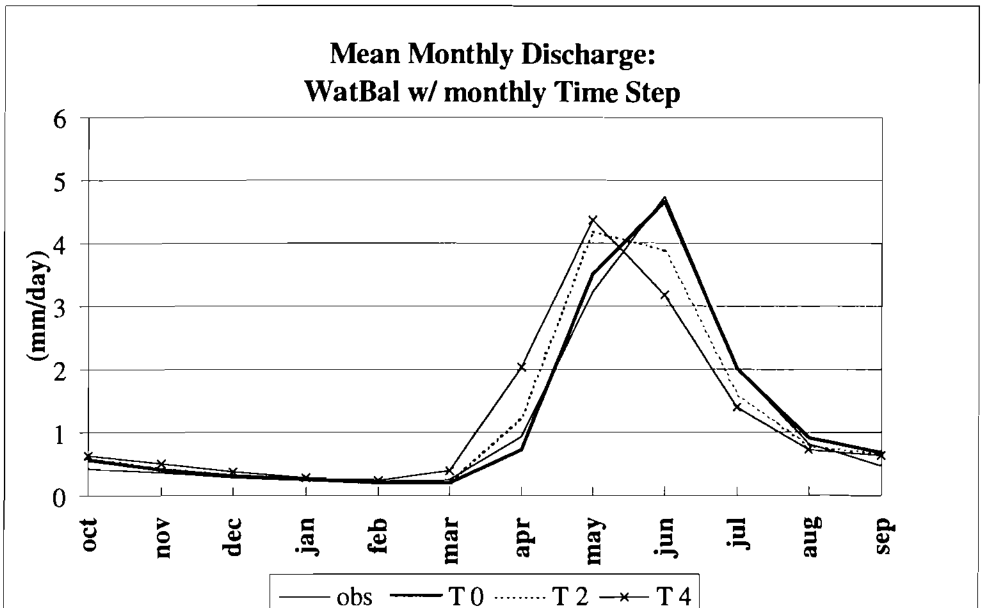
It is evident from these results, that care must be taken when performing sensitivity analysis on basins with snow melt as their main source of runoff. Different climatological scenarios give drastically different results when applying climate change, so the mechanisms of runoff and the computation of effective precipitation (i.e. the snow melt rate and distribution) are critical for a basin such as the East. The question that arises out of this comparison is which model is correct? The lumped integral model, WatBal, run on a monthly time step produced significantly different results than the same model on a monthly time step. The distributed integral model on a 6 hour step is similar to the daily lumped integral model, keeping in mind that the snowmelt processes are probably the dominating feature for this basin.

East	NWSRFS	WB DAY	WB MON	BCM	REG	HT	TURC
T+0 P+0	*	0%	0%	0%	0%	0%	0%
T+0 P+10	*	13%	13%	15%	2%	12%	11%
T+0 P+20	*	25%	17%	28%	12%	24%	21%
T+0 P-10	*	-12%	-8.5%	-18%	-17%	-11%	-12%
T+0 P-20	*	-24%	-16%	-31%	-30%	-22%	-22%
T+2 P+0	-9%	-6%	-1%	-6%	-18%	-2%	-2%
T+2 P+10	1%	5%	16%	7%	-24%	9%	9%
T+2 P+20	12%	17%	23%	18%	-27%	21%	19%
T+2 P-10	-19%	-18%	-13%	-14%	-24%	-13%	-13%
T+2 P-20	-28%	-29%	-21%	-9%	-32%	-24%	-26%
T+4 P+0	-17%	-6%	2%	-6%	-31%	-3%	-3%
T+4 P+10	-3%	7%	10%	13%	-25%	7%	8%
T+4 P+20	7%	19%	19%	24%	-21%	18%	18%
T+4 P-10	-25%	-17%	-11%	-6%	-40%	-14%	-14%
T+4 P-20	-33%	-28%	-19%	7%	-46%	-24%	-27%

Table 9. Annual climate change impacts on the East river discharge : ΔT, %P (NWSFRS results from, Nash and Gleick, 1993, * - no results reported)



a. Daily Time Step



b. Monthly Time Step

Figure 18 a.& b. Temperature change impacts on the East River using a lumped model (WatBal) on a daily time step and a monthly time step.

