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J. Niemann, K. Strzepek, D. Yates

1. Introduction

During the past decade, an increasing amount of attention has been paid to the possibility of human induced climatic change. While several studies have focused on the extent of climate change due to the increased levels of greenhouse gases in the atmosphere (National Research Council, 1979, 1987, World Meteorological Organization, 1986, Houghton et al. 1990), other studies have progressed beyond the fields of climatology and atmospheric science into the interdisciplinary study of impact assessment and policy analysis. Cohen (1991) reports the existence of more than 40 regional impact case studies that have been completed in Canada alone; Chang et al. (1993) compiled a list of about 100 references published between 1985-1990 that investigated some aspect of climate change impacts on water resources. Such studies have focused on the impact of climate change on sea level, agriculture, forestry, and water resources. Notable impact assessments which consider water resources include: Parry et al. (1987), Pearman (1988), Smith and Tirpak (1989), Waggoner (1990), UK CCIRG (1991), and Strzepek and Smith (1994).

Despite the diversity among the impacts considered, assessments generally have the same simple structure (Cohen, 1991):

1. Development of scenarios of global warming for the study area.
2. Development of an impact model for the activity (water resources, etc.) in question.
3. Application of scenarios to the impact model.

While much attention has been paid to the second step, less attention has been given to the first and third steps, and no attention has been given to feed-backs.

Regarding the development of scenarios, a wide variety of climate scenarios have been used, but most fall into four principle categories:

1. GCM based scenarios. This approach includes some variety but usually includes applying GCM derived adjustments to base climate values (see, for example, Smith and Tirpak, 1989, or Strzepek and Smith, 1994).

2. Hypothetical scenarios. This approach includes enormous flexibility and is often in the framework of a sensitivity analysis. For the purposes of forecasting runoff under climate change, it usually involves the application of uniform increases in temperature and precipitation.
3. Historically based scenarios. Chang et al. (1993) describe this approach as "close analyses of past experiences under unusual climate regimes or under heightened competition for increasingly scarce water resources." This approach employs data from historically "warm" periods under the assumption that greenhouse gas induced climate change will affect hydroclimatic processes in a similar fashion as "natural" (solar variations, volcanoes, etc., see Robock et al., 1993) climate variability.
4. Analog based scenarios. This approach assumes that the changed climate of one region might be similar in nature to the current or historical climate of another region (Chen and Parry, 1987).

Each of these approaches has their strengths and weaknesses (see Carter et al., 1992). Chang et al. (1993) give the following plot (Figure 1) showing the distribution between these methods of scenario development.

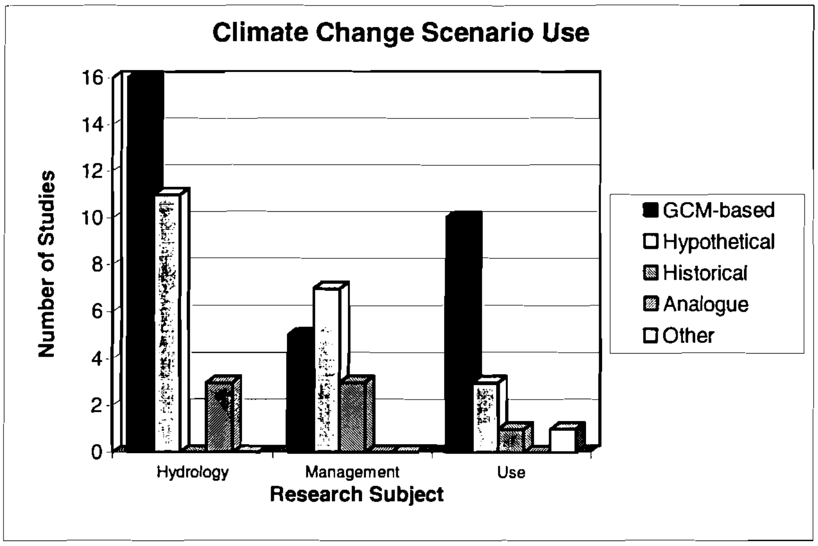


Figure 1. The use by type of climate change scenarios among hydrologic, management, and use studies (from Chang et al., 1993).

Despite the increasing number of impact assessments, the diverse methods of climate change scenarios make comparison of assessments difficult (Cohen, 1991). Cohen notes that even when two assessments use the same scenarios, the development of these scenarios may cause differences in the results.

Chen and Parry (1987) also express concern over the uncertainty created through the development of climate change scenarios. They consider GCM and hypothetical approaches as useful, and call the analog approach "helpful for conveying information at a policy level." However, they clearly cite the need to close the gap between large scale GCM output and smaller scale impact models (hydrologic models, for example). The grid size of commonly used GCM's (at least those used in the early 1990's) can be as large as 5° latitude by 10° longitude, which translates to an approximate area of 500,000 km^2 in equatorial regions. However, hydrologic processes take place on a much smaller scale. Interception, evaporation, infiltration, storage, and response time all depend on physical properties which can vary *greatly* even within a 1000 km^2 catchment (which could be considered a large catchment in hydrologic terms).

In addition to the question of scale, Robock et al. (1993) cites the poor ability of GCM's to match current climates in some locations. They conclude that $2xCO_2$ results cannot be trusted and criticize the reliance on GCM results for climate change scenarios. The authors recommend first considering the ability of the GCM's to match historical data, and then (if they match well) using GCM's to identify general trends in the climate parameters. With this knowledge (and location specific information), they suggest development of hypothetical/GCM hybrid scenarios.

While this paper will not attempt to address this wide variety of issues, it will consider one aspect of climate scenario development. Strzepek and Smith (1994) and Smith and Tirpak (1989) both apply the difference between $2xCO_2$ and $1xCO_2$ GCM results (for precipitation and temperature) to historical (or base) data. Other studies which employ a hypothetical scenario often apply uniform increases to historical climatic data. Even Robock's hybrid approach requires the adjustment of base climatic data (Robock et al., 1993). This paper considers four questions related to the selection of a base dataset and its impact on the assessment of runoff under climate change.

1. The paper considers the implications of utilizing mean monthly hydroclimatic data in a water balance approach. Can a single long-term "mean year" be utilized to gage the magnitude of changes in runoff for policy oriented impact assessment?
2. The paper investigates the impact of hydroclimatic record length. How sensitive is a climate change impact assessment to the length of base hydroclimatic data records?
3. The paper looks at the significance of increasing the density of climatic data stations. Under the circumstances of spars climatic data, how much information is gained by the addition of new climatic stations?
4. Finally, the paper briefly discusses the utilization of gridded base data.

The paper is oriented towards the use of a hydrologic model in policy related impact assessment of climate change on water resources. Within such a framework (in comparison to a pure hydrologic study), there is greater uncertainty in the future conditions, but there is also less detail required in the results. Specifically, the hydrologic model is used to determine the mean volume of water annually supplied by the Blue Nile River.

2. The Blue Nile River Basin

2.1 Characteristics of the basin

The Blue Nile Basin is situated in northwestern Ethiopia and eastern Sudan at a latitude ranging from 9° to 12° North (Figure 2). The total area of the Blue Nile basin is approximately 325,000 km^2. The upper part of the basin lies in the Ethiopian Plateau, a hilly/mountainous region with grass and scattered trees. The lower part of is situated on the Sudan Plain. This is a flat region mostly covered with Savannah forest (Shahin, 1985).

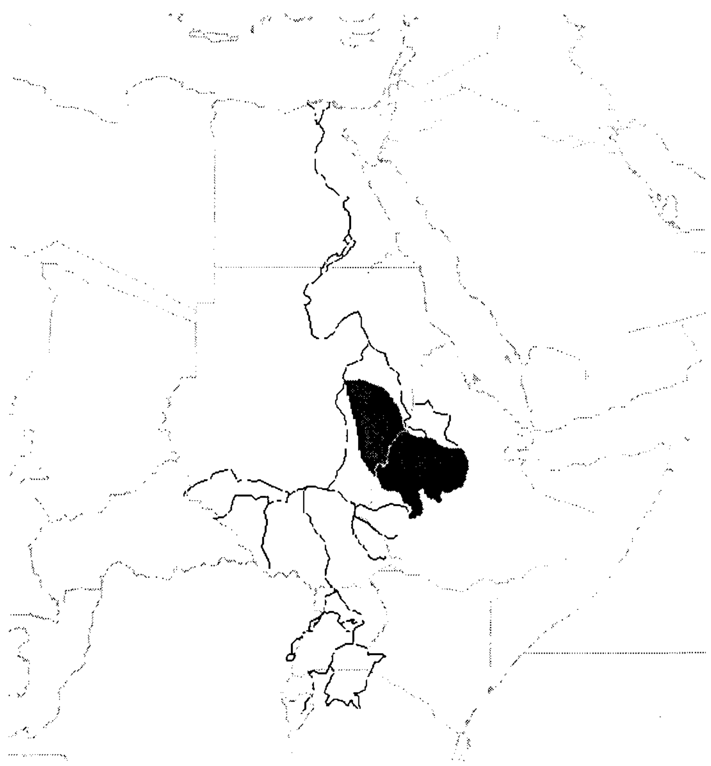


Figure 2. The Nile River and Blue Nile Basin in northeastern Africa.

The climate of the Blue Nile Basin has been classified as "highlands" and "semi-arid" (Abourgila, 1992, who cites Griffiths, 1972). The Highlands classification indicates that the climate is strongly affected by elevation. Semi-arid implies that the region has less than 400 mm/year. It should be noticed that the Blue Nile receives most of its precipitation in the Ethiopian Highlands and very little on the Sudan Plains (especially in winter).

The climate of the Blue Nile is quite distinct from the climate of the White Nile. In fact, virtually no correlation exists between annual precipitation in Uganda and Ethiopia (Hulme, 1990). The Blue Nile's climate shows great sensitivity to El Nino/Southern Oscillation (ENSO) events. El Nino events decrease precipitation over the Blue Nile, and anti El Nino events increase precipitation. Hulme (1990) writes, "The relationship between ENSO events and Nile Basin precipitations suggests that between 10 and 40 percent of interannual precipitation variability may be accounted for in this way."

The Blue Nile forms an especially interesting basin from a hydroclimatic perspective. With the mouth below 400 meters and springs as high as 2,900 meters, the Blue Basin has an extreme elevation distribution. In addition, the elevation range can be clearly divided into two zones (see Figure 3). The low range of elevations (below 600 meters) corresponds to the extremely flat Sudan Plain and accounts for about 38% of the basin; the higher, more-diverse elevation values correspond to the mountainous Ethiopian Plateau.

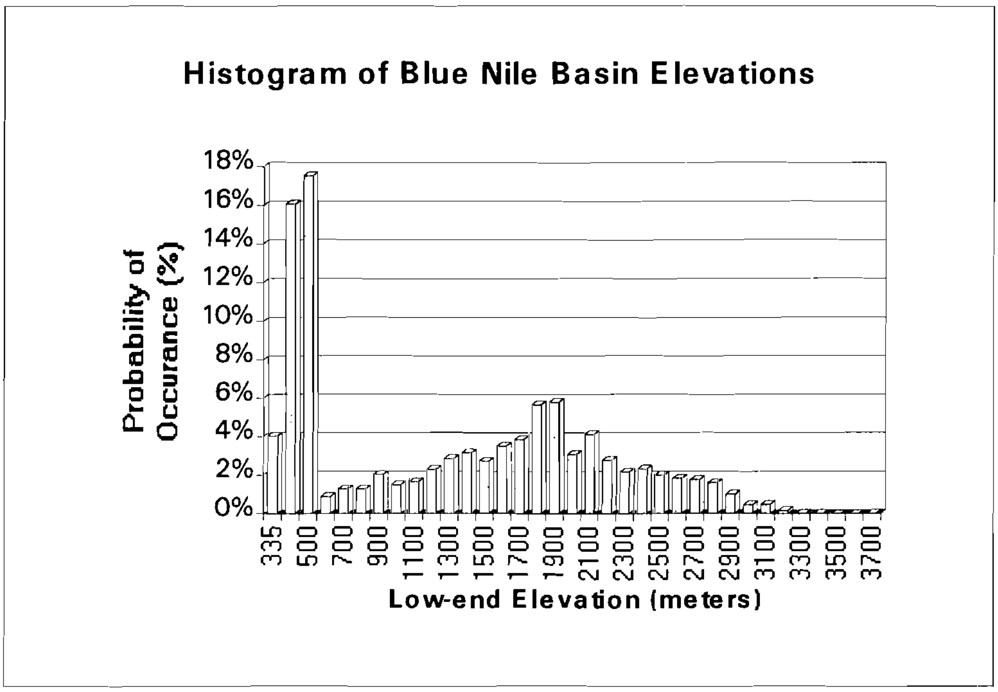


Figure 3. Histogram showing the distribution of elevations in the Blue Nile Basin.

