Water Resources Development, Vol. 12, No. 3, pp. 277–296, 1996

The Impacts of Climate Variability and Future Climate Change in the Nile Basin on Water Resources in Egypt

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ABSTRACT *This paper describes the application of hydrologic models of the Blue Nile and Lake Victoria sub-basins to assess the magnitude of potential impacts of climate change on Main Nile discharge. The models are calibrated to simulate historical observed runoff and then driven with the temperature and precipitation changes from three general circulation model (GCM) climate scenarios. The differences in the resulting magnitude and direction of changes in runoff highlight the inter-model differences in future climate change scenarios. A 'wet' case, 'dry' case and composite case produced* $+15$ *(*$+12$*),* -9 *(*-9*) and* $+1$ *(*$+7$*) per cent changes in mean annual Blue Nile (Lake Victoria) runoff for 2025, respectively. These figures are used to estimate changes in the availability of Nile water in Egypt by making assumptions about the runoff response in the other Nile sub-basins and the continued use of the Nile Waters Agreement. Comparison of these availability scenarios with demand projections for Egypt show a slight surplus of water in 2025 with and without climate change. If, however, water demand for desert reclamation is taken into account then water deficits occur for the present-day situation and also 2025 with ('dry' case GCM only) and without climate change. A revision of Egypt's allocation of Nile water based on the recent low-flow decade-mean flows of the Nile (1981–90) shows that during this period Egypt's water use actually exceeded availability. The magnitude of 'natural' fluctuations in discharge therefore has very important consequences for water resource management regardless of future climate change.*

Introduction

This paper presents an assessment of the sensitivity of runoff in the Nile Basin to climate change. This is achieved by using future climate change scenarios derived from general circulation models (GCMs) to drive hydrologic models of the Blue Nile and Lake Victoria sub-basins. Together these two sub-basins contribute over 70% of Main Nile discharge. A number of assumptions are made about the response of runoff in the other Nile sub-basins based on their similarities to either the Blue Nile or Lake Victoria sub-basins. Changes in runoff from all sub-basins are then used to derive an overall estimate of Main Nile discharge. The implications of these scenarios of Main Nile discharge are then discussed with reference to current 'natural' variability in runoff, future availability of water, and demand for water by the downstream riparian, Egypt.

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The Nile Basin is a complex hydrologic system draining an area of roughly 3 million km^2 and providing freshwater to millions of people (Figure 1). Within the Basin there are five major lakes of over 1000 km^2 surface area (Lakes Victoria, Edward, Albert, Kyoga and Tana), vast areas of permanent and seasonal wetlands (the Sudd, Bahr el Ghazal and Machar Marshes), five major reservoir dams (High Aswan Dam (HAD), Roseires, Khashm el Girba, Sennar and Jebel Aulia) and four important hydroelectric power dams (HAD, Tis Isat, Finchaa and Owen Falls). The course of the Nile flows from highland regions with abundant moisture to lowland plains with arid conditions. Egypt, and to a lesser extent Sudan, is almost wholly dependent upon water that originates from the upstream Nile Basin countries (Uganda, Ethiopia, Tanzania, Kenya, Rwanda, Burundi, Zaire and now Eritrea), which makes the issue of water resource management and ownership highly contentious and of strategic importance (Waterbury, 1979, 1982; Godana, 1985; Anderson, 1992; Howell & Allan, 1994).

Balancing the availability of water with demand for water is likely to become a major economic and environmental issue in many African countries in the future, and according to Falkenmark:

> By the year 2025, 1.1 billion people, representing two-thirds of the population of the African continent, will be living in conditions with severe water scarcity. (Falkenmark, 1991, p. 85)

The certainty of increased water demand in the future contrasts with the uncertainty of climatically induced changes in water supply. Estimates of future climate change due to greenhouse gas forcing alone with respect to the 1961–90 average (Hulme & Viner, 1996), are in the region of 0.6°C to 1.5°C increase in global-mean temperature by 2025. Associated with this increase in temperature will be changes in precipitation which, together with changes in potential evapotranspiration (PET), may have significant impacts upon river discharge. Population in Egypt is expected to double by 2025 (50 million in 1987 to 99 million in 2025) and the per capita supply of freshwater in Egypt is expected to decrease from 922 m^3 (1990) to 337 m^3 by 2025 (Abu-Zeid & Hefny, 1992). This makes it prudent to assess the sensitivity of runoff in the Nile Basin to potential future changes in climate.