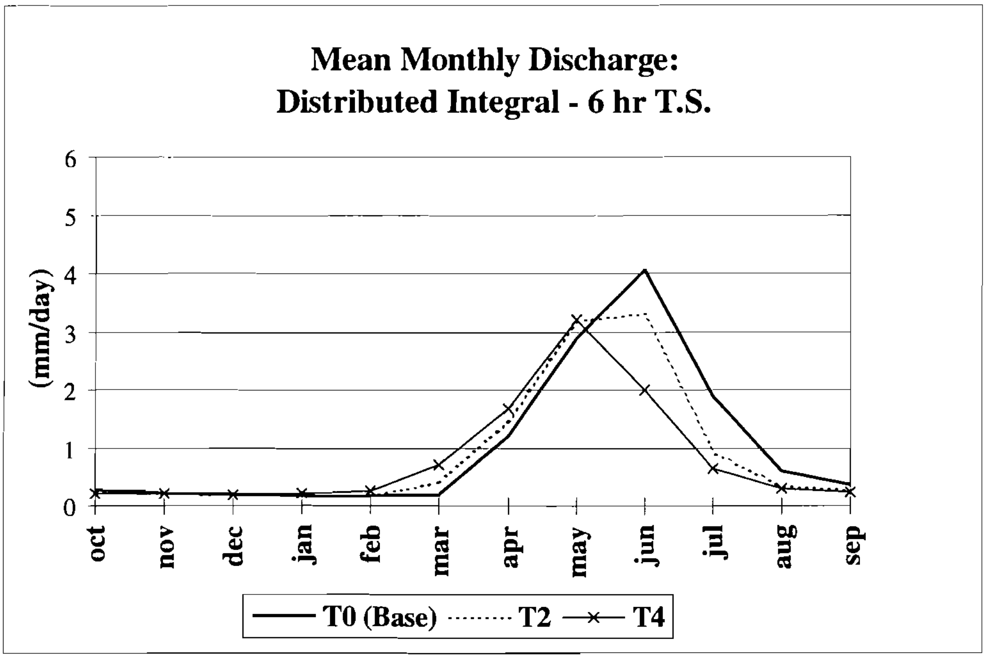


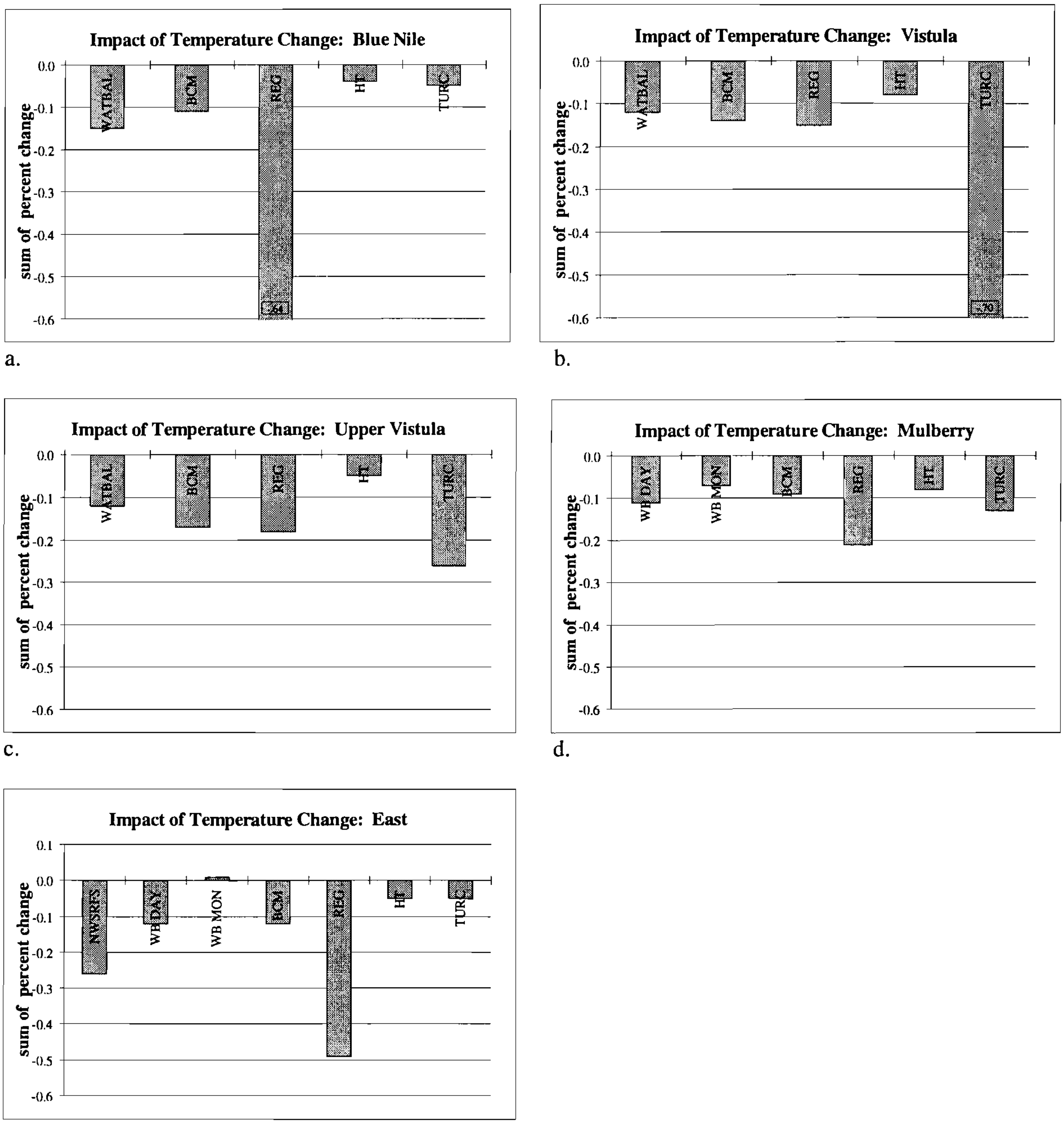
Figure 19. Temperature change impacts on the East River using a distributed integral model (Nash and Gleick, 1993).