This elevation distribution implies several problems in data collection and aggregation. Mainly, one cannot accurately assume that the basin is homogeneous. The climate, topography, and vegetation will greatly vary from the lower to the upper regions. Additionally, in the upper region, station locations may or may not be indicative for the local region. For example, a data point in a gorge clearly will not give accurate information about the temperature or precipitation in the hills. Consequently, the basin is expected to be sensitive to the density and location of data points. Plus, the diversity of elevation implies diverse climatological readings. This fact indicates a possible sensitivity to data aggregation technique.

The source of the Blue Nile River is a series of small tributaries into Lake Tana (1800 meters above sea level). From here, the river drops into a gorge cut deeply into the Ethiopian Plateau. Eventually, the Blue Nile drops to the Sudan Plain where it joins the White Nile at

Khartoum (less than 400 meters above sea level). There are two important tributaries of the Blue Nile--the Dinder and the Rahad. Both of these rivers are perennial and join the Blue below Roseires on the Sudan Plain. The Dinder has a catchment of about 16,000 km^2 and an annual yield of approximately 3 billion m^3 (Shahin, 1985). The Rahad has a smaller catchment of 8,200 km^2 and a average yearly yield of about 1.1 billion cubic meters (Shahin, 1985).

For the period 1912-1970, the Blue Nile had an average annual yield of 53.0 billion m^3 (about 1,680 m^3/s). Figure 4 compares the Blue Nile mean monthly runoff with the monthly runoffs from the White Nile and the Atbara River. Approximately 70% of the Blue Nile's flow occurs during the months of August, September, and October. The flow of the Blue Nile is heavily laden with sediment due in part to recent draughts in the Ethiopian highlands (see Smith and Al-Rawahy, 1990).

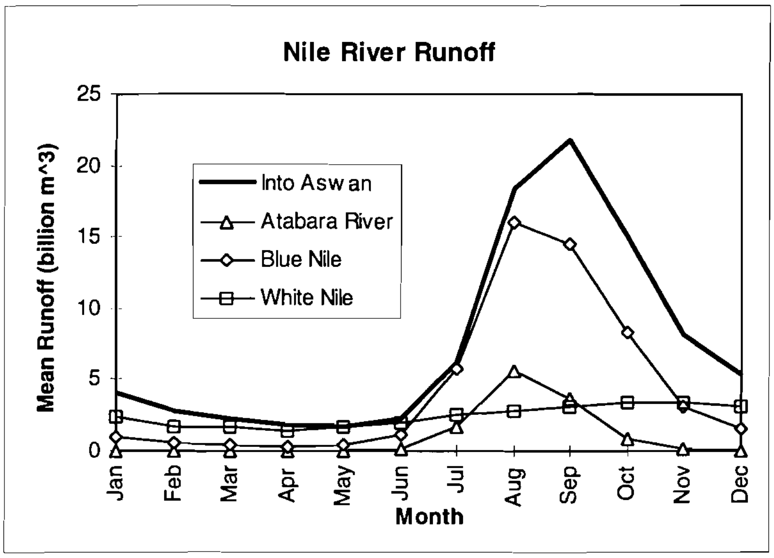


Figure 4. Mean monthly runoffs for the major Nile Tributaries: the Blue Nile, the White Nile, and the Atbara River.

The Blue Nile is perhaps the most important tributary of the Nile River, providing approximately 60% of the volume of water that reaches the Aswan Dam (Strzepek and Smith, 1994). Due to its sensitivity to climate (see above or Gleick, 1991), the effects of climate change on the Blue Nile will have a significant influence on the effects of climate change on the Nile flow entering Lake Nassar (formed by the Aswan High Dam).

Moreover, the importance of the Nile River to Northeast Africa is obvious. Approximately 25% of Egypt's electrical generation, 40% of its employment, and 20% of its GDP are directly related to the Nile (Strzepek and Smith, 1994). The Nile water allocation agreement allows Egypt and Sudan to withdraw up to $48x10^9$ m^3 and $14.5x10^9$ m^3, respectively. Although the other seven riparian nations are not party to the agreement, their interest in utilizing Nile water will almost certainly increase as they develop (see Smith and Al-Rawahy, 1990, and Gleick, 1991).

Despite such the political and economic importance (and the basin's expected sensitivity to climate), little hydroclimatic data exists for the Blue Nile Basin. After several thorough searches at the Egyptian Ministry of Public Works and Water Resources, it appears that no significantly long series of flow data exist for Blue Nile or its tributaries anywhere in Ethiopia. In addition, available climatological data is also extremely sparse for such a large basin: only twelve climatic data stations were found near the Blue Nile Basin (see Chapter 4 for a more detailed description of both the hydrologic and climatic data sources). Consequently, the sensitivity to data inputs of any investigation of the Blue Nile Basin must be examined.

2.2 Previous studies of the Blue Nile under climate change

Several studies have considered the implications of Climate Change for the Blue Nile, as a part of a broader study of the Nile River. Gleick (1991) uses a simple annual water balance model (with a GFDL based scenario) to determine the Nile's sensitivity to climatic change. For the combined Blue Nile and Atbara region, he shows a 50% decrease in runoff under a 20% decrease in precipitation.

From his analysis of historical analogues and output from several GCM's, Hulme (1990) suggests that the Blue Nile will experience some climatic forcing due to the greenhouse effect. From a composite scenario created from five GCM's, he shows winter temperatures in the Nile increasing between 3 and 4° C, and summer increases between 2 and 3° C. Regarding precipitation, he could find little agreement between the GCM's. By treating leading GCM results as samples of a probabilistic distribution, he determines a 0.5 probability of decreasing precipitation. He did find "a hint" that summer precipitation in the Blue Nile would decrease. He then translates these results into a qualitative assessment that Blue Nile runoff may decrease under climate change (and cites great uncertainty).

Abourgila (1992) presents a water balance model (similar to the one used in this study) for the assessment of the impact of climate change on the Nile Basin. Although the model is designed for use with GCM output, he does not present results for any climate change scenarios.

Miller and Russell (1992) use the GISS GCM grid cell runoffs to determine annual river runoff for 33 of the world's largest basins (and monthly runoff for several rivers--not the Nile). Although their modeled runoff compares well with observations in some cases, it does not match well for rivers in dry regions like the Nile. They present a 13% decrease in Nile runoff but do not distinguish between the Blue and White Nile Basins.

3. Hydrologic Modeling

The objective of a hydrologic model is to transfer climatic characteristics into the water balance of the watershed. To this end, there have been numerous efforts to describe the processes from the very simple annual water balance to the most sophisticated description of basin dynamics using differential equations describing mass and energy balance at a very disaggregated level. Todini (Todini, 1988) broadly categorizes the levels of complexity of watershed rainfall-runoff models by ranking them in increasing order of a prior knowledge: (1) purely stochastic, (2) lumped integral, (3) distributed integral, and (4) distributed differential.

In brief, the stochastic approach uses only statistical methods, with no physical basis for computing basin response. The lumped integral approach models the catchment as a whole and usually attempts to minimize the number of parameters needed to describe the main physical processes. The lumped integral model is commonly called the "bucket" model. Because of its simplistic representation of the watershed, the parameters of a lumped model tend to lose some of their physical meaning. Data requirements are somewhat small and might include: historic precipitation, runoff, estimates of potential evapotranspiration and basin area. The model used in this study falls within the broad context of the lumped integral model (a comparison of different runoff models for use in climate change impact assessment is given in a companion paper, Yates and Strzepek, 1994a). The third model type is the distributed integral model and is pertinent because many climate change studies have used this type of model (Nèmec and Schaake, 1982, Lettenmaier and Gan, 1988, Nash and Gleick, 1993). Such models give a more sophisticated representation of physical processes and attempt to maintain physical meaning to model parameters. Data requirements are large and can include: basin concentration times, routing intervals, percent impervious area, length of overland flow, watershed slopes, infiltration rates, storage capacities, potential evapotranspiration, etc. These models were primarily developed out of the necessity to analyze more event based phenomena such as flood forecasting. The Stanford, Sacramento, and NWSFRS models fall within this catagory of models. The final model type is the distributed differential model which describes basin response using differential equations in space and time and expresses both mass and momentum balances. This model type, for now, is practically confined to the laboratory due to its large data and computational requirements.

3.1 IIASA's Water Balance Model (WatBal)

The theoretical basis of this study's model was developed by Kaczmarek and Krasuski (1991) at the International Institute for Applied Systems Analysis and the Institute of

Geophysics in Warsaw, Poland. The uniqueness of this lumped conceptual model to represent water balance stems from the use of continuous functions of relative storage to represent surface outflow, sub-surface outflow, and evapotranspiration. The groundwater discharge element of the water balance has been referred to as sub-surface flow since it is a conceptualization of groundwater discharge using a single bucket. In this approach, the mass balance is written as a differential equation, and storage is lumped in a single mass balance (see Figure 5). All components of discharge and infiltration are dependent upon the state variable, relative storage, with the exception of base flow which is given as a constant in the mass balance equation (Equation 1). The model contains only three parameters ε, α, and S_{max} which are related to surface runoff, subsurface runoff, and maximum catchment water-holding capacity, respectively. Because of the model's differential approach, varying time steps can be used depending on data availability and basin characteristics. For larger basins with longer times to concentration, longer time steps are recommended (e.g., one month). This approach was implemented using the Visual Basic programming language within the Excel 5.0 spreadsheet environment, and the resulting software has been termed "WatBal."

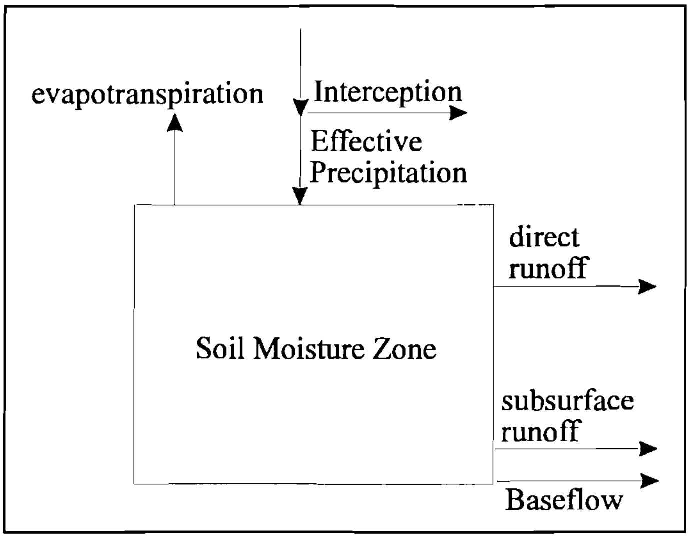


Figure 5. Conceptualization of storage and water balance in the WatBal model.

The continuity equation describing the mass balance is written as:

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

where,

$$\begin{aligned} P_{eff} &= \text{Effective Preciptation (length/time)} \\ R_s &= \text{Surface runoff (length/time)} \\ R_{ss} &= \text{Sub-Surface runoff (length/time)} \\ Ev &= \text{Evaporation (length/time)} \\ R_b &= \text{baseflow (length/time)} \\ S_{max} &= \text{Maximum storage capacity (length)} \\ z &= \text{relative storage } (0 \le z \le 1) \end{aligned}$$

The continuous functional forms of each term in Equation 1 are given below.

Evapotranspiration - *Ev*

Evapotranspiration is a function of potential evapotranspiration (PET) and the relative catchment storage state. For the purpose of this study, a calibrated temperature based potential evapotranspiration (Thornthwaite) model was used to estimate PET (Shaw, 1982). A companion paper (Yates and Strzepek, 1994b) closely examines the issue of PET estimation for climate change impact assessments. In the literature, a number of expressions have been given that describe evapotranspiration as a function of the soil moisture state, a non-linear relationship is used here (Kaczmarek and Krasuski, 1991).