A number of papers have looked at the implications of fluctuations in Nile discharge for water resources in Egypt, particularly since the prolonged period of low flows during the 1970s and 1980s (Demissie, 1990; Abu-Zeid & Biswas, 1991; Conway & Hulme, 1993). The historical fluctuations in Nile River discharge have also been reviewed by Shahin (1985), Evans (1990), Sutcliffe & Lazenby (1990) and Said (1993). Only a few studies, however, have attempted to evaluate the impacts of future climate change on runoff in the Nile Basin. The first of these was by Kite & Waititu (1981) who looked at the Nzoia river, a tributary of Lake Victoria, using the Sacramento Watershed catchment model. They analysed the effects on river flow and lake level of varying precipitation and evaporation in a sensitivity analysis. Hulme (1990) reviewed the factors affecting precipitation over the Nile Basin at different temporal and spatial scales. He presented future changes in temperature and precipitation, based on the results of a number of GCM experiments, for the Nile Basin with a discussion of their implications for Nile discharge. Gleick (1991) also analysed the vulnerability of Nile runoff to climate change. He applied Wigley & Jones's

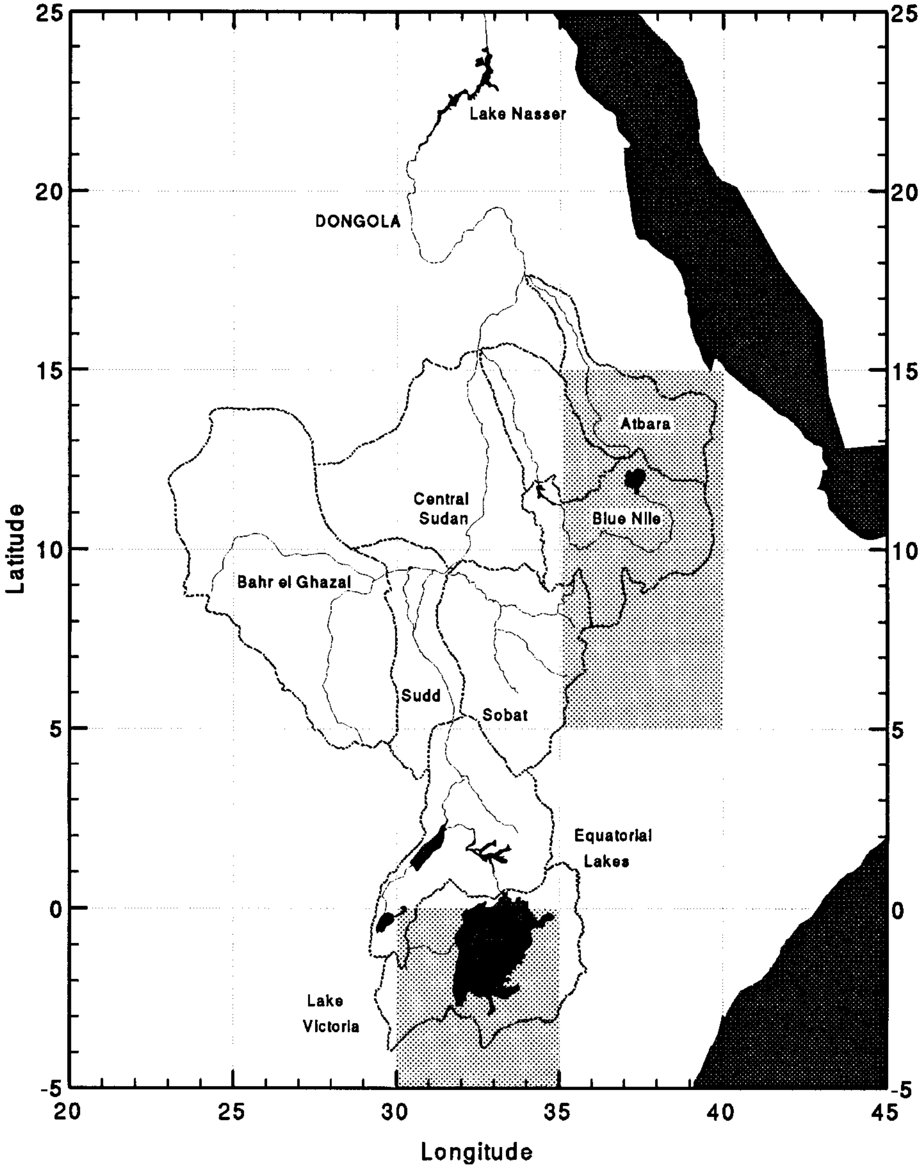

Figure 1. The Nile Basin, location of major sub-basins and GCM grid boxes used in the study (shaded areas, 5° × 5°).