Summary of Modeling Impacts under Climate Change Scenarios

Below are summary figures of the climate change impacts using the defined models on the five basins. Figures 20.a-e are the summed temperature impacts (ΔT2°C and ΔT4°C) with no precipitation change; figures 21.a-e are the summed precipitation impacts (±10%,± 20%P) with no temperature change; and figure 22.a-e are the absolue sum of the combined impacts.

Temperature

Generally the physical models do not exhibit dramatic variability, with the exception of the East where snowmelt dominates the runoff process (Figure 20.e). The regression model shows its drastic varibility in the two semi-arid basins (Blue Nile and East) and the more humid Mulberry basin. The Turc model, essentially an annual regression model, shows its inconsistency with respect to temperature change in the Vistula and Upper Vistula. The hyperbolic tangent model is generally the least sensitive to temperature fluctuations.



a.

b.

c.

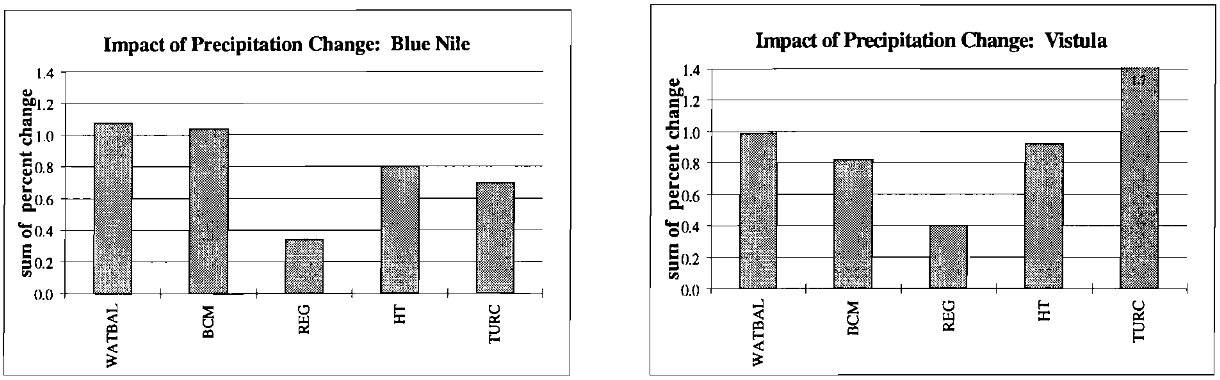
d.

e.