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

Surface Runoff - R_S

Surface runoff is described in terms of the storage state, z, the effective precipitation, P_{eff}, and the predefined baseflow. If the precipitation is less than the base flow, then it is assumed that no surface runoff occurs.

$$R_s(z, P, t) = \begin{cases} \dfrac{\varepsilon}{1+\varepsilon-z}(P_{eff} - R_b) & \text{for } P_{eff} > R_b \\ 0 & \text{for } P_{eff} \le R_b \end{cases} \tag{3}$$

The first parameter of the model, ε, is introduced here in the surface runoff term, R_S.

Sub-Surface Runoff - R_g

$$R_g = \alpha z^2 \tag{4}$$

Sub-surface runoff has been assumed to vary as a square of the relative storage state times a coefficient, α, where α is the second model parameter. The third and final model parameter is the maximum catchment holding capacity, S_{max}. The storage variable, z, is given as the relative storage state: $0 \leq z \leq 1$. Inputs to this model include: effective precipitation, potential evapotranspiration, and (for calibration purposes) runoff with units of length per time. In this study, mean monthly values have been used, although shorter or longer time periods could be used.

3.2 Potential evapotranspiration

Dooge (1992) states that any estimate of climate change impacts on water resources depends on the ability to relate change in actual evapotranspiration to predicted changes in precipitation and potential evapotranspiration. If it is necessary to predict proper *changes* in potential evapotranspiration then it is obviously important to begin with a good *estimate* of potential evapotranspiration.

The PET model that was used in this study was based on the temperature method developed by Thornthwaite (Shaw, 1982). However, it was assumed that the Thornthwaite method did not give a good representation of the basin's "actual" potential evapotranspiration, so a calibration coefficient was placed in front of the Thornthwaite PET estimate. The calibration procedure that was used to adjusted PET was based on the notion that the long-term water balance of a large catchment can be simply written as $R_a = P_a - Ev_a$; annual runoff equals annual precipitation minus annual evaporation (Dooge, 1992). If it is assumed that there is no over-year storage when using long-term averages, then a simple monthly runoff model for a basin such as the Blue Nile can be expressed as follows.

$$R_i = \begin{cases} 0, & \hat{PET}_i \geq P_i \\ P_i - \hat{PET}_i, & \hat{PET}_i < P_i \end{cases} \tag{5}$$

Then by summing up the monthly runoff values and setting them equal to the observed values,

$$\sum R_i = \sum Ro_i \tag{6}$$

it is possible to find a coefficient, β, that gives an estimate of the potential evapotranspiration value for the basin based on a given potential evapotranspiration.

$$\hat{PET}_i = \beta \; PETtw_i \tag{7}$$

Ro_i = observed runoff in month i

R_i = computed runoff in month i

$\hat{PET}_i$ = estimate of potential evapotranspiration in month i

$PETtw_i$ = Potential evapotranspiration by Thornthwaite in month i

P_i = Precipitation in month i

β = calibration coefficient for Thornthwaite

4. Data Sources

Four data sources were utilized in this analysis. The following sources provided climatological (temperature and precipitation) data: the 1993 NCAR World Monthly Surface Climatology Database, the Africa89 database, and the IIASA database. Runoff data was obtained from the Egyptian Ministry for Public Works and Water Resources.

The NCAR World Monthly Surface Climatology Database is a global climate database that includes 37 stations inside Sudan and Ethiopia. The record lengths vary from station to station but usually begin after 1900. For this study, all records after 1970 were disregarded to avoid the possibility that climate change influenced this historical data. The 1993 data was obtained from the Global Ecosystems Database Version 1.0 on CD ROM (from the National Organization of Atmospheric Administration).

The second data source is the 1989 Africa Climate Tape supplied by NCAR (Strzepek and Yates, 1994). This tape contains monthly temperature and precipitation data for the African continent. For Sudan and Ethiopia, it includes 39 precipitation and 26 temperature stations. The difference between the 1993 NCAR data and the Africa89 data is that the Africa89 data contains 2 additional precipitation stations and 11 less temperature stations. However, the key difference for modeling the Blue Nile Basin is that the 1993 NCAR data includes a temperature station at Lake Tana, where the Africa89 data does not. To determine areal climatic values for the station data, Strzepek and Yates (1994) determine mean station values using any available records before 1970. By employing GIS, the mean values were plotted in a latitude/longitude projection, and an interpolated surface was developed using GRASS's inverse distance weighting technique (see Isaaks and Srivastava, 1989).

The IIASA database is a gridded global climatological database which includes temperature, precipitation, and cloudiness values (Leemans and Cramer, 1991). Station data was gathered from a variety of sources which resulted in varying densities throughout the world. Stations were accepted under the criteria of a minimum observation length of five years during 1931-1960. Leemans and Cramer gridded the data using their latitude/longitude locations on a Cartesian plane (i.e., a sinusoidal projection). They performed the interpolation with a triangulation technique from Green and Sibson (1978). Temperature was adjusted to mean sea level using an adiabatic lapse rate. Although they considered a similar correction for precipitation, they found that such an adjustment did not significantly improve the data.

Naturalized historical Blue Nile runoff data was obtained from the Planning Studies and Modeling Program at the Egyptian Ministry for Public Works and Water Resources in 1991. This data was available at Khartoum for the entire span of the climatic data.

5. Temporal Issues: Comparing Time Series to Long-Term Mean Values

Most climate impact assessments which study the response of river basins to climate change have made use of long time series to assess the response of basin discharge to climate variability (Nèmec and Schaake, 1982, Lettenmaier and Gan, 1990, Gleick, 1987, Nash and Gleick, 1993). Of course, these studies were confined to those basins which had long records available. However, in many regions throughout the world, and particularly within the developing world, long-term climatological data is seldom available. For those regions with scarce data, the use of gridded data bases could prove useful in performing climate change impact assessments on river basins. With this in mind, one of the goals of this study was to test the validity of using long-term monthly mean values for impact assessment. This study made use of mean monthly values of precipitation, potential evapotranspiration, and runoff to assess potential climate change impacts on the Blue Nile Basin. It was proposed that monthly mean values would give comparable estimates of basin response to climate change as the results derived from a monthly time series.

In order to test this hypothesis, an experiment was performed using a 26 year record, from 1945-1970 (a portion of the T58 scenario below, see Section 6.1). The first 13 years (1945-1957) were used for calibration and the second 13 years (1958-1970) for validation using the WatBal model. Figure 6 is the one year moving average of the modeled and observed discharge as well as precipitation for the 26 year record on a monthly basis (both the calibration and validation series). The moving average was chosen to remove seasonality, making it easier to observe the difference between modeled and observed discharges. Generally, the model tends to over estimate the sensitivity of the basin to precipitation fluctuations primarily caused by the calibration objective of minizing the residual error. This objective causes the model to choose model parameters which calibrate closely to the mean year, with a subsequent over estimation of low and high flow years (Figures 6 and 7). For example in the early portion of the record (1945-1948) the historic precipitation is significantly above the mean without a corresponding increase in discharge and during a dry period (1960-1962) the model over predicts the decrease in discharge (Figure 6). Because the model is only using precipitation and temperature data to derive discharge, the water balance model will not be able to predict this type of discharge response, as there appear to be additional basin dynamics that are not explainable with only the precipitation, temperature and discharge data. Table 1 gives the correlation coefficient and the standard monthly error value for the modeled time series. The standard error measures the amount of error in the model's prediction of discharge versus the observed discharge. From this table, it is apparent that the calibration/validation procedure has validated the use of this water balance model for this basin. The correlation and error values did not change dramatically between the two portions of the time series, which include several high and low flow years in both the calibration and validation portions of the record.

Table 1. Calibration and validation statistics (comparing observed and calculated mean monthly flows) for the period 1945 to 1970.

	Correlation	Error (mm/day)
1945-1957	0.94	0.20
1958-1970	0.93	0.21

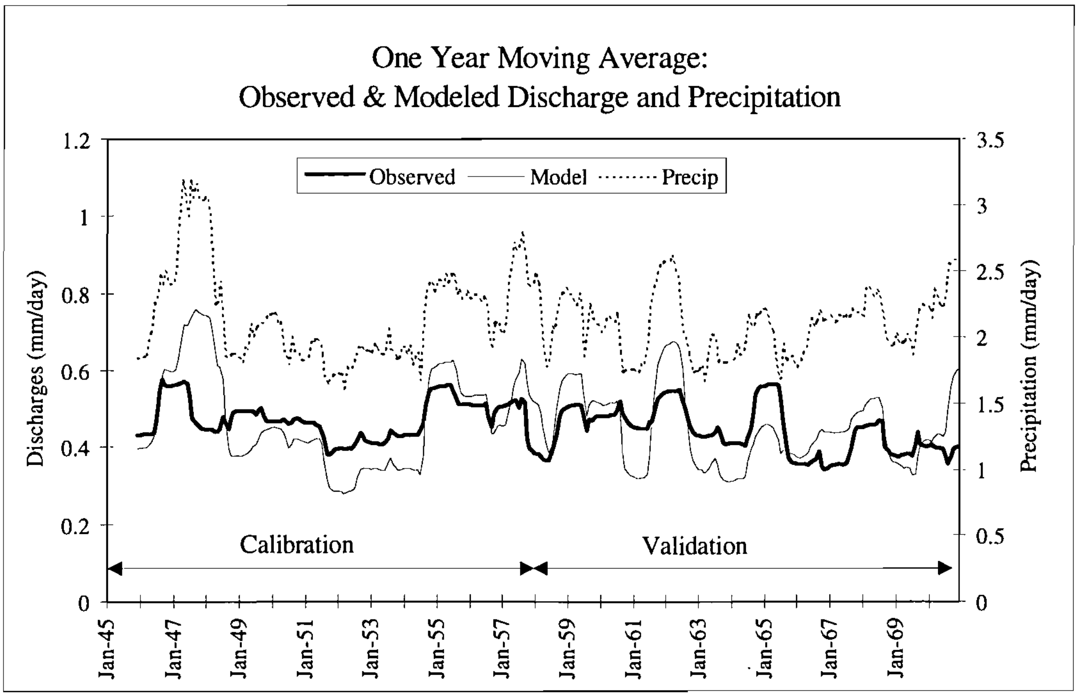


Figure 6. One year moving average of observed discharge, modeled discharge, and precipitation for the period 1945 to 1970.

Figure 7 shows a comparison between the model results when run on the time series and on the mean This figure displays: mean monthly discharges computed from the observed time series (labeled "Observed"), calculated monthly discharges using "mean year" values in the model (labeled "Mean"), and the means of the calculated monthly discharges using time series values in the model (labeled "Time Series"). Clearly, there is a great similarity between the Mean and the Time Series discharges, which leads to an interesting conclusion. When using the actual time series within the water balance model, it appears that WatBal chooses calibration parameters which calibrate closely to the mean year.

This conclusion might bring into question how the model behaves during extreme events (i.e., periods of high and low flow). Figure 6 shows that during portions of the 1945-1970 record, the model tends to exaggerate some of the extreme events that were recorded during that period. For example, the period from 1945 to 1948 appears to be a rather wet period with regards to the precipitation record, yet the model tends to over-predict the discharge response of the basin. Similarly, during a dry period (1951 to 1954), the model tends to under-predict the flows (Figure 6). This observation could be important when looking at the impacts of climate change. Is there any reliability in the model to estimate plausible basin response during more extreme wet and dry periods, or is the model limited to estimating impacts only around the monthly mean year?