(1985) theoretical model (based on the annual water balance) to three sub-basins of the Nile Basin, the Upper White Nile, Sobat and Blue Nile/Atbara. The model produced a 50% reduction in runoff in the Blue Nile catchment due to a 20% decrease in precipitation. Abu-Zeid & Biswas (1991) considered the implications of climate fluctuations for water management with an emphasis on Africa and the Nile. They stressed the uncertainties involved in predicting future climate change and that existing planning processes and hydrologic methodologies need to be improved to deal with such challenges. They also emphasized the importance of fluctuations in river flow over the historical period for managing water resources. Onyeji & Fischer (1994) undertook an economic analysis of potential impacts of climate change in Egypt. Their projections indicate a decline in self-sufficiency (agricultural and non-agricultural) and that climate change has a number of potentially negative effects. Their analysis does not incorporate climatically induced changes in Nile supply, although this is addressed by Strzepek *et al*. (1995). Other studies have concentrated on the potential impacts of sea-level rise in the Nile Delta (Milliman *et al*., 1989; Sestini, 1992). The models used in this study were used by Conway *et al*. (1996) as part of an integrated modelling approach to assess the impacts of driving forces at different spatial scales (global: climate change; regional: land-use change; river basin: water resource management policy) on runoff in the Nile Basin. To date this has been the only attempt to utilize basin-specific models of the Nile sub-basins with climate change scenarios taken from GCM experiments.

The Nile Hydrologic Models

Owing to the coarse spatial resolution of GCM output and the crude representation of runoff processes in GCMs most water resource impact studies use regional water balance models with only the temperature and precipitation changes taken from GCM experiments (Gleick, 1989). The hydrologic models used for climate impact studies are often data intensive, yet most of the Nile sub-basins have limited rain gauge coverage, few long-term temperature records, poor river gauge data since the early 1980s, and very scarce daily data. The size and complexity of the Nile sub-basins, together with the lack of data, is a severe constraint to the development of sophisticated catchment models. The development of less complex grid-based hydrologic models that require limited data inputs and run on monthly time-steps is, however, feasible for some of the Nile sub-basins. The Nile Basin may be divided into a number of sub-basins with very different physical, climatic and hydrological characteristics (Conway & Hulme, 1993). For impact assessment studies it is therefore necessary to treat each sub-basin separately. This section briefly describes the two hydrologic models used for this study (see Conway, 1993, for a more detailed description).

A model of the Blue Nile was developed along the lines of the hydrologic modelling approach used for the Amazon and Zambezi rivers by Vorosmurty *et al*. (1989; Vorosmurty & Moore, 1991). The model covers the catchment upstream of the El Diem river gauge on the Sudan–Ethiopia border, an area of roughly 170 000 km^2. In the model the catchment is divided into 10-minute latitude by 10-minute longitude grid cells. Estimates of mean monthly precipitation and evapotranspiration are calculated for all grid cells and fed into a simple monthly water balance. The runoff obtained for each cell is then summed to produce an overall estimate of catchment runoff (see Figure 2 for an overview of the model structure). The model has three adjustable parameters which are constant for all grid cells except for the cells representing the Lake Tana and Dabus swamp subcatchments. The grid cells in these two subcatchments require different parameter values in order to simulate the storage and delaying effect on runoff from these hydrologically special areas. The model was calibrated to reproduce mean monthly runoff at El Diem/Roseires (1951–87, extracted from World Bank, 1989; Hurst & Philips, 1933) and validated by its ability to simulate subcatch-