Figure 20.a-e Sum of the % change in runoff for ΔT°C=2 and ΔT°C=4 scenarios with %ΔP=0

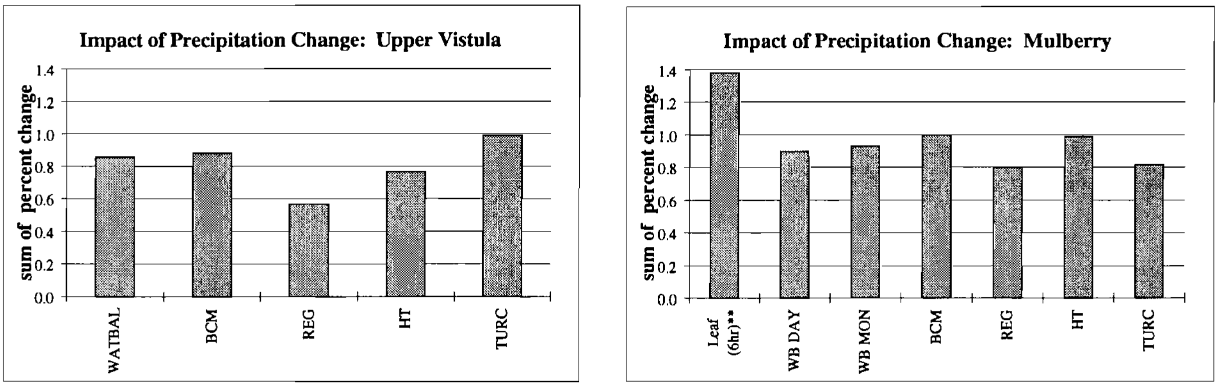
Precipitation

Again WatBal and BCM produce similar results under the precipitation scenarios, revealing the consistency of the physically based approach. WatBal run on the Mulberry basin with a daily time step produced similar results to a monthly time step (Figure 21.d). The distriubted model used by Nemec and Shaake (1982) for the Leaf river shows its greater sensitivity to precipitation change (Figure 21.d). It was assumed that the Leaf and Mulberry will respond similarly under climate change. The biggest differences with the lumped models were in the Vistula and East, where snowmelt plays an important rold. The regression model tends to under-predict precipitation changes in all basins. The Turc model showed a wide range of variability, matching closely in some basins (Mulberry, Upper Vistula, and East) and being quite different in others (Vistula and Blue Nile). The hyperbolic tangent model was consistently close to WatBal and BCM, although in some cases it showed stronger precipitation change impacts and in others less precipitation change impact (Figure 21.a-e).