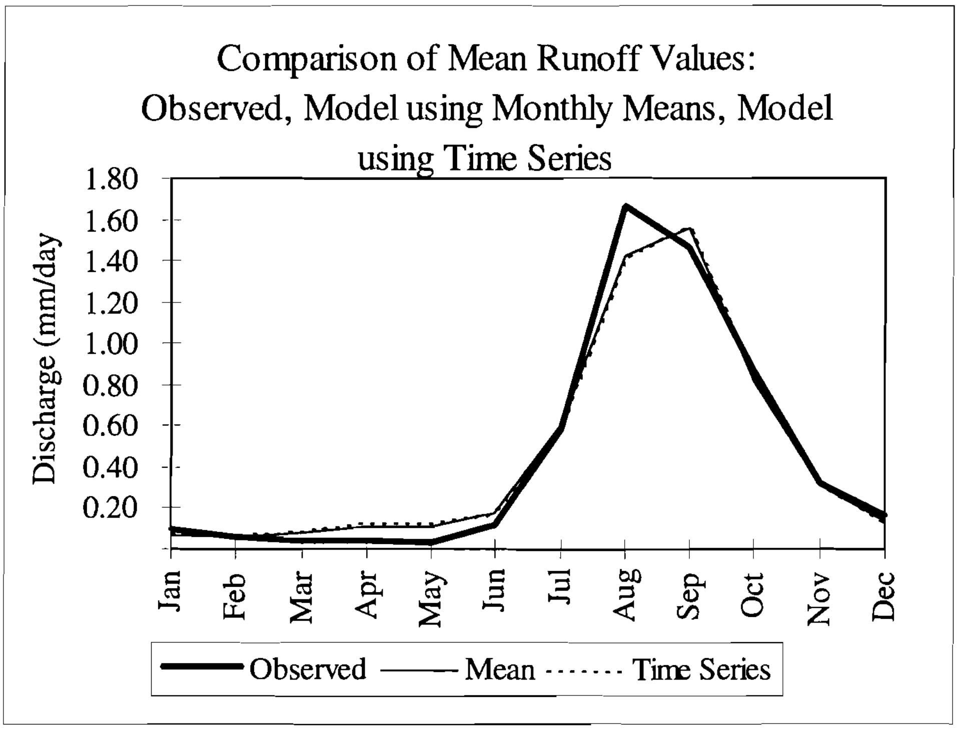


Figure 7. Comparison of mean monthly discharges: observed, modeled using the mean values, and modeled using the time series.

Table 2 is a summary of the climate change scenarios that were implemented using both the time series and the long-term monthly mean values. When comparing the results for the means and the time series, it is apparent that the mean is a good estimate of climate change impact relative to the time series. No scenario gave a difference greater than 2%, which is currently much less than the uncertainty in the estimation climate change or its potential impacts. This procedure thus validated the use of the mean values to estimate the impact of climate change on the Blue Nile Basin.

Table 2. Comparison of climate change impacts using mean values and time series (Scenario T58) in percent change

Runoff (Δ%)	Change in Precipitation					
	0%		+10%		-10%	
Change in Temperature	Mean	T.S.	Mean	T.S.	Mean	T.S.
+0 C	0%	0%	21%	22%	-16%	-18%
+2 C	-16%	-18%	-0%	0%	-31%	-33%
+4 C	-34%	-36%	-21%	-23%	-46%	-48%

6. Temporal Issues: Length of Station Records

In addition to the uncertainty regarding the influence of future greenhouse forced climate change, there is considerable limitations in the availability of historical climatic and hydrological information. As already noted, this statement is particularly serious in (although not exclusive to) the developing world. However, historical information is required to establish a climatic baseline and to calibrate and validate hydrologic impact models. Consequently, the impact community continuously wrestles with the question: how sensitive is the impact assessment to the length of record available for the base climatic stations? This chapter studies this issue as it relates to the assessment of climate change impacts on Blue Nile runoff.

6.1 Development of scenarios

Two scenarios were developed which give different record lengths in their representation of the basin. The first scenario, called Scenario T8 can be considered the base (or worst case) were the span of recorded data is extremely limited. The other scenario, Scenario T58 represents the ideal case where an extended period of hydrologic and climatic data is available.

Both of these scenarios were realized by using the data from the 1993 NCAR World Monthly Surface Climatology Database (see above), and they both employ the same 3 data stations: Khartoum, Kosti, and Addis Ababa. The locations of these stations in comparison with the basin boundaries are shown in Figure 18 (with the discussion of spatial representation below). Scenario T8 utilizes a period of 8 years, spanning 1953 to 1960.

Although any short span could have been selected, this period was chosen so that it could also be used in the spatial comparison below. In addition, this span contain relatively few "holes" in the data. Scenario T58 spans a period of 58 years from 1912 to 1970. The spans of recorded temperature and precipitation data for all stations near the Blue Nile Basin are given in Figures 8 and 9.

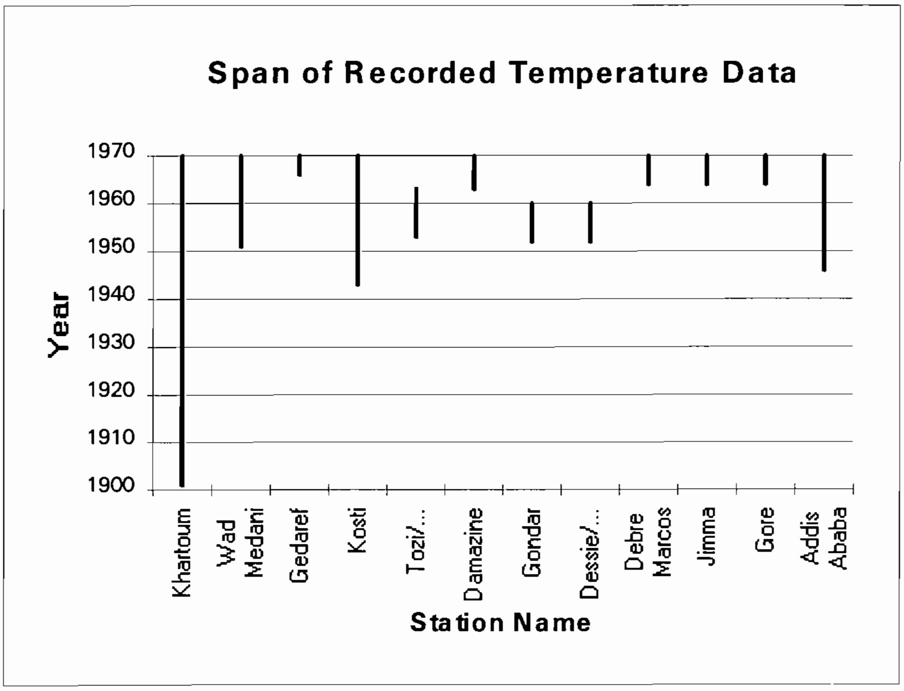


Figure 8. Spans of recorded temperature data for NCAR stations near the Blue Nile Basin.

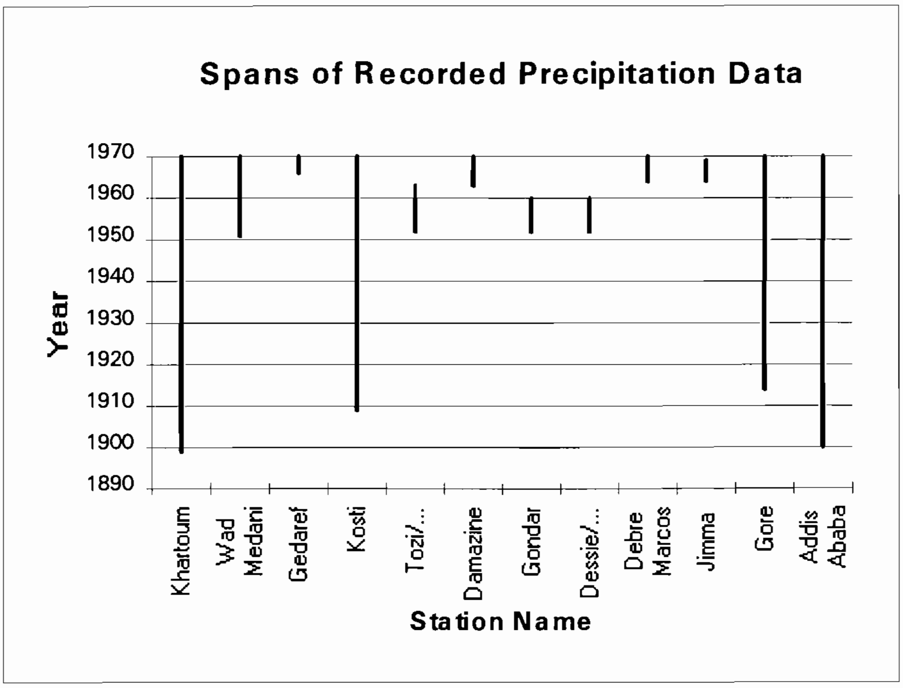


Figure 9. Spans of recorded precipitation data for NCAR stations near the Blue Nile Basin

Temperature records are not available for all three stations for the 58 year span of Scenario T58. However, the coefficients of variation for the Addis Ababa and Kosti temperature data 0.105 and 0.104, respectively (C.O.V. for Khartoum was 0.133), so the lack of this data is probably not as critical as precipitation records for the development of a "mean year." Figure 10 shows the mean and standard deviations of the monthly precipitation and potential evapotranspiration (PET) values for the Addis Ababa station. Potential evapotranspiration was calculated using Thornthwaite. Since a simple water balance approach determines runoff as the area between the precipitation and PET curves, this figure shows that the large variations in precipitation will have a much greater influence on runoff than the narrow PET distribution.

Because of the general proximity of Khartoum and Kosti (as well as similarity in their topography and climate), a strong correlation (r^2 = 0.79) exists between their temperature series (1943 and 1970, see Figure 11). Consequently, a relationship could be used to develop an extended time series at Kosti. A similar comparison showed no strong correlation (r^2 = 0.08) between the temperatures at Khartoum and Addis Ababa for the available data (1964 and 1970, see Figure 12). This independence stems from the vast differences in climate, topography, and location between these regions as discussed above.

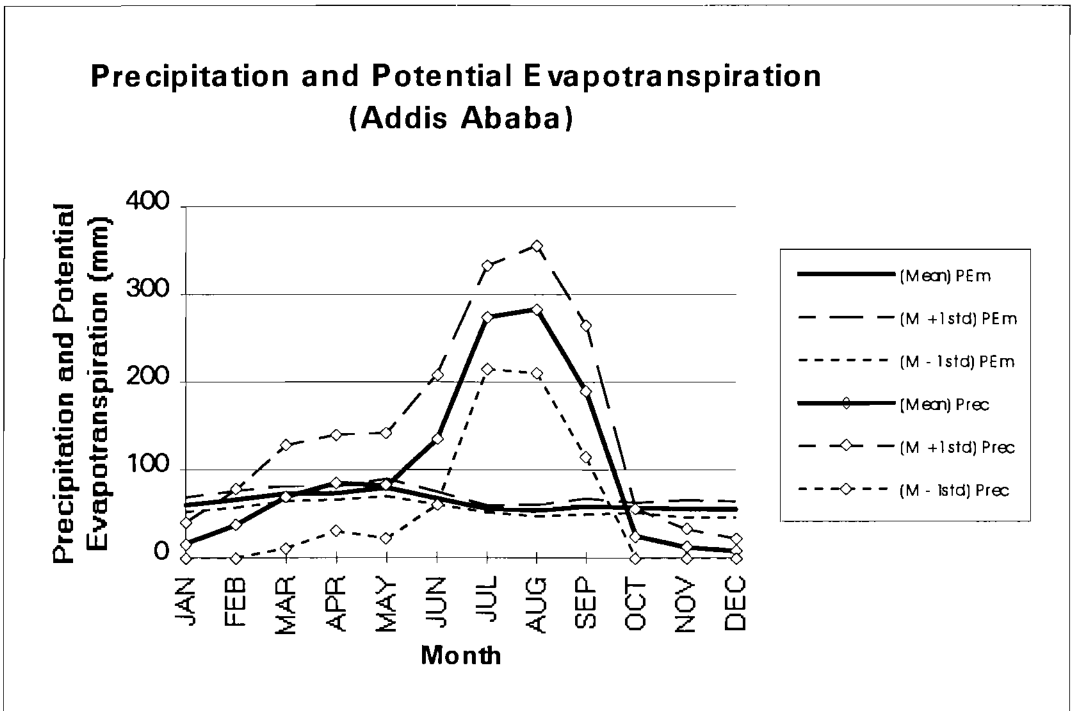


Figure 10. Monthly precipitation and potential evapotranspiration values for the Addis Ababa climate data (mean, mean + 1 standard deviation, mean - 1 standard deviation).