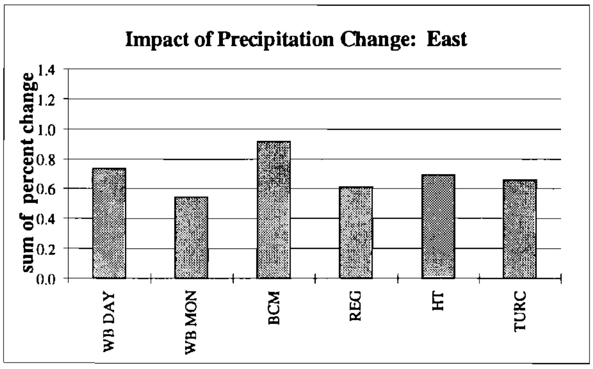
a. Blue Nil

b. Vistula



c. Upper Vistula

d. Mulberry

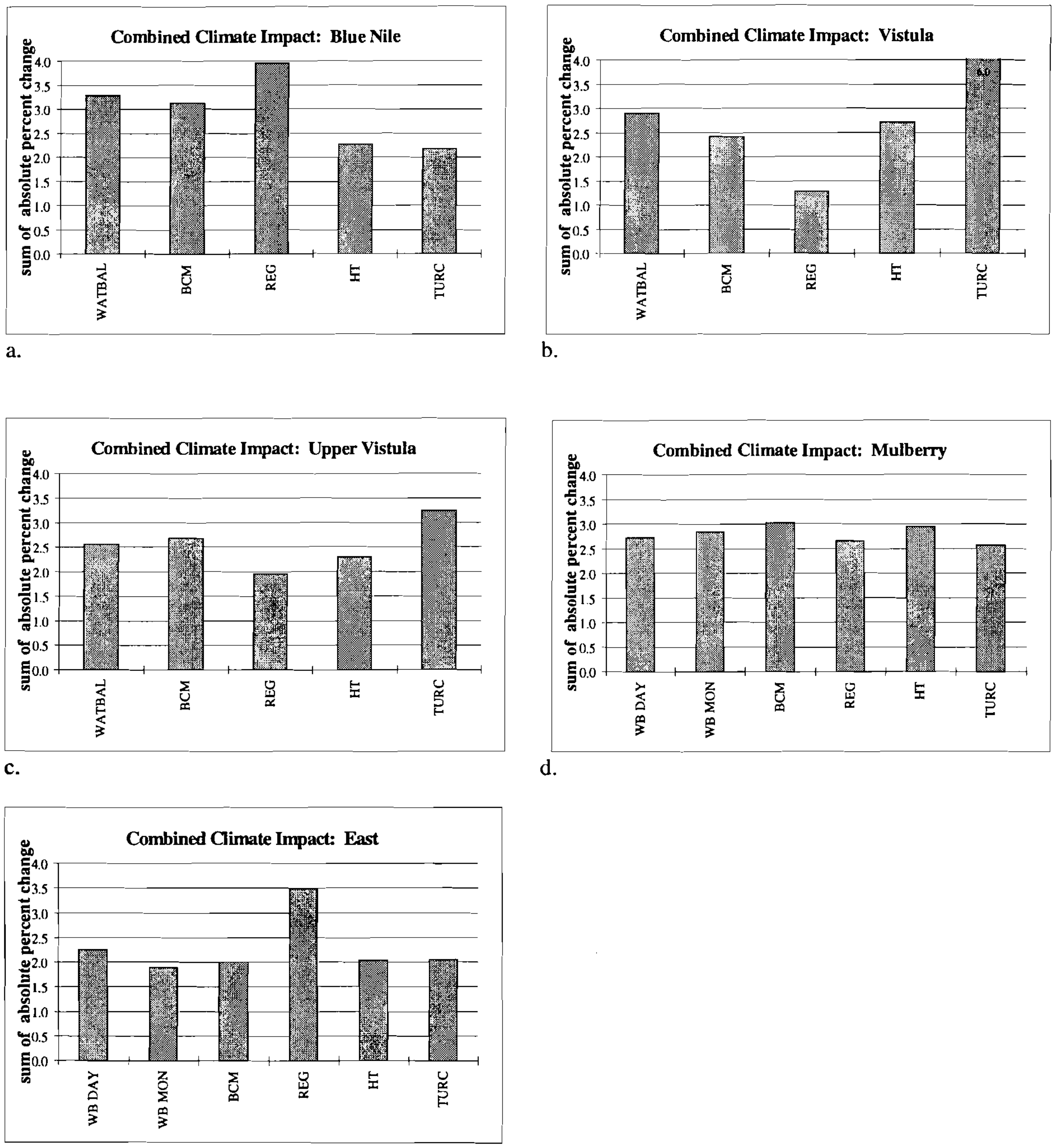


e. East

Figure 21.a-e. Sum of the absolute values of % change in runoff for the four precipitation (%ΔP = ±10 & ±20) scenarios with no change in temperature (ΔT°C=0)

Combined

Figure 22.a-e are plots of the sum of the absolute values of the percent changes for each climate change scenario. Combined trends are difficult to draw conclusions from because of the possibility of compensating errors. For instance in the Blue Nile temperature changes might give dramatic decreases while precipitation changes give large increases in discharge. When these impacts are combined they tend to offset each other (Figures 20.a, 21.a, and 22.a). However Figures 22.a-e due point to a general trend- the superiority of the physically based approach which includes the annual hyperbolic tangent model. The only basin that does not show extreme variability between the different approaches is the Mulberry (Figure 22.d).



a.

b.

c.

d.

e.

Figure 22.a-e. Absolute sum of model results for the five basins. For example, the bar labeled WATBAL in Figure 22Figure 22.a has a value of approximately 3.3. If the column labeled Watbal in Table 5 is summed after taking the absolute value of all entries, then this sum would equal 3.3.

Conclusion

There have been a considerable number of efforts to find tools that properly model the impact of climate change on river basin runoff. Yet there is still no consensus on the best techniques, the minimum data needed, the proper assumptions to assume, etc. This work has been an attempt to address some of these issues and help to draw some conclusions on adequate methodologies and approaches that can be applied to the assessment of climate change on catchment runoff. This has been done by looking at a number of modeling techniques and applying them to several different types of basins. Below is a brief summary of issues addressed and conclusion drawn in regards to the modeling of climate change impacts on runoff.