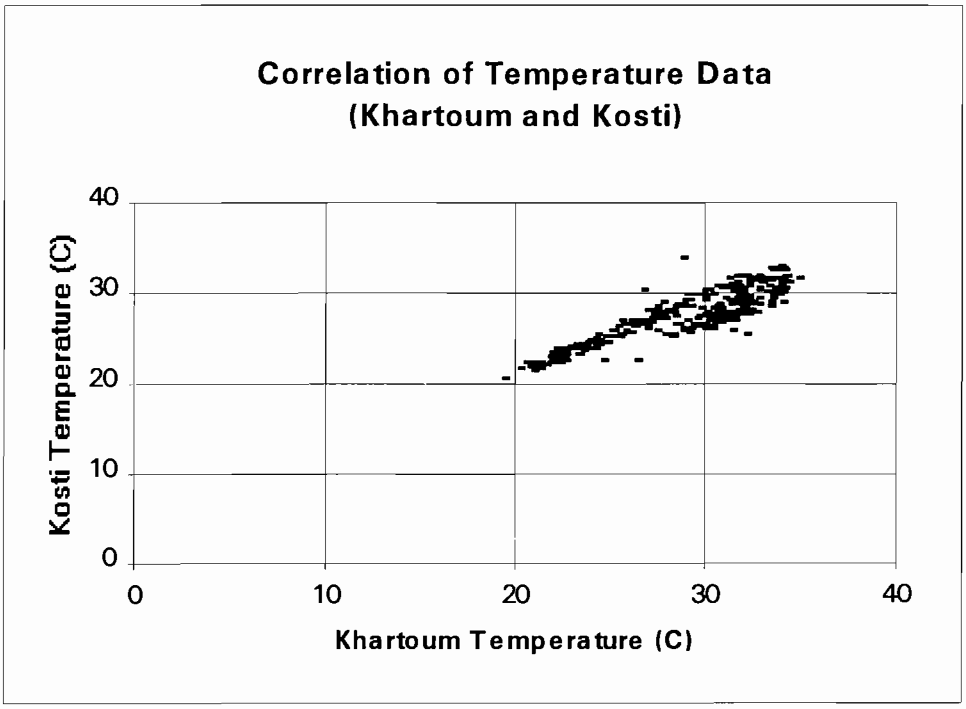


Figure 11. The correlation between NCAR temperature data at Khartoum and Kosti.

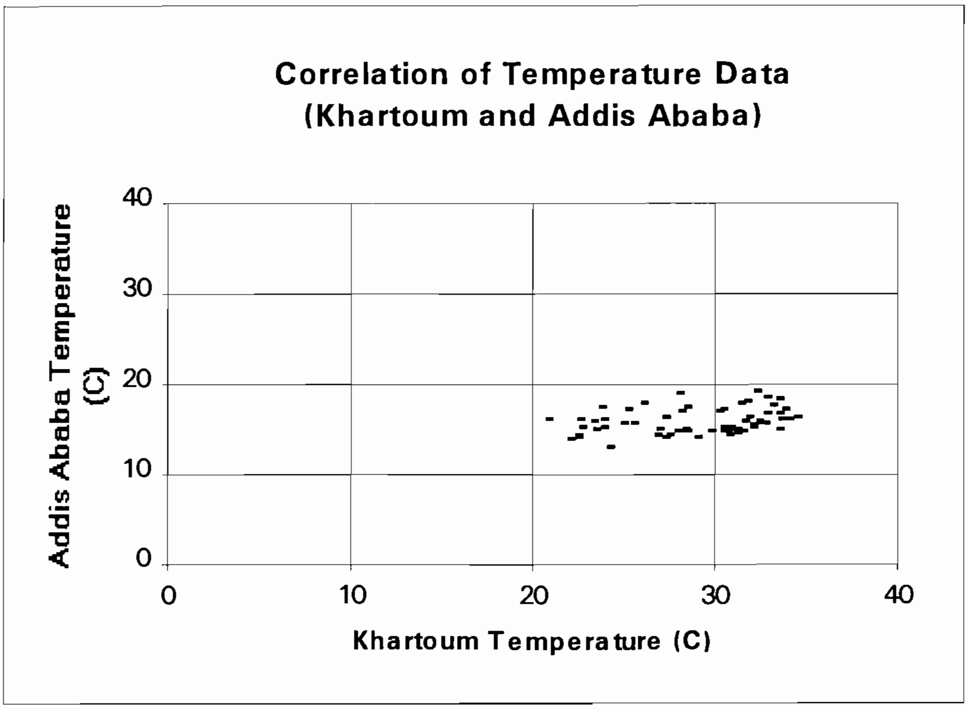


Figure 12. The correlation between NCAR temperature data at Khartoum and Addis Ababa.

To determine areal precipitation averages, a simple Thiessen Polygon approach (Chow, 1988) was initiated using GIS. The Blue Nile Basin boundaries were established utilizing paper maps of the region and were compared to available literature (Shahin, 1985, and Strzepek and Smith, 1994). According to Shahin and Strzepek and Smith, the total area of the Blue Nile Basin is 324,530 km^2 and 312,600 km^2, respectively. The total area as digitized for this study was 325,600 km^2.

For the period of 1953-1960 (Scenario T8), the mean annual runoff is 56.8 billion m^3. Compared to the 53.0 billion m^3 average for the whole series (Scenario T58), this period represents a relatively high flow period but lies within the standard deviation of 9.4 billion m^3. From the areal averages, Scenario T8 shows a mean temperature and an average annual precipitation value of 22.3 C and 789 mm, while Scenario T58 gives values of 22.2 C and 793 mm, respectively. While these values are quite similar, the monthly distribution also plays an important role in determining the modeled runoff. Figures 13 and 14 show the monthly mean temperatures and monthly total precipitation for both scenarios.

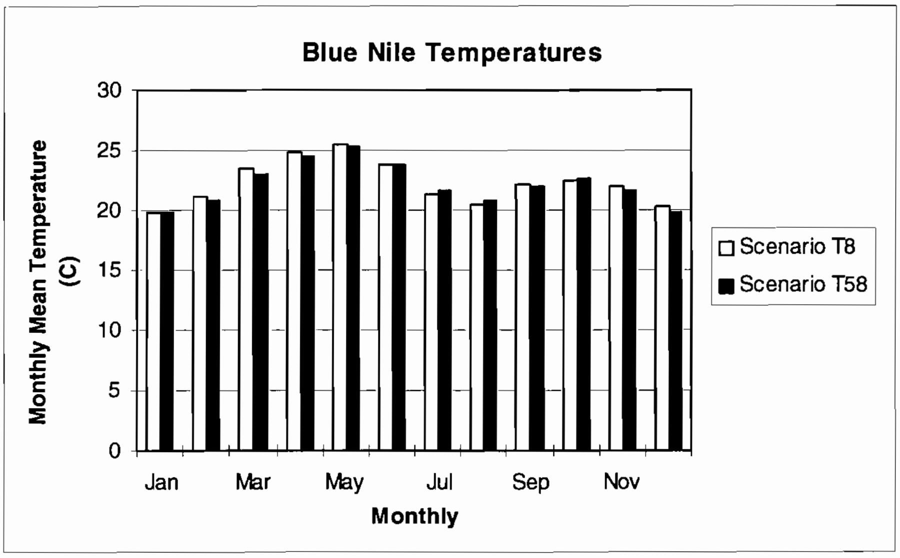


Figure 13. Monthly mean temperatures in the Blue Nile Basin for Scenarios T8 and T58.

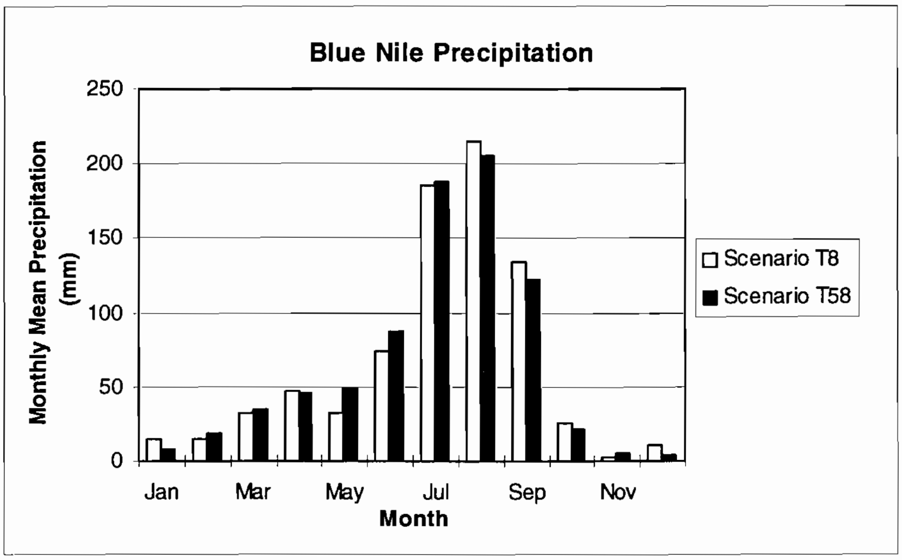


Figure 14. Monthly mean total precipitation in the Blue Nile Basin for Scenarios T8 and T58.

6.2 Results and the importance of record length

The water balance model WatBal was calibrated to the mean monthly values of each scenario (see Chapter 5). Potential evapotranspiration was determined with Thornthwaite and calibrated as explained in Chapter 3. However, the PET calibration coefficients do not vary significantly between the two scenarios (1.26 and 1.21 for Scenarios T8 and T58, respectively). Figures 15 and 16 show a comparison between the calibrated runoff for both scenarios and the measured (naturalized) runoff. While the calibrated results fit generally well, both calibrated runoff curves miss the timing of the observed peak flow. However, this observation is not important for the purpose of determining annual volumes of flow. In comparing the two calibrations, one can see that they give significantly different estimations of the proportion of runoff going to surface and subsurface flow.

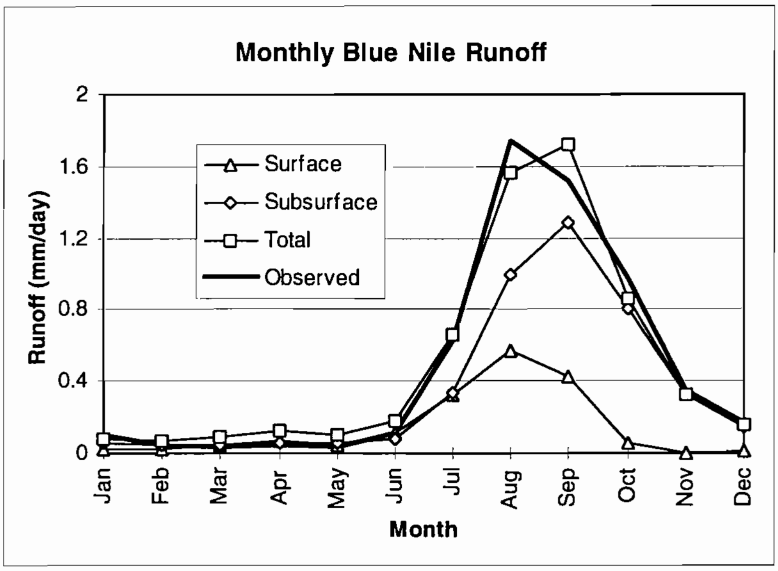


Figure 15. Comparison of modeled monthly runoffs (using Scenario T8 calibration) with historical (1953-1960) monthly means.

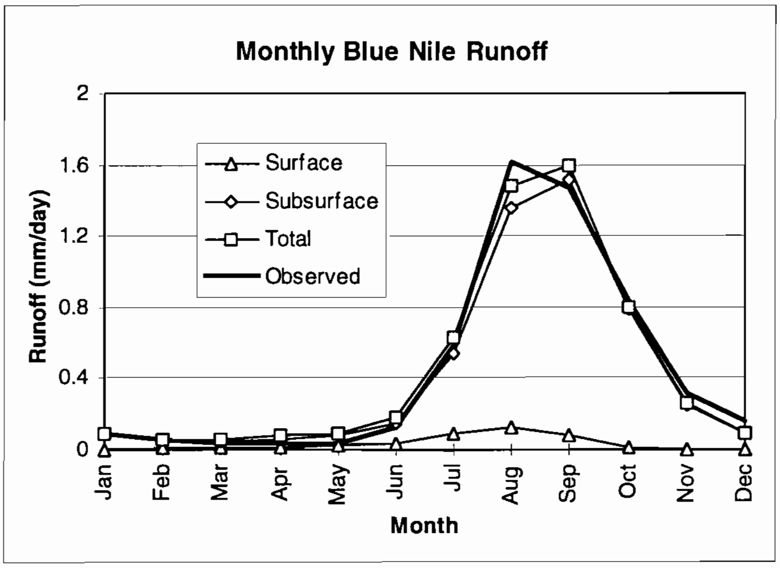


Figure 16. Comparison of modeled monthly runoffs (using Scenario T58 Calibration) with historical (1912-1970) monthly means.

Using these calibrations, the model was employed to forecast runoff under a variety of hypothetical climate change conditions. The scenarios were developed in accordance with the best available information regarding the extent and characteristics of climate change in the Blue Nile Basin (Hulme, 1990, and Strzepek and Smith, 1994). However, these runs are intended only to demonstrate the sensitivity of the basin to greenhouse gas forced climate change; they are not predictions regarding the nature of such climatic change. Tables 3 and 4 show the results of these runs; Table 5 shows the difference between the Scenario T8 and T58 results.

Table 3. Forcasted annual runoff (using Scenario T8 calibration) in millimeters and percent increase for a variety of uniform temperature and precipitation adjustments.

Runoff (mm/day, Δ%)	Change in Precipitation		
Change in Temperature	0%	+10%	-10%
+0° C	5.92, +0%	6.99, +18%	4.93, -17%
+2° C	4.93, -17%	6.01, +2%	4.23, -29%
+4° C	4.18, -29%	4.95, -16%	3.47, -41%

Table 4. Forecasted annual runoff (using Scenario T58 calibration) in millimeters and percent increase for a variety of uniform temperature and precipitation adjustments.

Runoff (mm/day, Δ%)	Change in Precipitation		
Change in Temperature	0%	+10%	-10%
+0° C	5.42, 0%	6.39, +18%	4.51, -17%
+2° C	4.49, -17%	5.31, -2%	3.72, -31%
+4° C	3.52, -35%	4.19, -23%	2.91, -46%

Table 5. Difference in percentage increase/decrease between Scenarios T8 and T58 modeled runoffs (T8 minus T58) under various climate change scenarios.

Dif. in Δ% Runoff	Change in Precipitation		
Change in Temperature	0%	+10%	-10%
+0° C	0%	0%	0%
+2° C	0%	4%	2%
+4° C	6%	7%	6%

As one looks horizontally across the table, the differences in model projections do not significantly change. This result implies that the addition length in record does not impact forecasts of runoff under precipitation changes. As one moves vertically down the table, the forecast begin to visibly diverge. Increasing temperatures apparently cause the additional information to become more important.

The observation that the runoff forecasts begin to diverge with increases in temperatures is not surprising. At higher temperatures, Thornthwaite's potential evapotranspiration becomes increasingly nonlinear. This statement is evident from the sample PET values given by Thornthwaite's method in Figure 17. Because of this non-linearity, any differences in the temperature of the base data will have increasing impact on the evaporation values at higher temperatures.

The timing of the temperature difference also contributes to the different changes in runoff at higher temperatures. Although the annual mean temperatures of the two scenarios do not greatly differ, Scenario T58 has higher temperature values in July and August. These months coincide with the highest precipitation values. Since water balance defines runoff as the difference between the precipitation and evapotranspiration, variation in the evapotranspiration during the runoff producing months will have an important effect on the annual quantity of runoff.

The dynamics of this time series do not have a significant affect on the assessment of climate change impacts. Chapter 5 shows that the mean values obtained from the sample of the time series are more important than the inter-year variability. A time series where the period of sample can greatly affect the mean can still affect the climate change impact assessment. However, this sensitivity is greater with respect to temperature than precipitation, and variability in temperature series is normally small (which is true for the Blue Nile Basin).

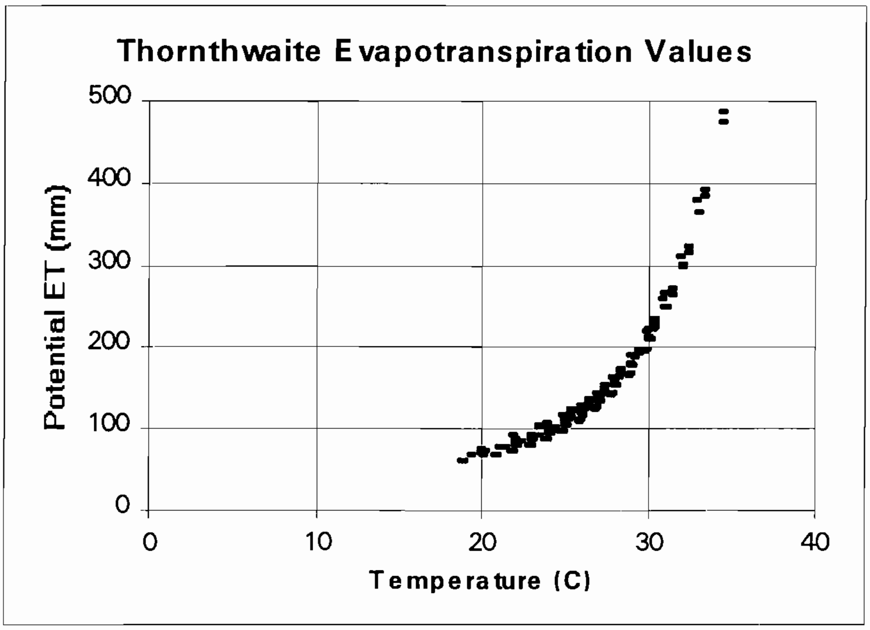


Figure 17. Potential evapotranspiration values for various temperatures as given by Thornthwaite's equation. A generic base year of monthly values are shown along with increased monthly temperature values.

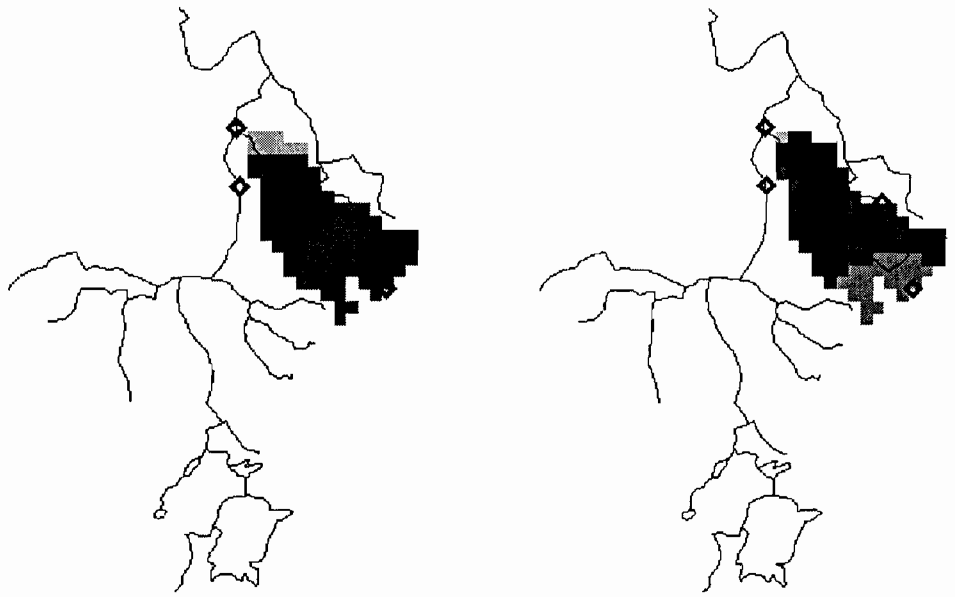
7. Spatial Issues: Density of Hydroclimatic Stations

In addition to the question of temporal sampling in determining a "base climate," the issue of spatial representation is also important. As stated above, the Blue Nile Basin cannot accurately be assumed to be homogeneous (neither for climate nor for topography). Consequently, good spatial representation is expected to be important in this basin. For the Blue Nile Basin case study, this section investigates the impact of increasing the number of base climatic data stations on the runoff assessments under climate change.

7.1 Definition of scenarios

Similar to Chapter 6, two scenarios were utilized to evaluate the importance of spatial representation. Again, both scenarios were developed from the 1993 NCAR world monthly Surface Climatology database. Scenario S3 represents the worst case: sparse representation of the basin. This scenario uses 3 stations for the period of 1953-1960; *notice that this is the same scenario as Scenario T8 in Chapter 6.* Scenario S7 has better (although still sparse) spatial representation with 7 stations for the same 8 year period. Both scenarios use an integrated approach in modeling the basin.

Areal precipitation and temperature averages were determined using simple Thiessen Polygons. The locations of the stations for each scenario with respect to the basin boundaries are shown in Figure 18 A and B. Notice that Scenario S3 does not include any stations within the basin boundaries (only Khartoum on the basin boundary). The station elevations (for both scenarios) are plotted along the elevation of the river's center line in Figures 19 and 20. As stated above Scenario S3 gives a mean temperature and mean annual precipitation of 22.3 C and 789 mm, respectively. Scenario S7 gives values of 23.2 C and 895 mm, respectively. The scenario with the greater density of stations clearly shows the basin as both warmer and wetter on average. In addition, the scenarios disagree on which month has the highest precipitation value--July or August. Figures 21 and 22 show monthly mean temperature and total precipitation values for Scenarios S3 and S7.



(A) **(B)**

Figure 18. Scenario S3 (A) and S7 (B) station locations and associated Thiessen Polygons with the Blue Nile Basin boundary overlaid.

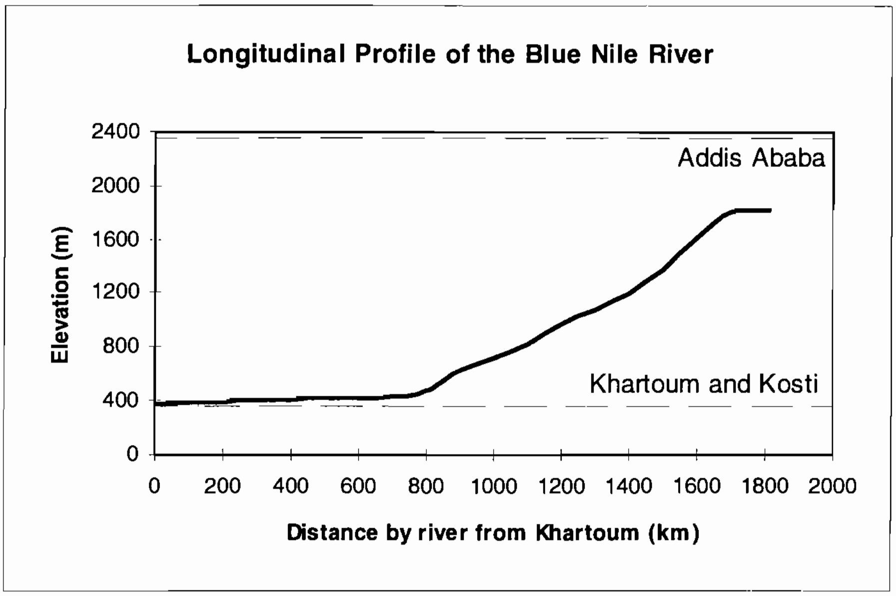


Figure 19. Scenario S3 station elevations plotted with the Blue Nile River longitudinal profile (from Shahin, 1985).

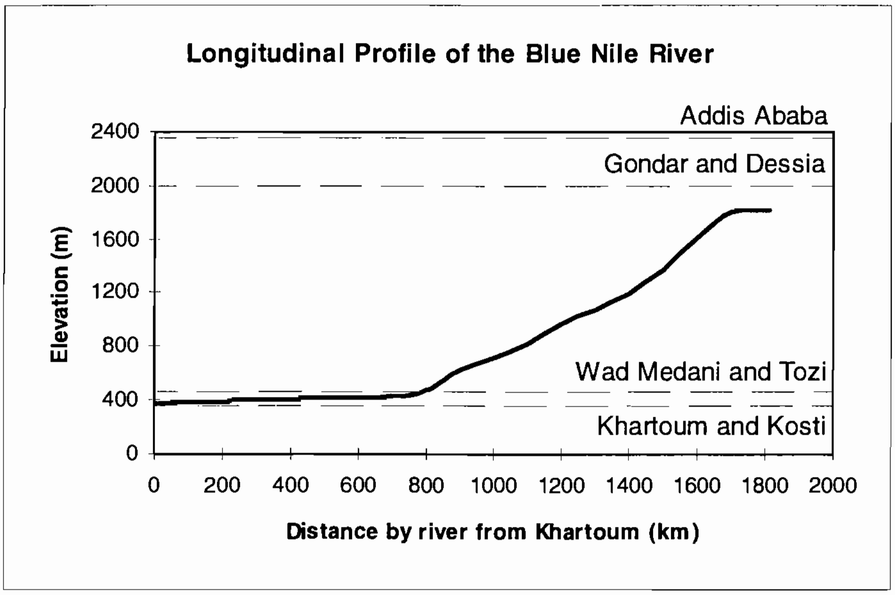


Figure 20. Scenario S7 station elevations plotted with the Blue Nile River longitudinal profile (from Shahin, 1985).