The two annual models, Turc and the hyperbolic tangent, were investigated in order to determine the applicability of simple modeling techniques for assessing climate change on annual water availability. Not surprisingly, the Turc model did not performed consistently in all basins and can be considered inadequate for assessing climate change impacts on most basins. A regression model such as Turc should be cautiously used in basins for which it was developed. The Turc model is simply not a robust model which can be widely applied. The simple hyperbolic tangent model produced reasonable results in all basins, showing its strength as a quick way to obtain plausible climate change scenarios. The hyperbolic tangent tends to under-estimate the impacts of temperature fluctuations. One weakness of the model as a quick assessment tool is the need for proper estimation of annual potential evapotranspiration. The hyperbolic tangent closely matched the results found with the water balance models for the Vistula, Upper Vistula and Mulberry, which are the more humid basins. The biggest difference between the hyperbolic tangent model and the other methods was in the Blue Nile basin which, interestingly, is the most arid of the basins (plotting to the extreme right of Figure 1). Arid basins plot on the linear portion of the hyperbolic tangent model so climate change impacts will tend to be underestimated in these basins when using this model.

The regression model performed well under calibration in all cases, but the validation time series for all basins shows the weakness of this model for assessing climate change impact studies. The validation series showed consistently poor performance. The model generally over-estimates the relationship between runoff and temperature and so gives unrealistic results under the climate change scenarios for most of the basins. In the case of the Blue Nile basin, there is practically no correlation between temperature and runoff in this basin, so the regression model performed most poorly in this basin. It is felt that a regression approach such as the one used here is inadequate for assessing the impacts of climate change on runoff. For this reason, more discussion is given regarding the applicability of the physically based models.

Interesting conclusions were drawn regarding the physically based models that were used in this study. Generally speaking, basins that have large variations in soil moisture are more difficult to accurately model. This was seen in both the East and Mulberry Rivers basins in the USA, where the mechanisms of runoff and the seasonal variability make it difficult to apply the lumped models. The two lumped models gave quite different results under the extreme climate variability scenarios, showing that modeling assumptions, approaches, and calibration procedures are important. For smaller catchments whose main source of runoff is snowmelt (East), the lumped models are very sensitive to the definition of effective precipitation. Figures 18 and 19 and Table 8, show a comparison between the lumped approach (WatBal) on a monthly and daily step and a distributed model on a 6 hour step. The distinct approaches give quite different results. The conclusion drawn is that the lumped model on a monthly time step is questionable for this type of basin with the simplistic snowmelt model. The lumped model with a daily time step more closely matched the results of the distributed integral model, although with significantly different conclusions drawn regarding the impact of temperature fluctuations on runoff (Table 7). Snowmelt driven basins require special attention.

In basins with large changes in the runoff mechanism (Mulberry), the lumped models do not capture some of the seasonal variability which is undoubtedly an important component of the runoff process. The analogous basin (Nemec and Schaake, 1982) using a distributed integral model showed the basin to be more sensitive to precipitation changes. A more thorough investigation would need to be performed to draw definite conclusion about a distributed integral vs. the lumped integral approach. The Mulberry basin was run on a daily and hourly time step using the WatBal model. and the climate change impacts using different time steps were not significant using WatBal on this basin. The BCM and WatBal models (both lumped integral approaches) gave similar results, although the BCM was consistently less sensitive to temperature variations than the WatBal model. For larger basins with smaller fluctuations in precipitation, soil moisture, and runoff the two lumped models gave quite similar results (Upper Vistula and Vistula). The lumped approach appears very adequate for this type of basin.

Further Study

Further work could focus attention on a single basin, performing the same type of investigation but more thoroughly investigating different types of models, especially a more detailed comparison between the lumped integral and distributed integral approaches. At the same time, a wider range of different climatological conditions (additional basins) would an interesting and informative investigation. These might include more arid regions (plotting further to the left of Figure 1) or more temperate, humid or tropical regions (plotting further to the right of Figure 1). Basins that are dominated by snowmelt need special attention and more work needs to be done on determining the impact of climate change in these types of basins. Finally, alternative annual analytical expressions have been given (Dooge, 1992) which would be interesting to investigate.

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