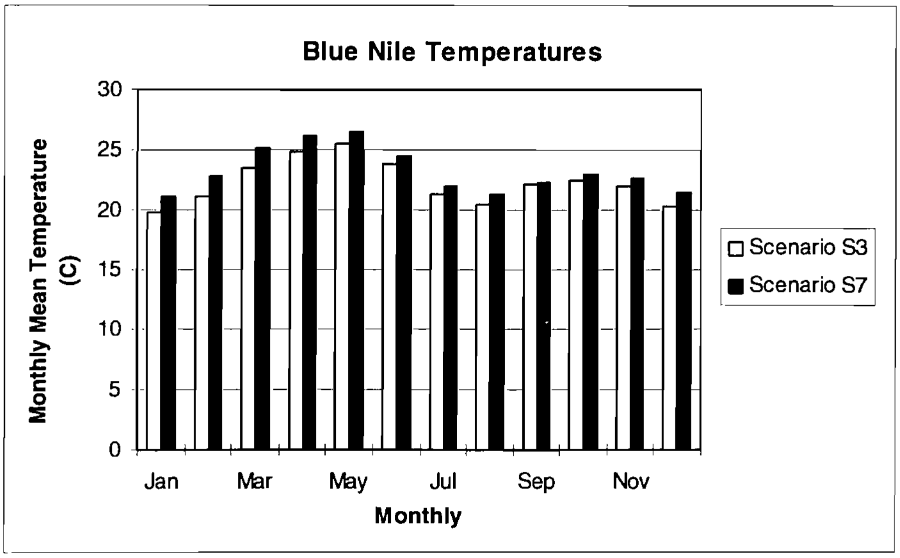


Figure 21. Monthly mean temperature in the Blue Nile Basin for Scenarios S3 and S7.

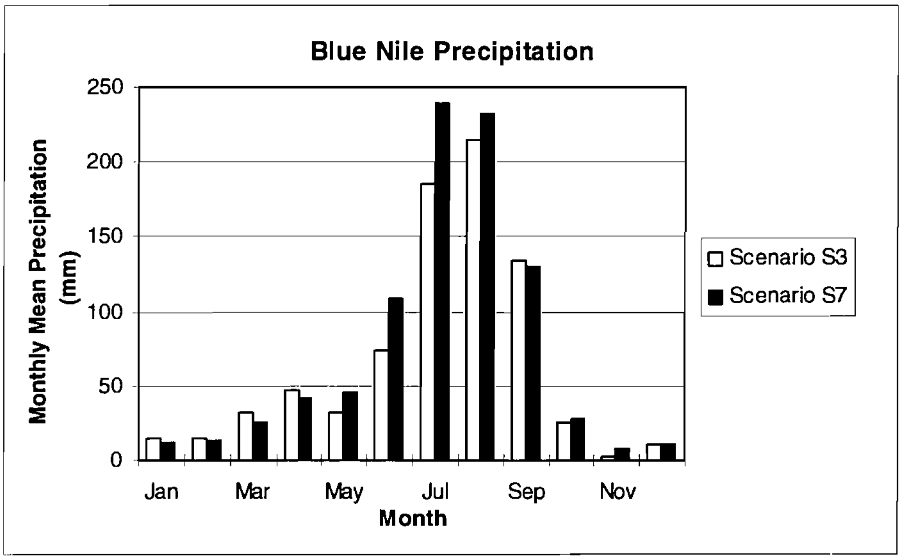


Figure 22. Monthly mean total precipitation in the Blue Nile Basin for Scenarios S3 and S7.

7.2 Results and the importance of station density

In a fashion similar to Chapter 6, the model was calibrated to the base data of Scenario S7; the calibration from Chapter 6 was used again for Scenario S3. Since the scenarios spanned the same period, the calibration technique involved calibrating different climatic data to the same naturalized stream flow. The two calibrations show significantly different contributions from surface and subsurface flow. Figure 23 shows a comparison between the calibrated model and the measured streamflow for Scenario S7. Tables 3 and 6 give the forecasted runoffs for each of the climate change scenarios. Table 7 compares the output for Scenarios S3 and S7 for each of the climate change runs.

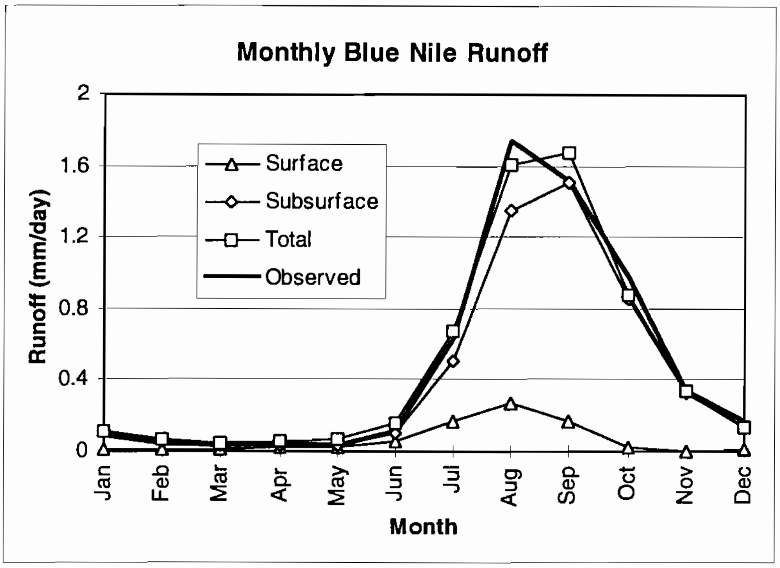


Figure 23. Comparison of modeled monthly runoffs (using Scenario S7 calibration) with historical (1953-1960) monthly means.

Table 6. Forecasted annual runoff (using Scenario S7 calibration) in millimeters and percent increase for a variety of uniform temperature and precipitation adjustments.

Runoff (mm/day, Δ%)	Change in Precipitation		
Change in Temperature	0%	+10%	-10%
+0° C	5.81, 0%	6.91, +19%	4.81, -17%
+2° C	4.75, -18%	5.66, -3%	3.93, -32%
+4° C	3.69, -37%	4.40, -24%	3.04, -48%

Table 7. Difference in percentage increase/decrease between Scenarios S3 and S7 modeled runoffs (S3 minus S7) under various climate change scenarios.

Dif. in Δ% Runoff	Change in Precipitation		
Change in Temperature	0%	+10%	-10%
+0° C	0%	-1%	0%
+2° C	1%	5%	3%
+4° C	8%	8%	7%

Here again, the differences between the scenario outputs are relatively small. With the increased precipitation in the base data, Scenario S7 has more water entering the system. However, with increased evapotranspiration, this scenario allows less to runoff. This is evident when comparing the runoff under each scenario's base run. For base temperature with increases and decreases in precipitation, the models forecast similar changes in runoff. As temperature increases, the model calibrations respond differently, giving up to an 8% difference in (percent) change in forecasted runoff. This again is expected due to the non-linearity of Thornthwaite's PET. Thus, the scenario with the warmer base run temperatures shows the more dramatic decrease in runoff under climate change.

Further investigation could be valuable in investigating the importance of station density. Seven stations remain a sparse climatic representation for such a large basin. A similar investigation with more climatic stations would offer another point on the "value of information curve." Also, both scenarios in this study utilize an integrated approach to model the basin hydrology. With a sub-basin approach (where the model is run for a set of sub-basins but calibrated simultaneously), the information gained by greater station density may become more important. Considering the topography of the Blue Nile Basin (see Figure 3), it is likely that such an approach could provide additional insight.

8. Gridded Base Data Sources

With the emergence of long-distance data transfer and the low cost of CD-ROM production, the scientific community is beginning to see a blossoming of the number of global and regional databases as well as an endless updating of data. These databases are often passed from scientist to scientist without much information about the quality of the data or the original intent for which the data was prepared. They are sometimes used quite indiscriminately, and frequently, results cannot be replicated due to different releases of the data or different manipulation of the raw data. The authors faced these very issues and performed the followed experiments to investigate the importance of different data sources on climate impact assessment.

8.1 Definition of the issues

Although two databases may attempt to represent the same information (i.e., average monthly temperature and precipitation in the Blue Nile Basin), this does not preclude their supplying different values. Such differences may stem from a variety of sources including the following:

- Different sets of stations may be used. To date, no complete cataloguing of available climatic data has been performed and not all data are readily available to the public. Consequently, database creators can utilize only *known* and *available* data.
- Some data may be disregarded as untrustworthy (e.g., how to handle outliers).

- Databases are often updated. Therefore, stations may be added or removed with an update.
- Different adjustment techniques may be applied to the data. Data may require adjustments to compensate for under-estimation of precipitation (snowfall, etc.) or relocation of station, etc.
- A variety of interpolation techniques can be utilized to obtain areal averages of climatic values. Commonly used techniques include: inverse distance weighting, kriging, and trend surface interpolation. Interpolation may also vary according to the projected used.
- Correlations with other information may also be employed to enhance the interpolation scheme. Temperature and precipitation, for instance, decrease and increase with elevation. As a result, lapse rates can be developed to adjust the data according to the cell elevations

8.2 Existing results

Although a thorough consideration of the above issues is beyond the scope of this paper, a sample case will be given. Two gridded databases were used to obtain base climate values for the water balance model: the Africa89 database and the IIASA database (see descriptions above).

The IIASA database shows the Blue Nile Basin as being significantly cooler and wetter than the Africa89 representation. According to the Africa89 and IIASA databases, the mean annual precipitation was 784 mm and 1004 mm, respectively. They also gave mean temperature values of 25.6 C and 22.0 C, respectively. Although a lower temperature value might be expected as (a result of the application of the adiabatic lapse rate to interpolate the temperature values of higher elevation cells), the temperature is relatively similar to those calculated throughout Chapter 6 and 7. Therefore, the difference is probably due to the lack of the Lake Tana temperature station in the Africa89 representation. The differences in precipitation are probably the result of the wider variance of historical precipitation values (compared to temperature). Consequently, the differences in stations and record spans may significantly affect these values (see Chapter 6 and 7). Figure 24 and 25 compare the calibrated model with the observed discharges for each representation of the Blue Nile Basin.

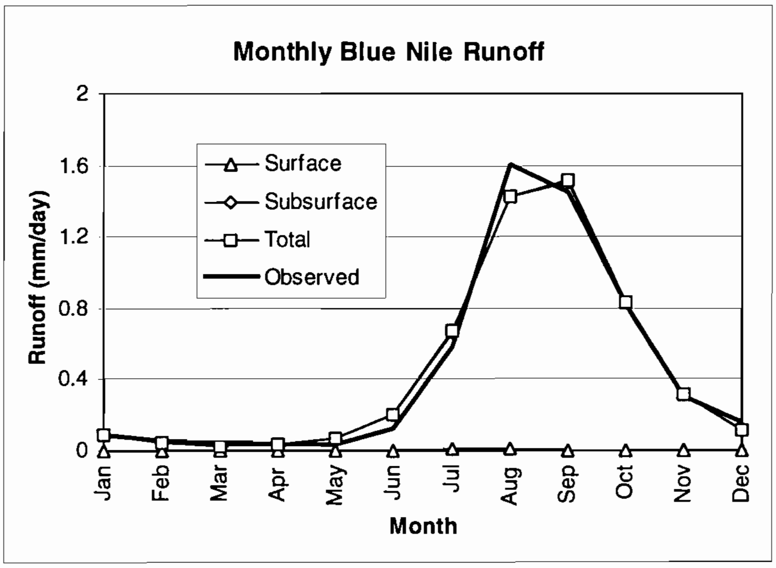


Figure 24. Comparison of modeled monthly runoffs (using Africa89 Calibration) with historical (1912-1970) monthly means.

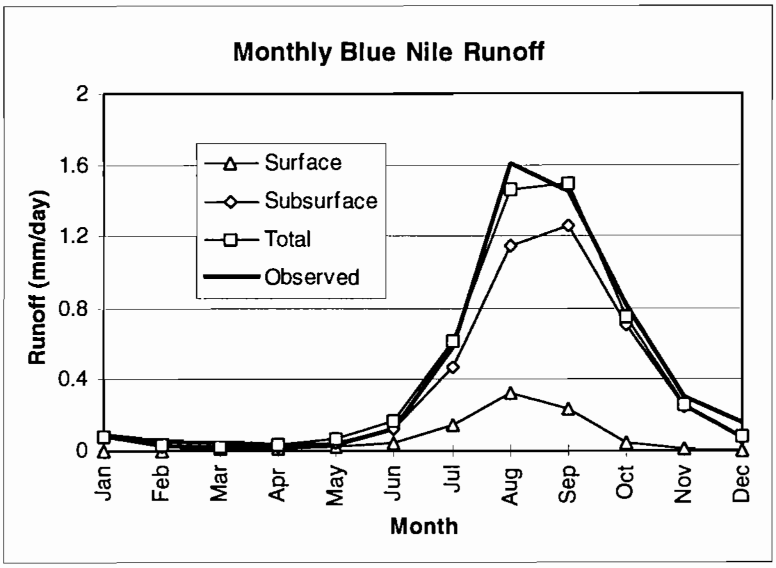


Figure 25. Comparison of modeled monthly runoffs (using IIASA Calibration) with historical (1912-1970) monthly means.

Tables 8 and 9 display the forecasted runoff values and contain some surprising results. In addition to the difference in base run, the different databases imply slightly different impacts due to climate change. As Table 10 shows, the differences (again) become more severe as temperature increases, however, they are not limited to temperature increases. Noticeable variations occur even without increasing temperature. The table also shows a surprising large difference of 10% for the 2° and 10% increase (temperature and precipitation, respectively).

Table 8. Forecasted annual runoff (using Strzepek and Smith Database) in millimeters and percent increase for a variety of uniform temperature and precipitation adjustments.

Runoff (mm/day, Δ%)	Change in Precipitation		
Change in Temperature	0%	+10%	-10%
+0° C	5.36, 0%	6.28, +17%	4.49, -16%
+2° C	4.00, -25%	4.73, -12%	3.33, -38%
+4° C	2.73, -49%	3.25, -39%	2.26, -58%

Table 9. Forecasted annual runoff (using IIASA Database) in millimeters and percent increase for a variety of uniform temperature and precipitation adjustments.

Runoff (mm/day, Δ%)	Change in Precipitation		
Change in Temperature	0%	+10%	-10%
+0° C	5.25, 0%	6.41, +22%	4.25, -19%
+2° C	4.20, -20%	5.15, -2%	3.38, -36%
+4° C	3.16, -40%	3.87, -26%	2.54, -52%

Table 10. Difference in percentage increase/decrease between Africa89 and IIASA modeled runoffs (Africa89 minus IIASA) under various climate change scenarios.

Dif. in Δ% Runoff	Change in Precipitation		
Change in Temperature	0%	+10%	-10%
+0° C	0%	-5%	3%
+2° C	-5%	-10%	-2%
+4° C	-9%	-13%	-6%

8.3 Need for Future Investigation

Clearly, the issues of the impact of using different gridded databases on climate change requires more complete study. The results of this study show that the impact of alternative input data to the hydrologic modeling of the Blue Nile is most sensitive to temperature (see discussion below). This experiment showed that spatially interpolating climate data particularly temperature can make significant difference in the lumped spatially averaged climate parameters, in this case 2.6 C in the annual average. Although this is only a 10%

difference, it is much more significant due to the fact that PET is highly non-linear. These experiments show only a 13% difference between the two data sets for the mean annual runoff, but it may have greater impacts when analyzing hydrologic extremes. More detailed study in different hydroclimatic zones also needs to be undertaken to examine this issue.

9. Conclusions

This study examines the impact of four different aspects of data on the assessment of climate change impact on Blue Nile Runoff. The goal of the type of climate impact modeling that is being tested here is policy analysis. What are the magnitude of potential climate change impacts on a river basin's (or a region's) water resources? Thus, the key model output of interest to the policy analyst is the impact on mean annual runoff. So the evaluation of these experiments are from this perspective and might not be the same if one is examining hydrologic extremes for more precise purposes. From the sensitivity analysis of runoff under temperature and precipitation changes (within the range suggested by Hulme, 1990, under a doubling of CO_2), we found:

- There was almost no difference in the results for mean annual runoff using a multi-year time series of monthly data for model input versus mean monthly values.
- The length of the data record proved to have only a small impact on the mean annual runoff, even though the annual mean runoff and climate variables over the periods of record had slightly different statistical relations.
- The spatial coverage of 3 versus 8 stations also proved to have only a small impact on the mean annual runoff. This result implies that for the Blue Nile Basin the information in the 3 station set describes the mean value processes over the large area nearly as well as the 8 station set.
- The difference between the two gridded databases exhibited the greatest difference of all the experiments. Even so, the difference of 13% would not be significant from a policy analysis viewpoint.
- When reviewing the results from all of the experiments, several trends were observed. The largest deviation consistently occurred at +4 C and +10% precipitation. The differences were generally small for changes in precipitation with temperature held constant, and they grew for increases in temperature with precipitation held constant. This result would suggest that the non-linearity in the relationship between temperature and PET spotlights the difference in the data. Even though the differences are small and do not impact the policy results, they do point to important issues about the model being used to perform these experiments.

Two companion papers Yates and Strzepek, 1994a and 1994b compare a number of climate impact hydrologic models over a range of basins in different hydroclimatic zones including the Blue Nile and the impact of different PET models on climate impact assessment.

This paper presents some useful results on the potential impact of data source on climate change impact assessment. The results are very specific to the Blue Nile basin and may not be transferable to other basins. However, they do highlight some interesting issues that need to be more fully explored, and the study represents one of the first entries into this arena for exploring some of the more basic areas of climate change assessment.

10. References

Abourgila, A. E. (1992), "Large Scale Hydrological Modelling of the Nile Basin for the Assessment of the Impact of Climate and Land Use Changes," Dept. of Civil Engineering, Imperial College of Science and Technology, London.

Carter, T.R., M.L. Parry, S. Nishioka, H. Harasawa (1992), "Preliminary Guidelines for Assessing Impacts of Climate Change," Intergovernmental Panel on Climate Change, WMO/UNEP.

Chang, L.H., C.T. Hunsaker, and J.D. Draves (1992), "Recent Research on effects of climate change on water resources," Water Resour. Bul., 28(2): 273-286.

Chen, R.S. and M.L. Parry (1987), "Policy-Oriented Impact Assessment of Climatic Variations," International Institute for Applied Systems Analysis, RR-87-7, Laxenburg, Austria.

Chow, V.T., D.R. Maidment, and L.W. Mays (1988), "Applied Hydrology," McGraw-Hill Publishing Company, New York.

Cohen, S.J. (1991), "Caveats in Applying GCM Output to Regional Impact Assessments," Proceedings of a Symposium on Climate Scenarios, M. Sanderson (Editor), University of Waterloo, June 12, 1991.

Dooge, J.C.I. (1992), "Hydrologic Models and climate change," J. of Geophysical Res., 97(D3): 2677-2686.

Gleick, P.H. (1987), "The Development and Testing of a Water Balance Model for Climate Impact Assessment: Modeling the Sacramento Basin," Water Resour. Res. 23(6): 1049-1061.

Gleick, P.H. (1991), "The Vulnerability of Runoff in the Nile Basin to Climatic Changes, Envir. Professional," 13: 43-58.

Green, P.J., and R. Sibson (1978), "Computing Dirichlet Tessellations in the Plane," The Computer Journal, 21, 168-173.

Griffiths, J.F. (72), "Climates of Africa," World survey climatology, Vol. 10.

Houghton, J.T., G.J. Jenkins, and J.J. Erasmus (Editors) (1990), "Climate Change: The IPCC Scientific Assessment," Cambridge University Press, Cambridge, UK.

Hulme, M. (1990), "Global Climate Change and the Nile Basin," In: The Nile: Resource Evaluation, Resource Management, Hydropolitics and Legal issues, P.P Howell and J.A. Allen (Editors), for a Royal Geographical Society Conference, London.

Isaaks, E. H. and R. M. Srivastava (1989), "Applied Geostatistics," Oxford University Press.

Kaczmarek, Z. and D. Krasuski (1991), "Sensitivity of Water Balance to Climate Change and Variability," IIASA Working Paper, WP-91-047, Laxenburg, Austria.

Leemans, R. and W.P. Cramer (1991), "The IIASA Database for Mean Monthly Values of Temperature, Precipitation, and Cloudiness on a Global Terrestrial Grid," RR-91-18, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Lettenmaier, D.P. and T.Y.Gan (1990), "Hydrologic Sensitivities of the Sacramento-San Joaquin River Basin, California, to Global Warming," Water Resour. Res. 26(1): 69-86.

Miller, J.R. and G.L. Russell (1992), "The Impact of Global Warming on River Runoff," J. of Geophysical Res., 97(D3): 2757-2764.

Nash, L.L. and P.H. Gleick (1993), "The Colorado River Basin and Climate Change: The Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation," United States Environmental Protection Agency, EPA230-R-93-009.

National Research Council (1979), "Carbon Dioxide and Climate: A Scientific Assessment," National Academy Press, Washington, D.C.

National Research Council (1987), "Current Issues in Atmospheric Change," National Academy Press, Washington, D.C.

Nèmec, J. and J. Schaake (1982), "Sensitivity of Water Resource Systems to Climate Variation," J. Sci. Hydrol. 27(3): 327-243.

Parry, M.L., T.R. Carter, and N.T. Konijn (Editors) (1987), "Assessment of Climate Impacts on Agriculture," Reidel, Dordrecht, The Netherlands.

Pearman, G.I. (Editor) (1988), "Greenhouse: Planning for Climate Change," CSIRO, Melbourne.

Robock, A., et al. (1993) "Use of General Circulation Model Output in the Creation of Climate Change Scenarios for Impact Analysis," Climatic Change, 23: 293-335.

Shahin, M. (1985), "Hydrology of the Nile Basin," Developments in Water Sci., 21, Elsevier, Amsterdam.

Shaw, E.M. (1983), "Hydrology in Practice," Van Nostrand Reinhold, Wokingham, Berkshire, United Kingdom.

Smith, J.B. and D. Tirpak (Editors) (1989), "The Potential Effects of Global Climate Change on the U.S.," US EPA, Washington, D.C.

Smith, S.E. and H.M. Al-Rawahy (1990), "The Blue Nile: Potential for Conflict and Alternatives for Meeting Future Demands," Water International, 15: 217-222.

Strzepek K. and J. Smith (1994), "As Climate Changes: International Impacts and Implications," Cambridge University Press, Cambridge, U.K.

Strzepek, K. and D. Yates (1994), "An Assessment of Climate Change Impacts on the Nile Basin: a Monthly Water Balance Approach," IIASA Working Paper, WP-94-47, Laxenburg, Austria.

Todini, E., (1988), "Rainfall-Runoff Modeling--Past, Present, and Future," J. of Hydrology, 100, 341-352.

United Kingdom Climate Change Impacts Review Group (1991), "The Potential Effects of Climate Change in the United Kingdom," UK Department of the Environment, London, UK.

Waggoner, P.E. (Editor) (1990), "Climate Change and U.S. Water Resources," Wiley Series in Climate and the Biosphere, M.H. Glantz and R.E. Dickinson (Series Editors). John Wiley and Sons, New York, New York.

World Meteorological Organization (1986), "Atmospheric Ozone 1985: Assessment of Our Understanding of the Processes Controlling Its Present Distribution and Change," Global Ozone Research and Monitoring Project - Report No. 16, Geneva, Switzerland.

Yates, D. and K. Strzepek (1994a), "A Comparison of Models for Climate Change Assessment of River Basin Runoff," IIASA Working Paper, WP-94-45, Laxenburg, Austria.

Yates, D. and K. Strzepek (1994b), "A Comparison of Potential Evapotranspiration Methods for Use in Climate Change Impact Assessments," IIASA Working Paper, WP-94-46, Laxenburg, Austria.