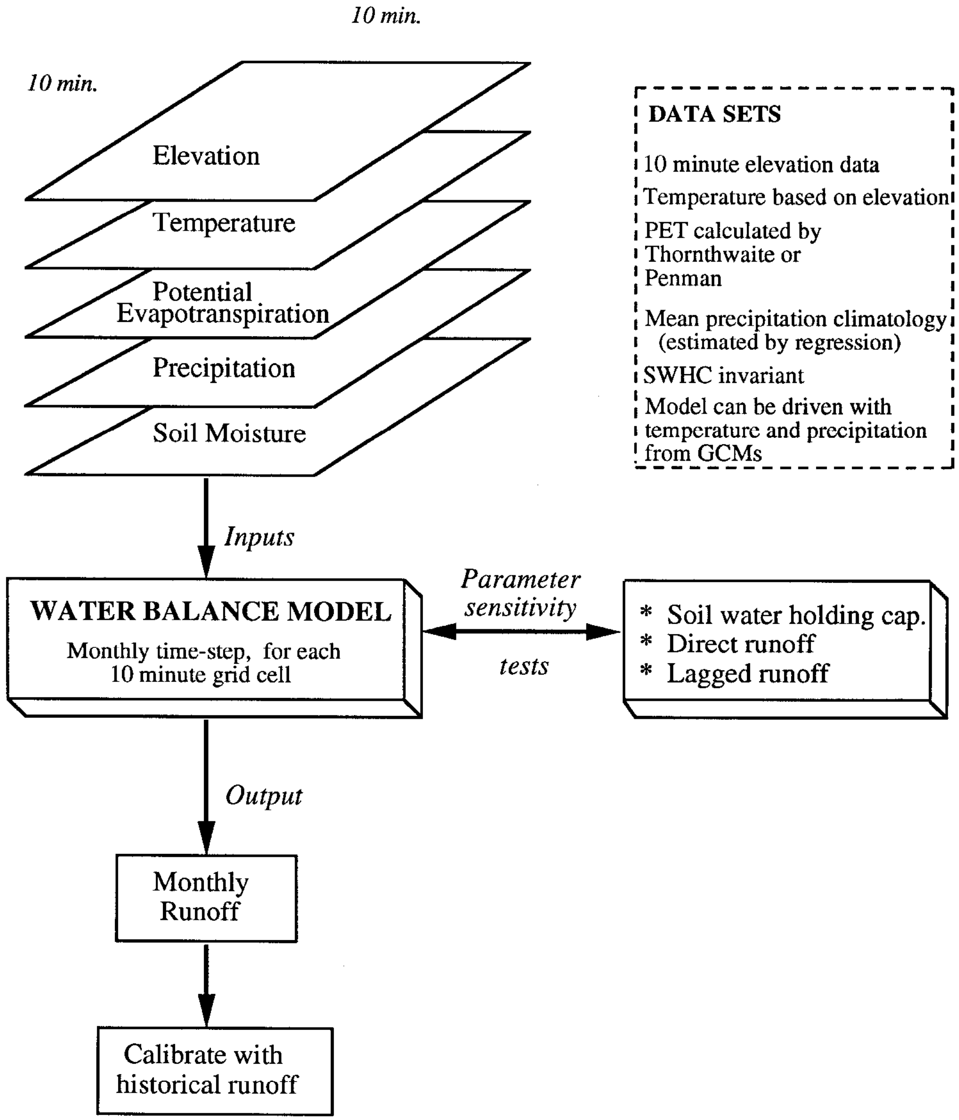

Figure 2. Structure of the water balance model of the Blue Nile River Basin (SWHC = Soil water holding capacity).

ment runoff and historical variations in Blue Nile runoff. Simulated mean annual runoff was within 3% of the observed, although fairly significant errors occurred in individual years. Considering the paucity of precipitation data for the sub-basin these results are reasonable. Figure 3 shows the observed and simulated monthly runoff for the Blue Nile upstream of Roseires/El Diem for the period between 1967 and 1986.

For Lake Victoria an existing monthly water balance model of the lake catchment was used. The model was developed by the Institute of Hydrology (IH) based on earlier work by Hydromet (Kite, 1981) to understand the cause of an unprecedented rise in the lake levels and outflows of the White Nile lakes

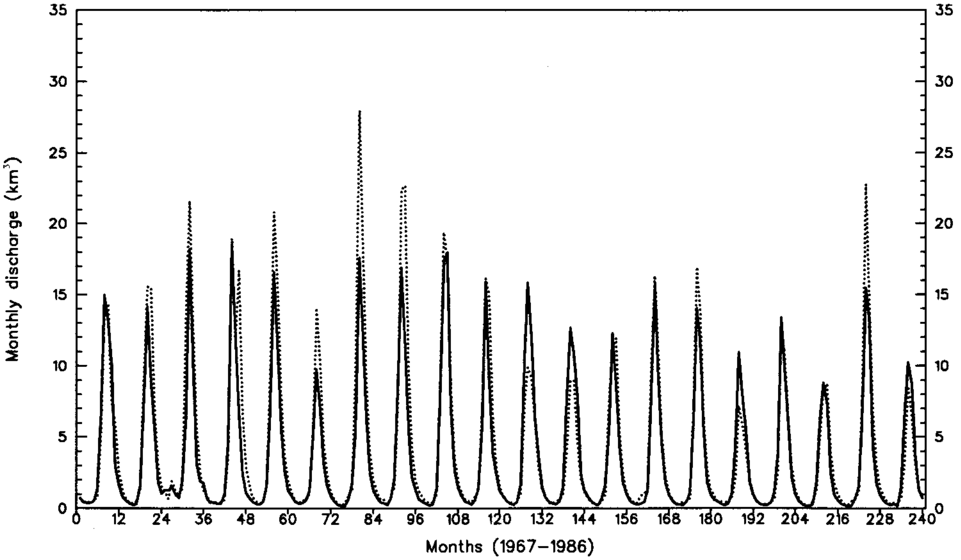

Figure 3. Observed (bold line) and simulated (dashed line) monthly Blue Nile discharge (km^3), 20-year period, 1967–86.

that occurred in the early 1960s (IH, 1984; Piper *et al.*, 1986). The model was recently updated by Sene & Plinston (1994) and used for climate impact studies by Conway (1993). The model uses historical observations of over-lake precipitation, lake tributary inflows, lake evaporation, lake levels and lake outflows. The best period for data availability (primarily limited by tributary inflow data) was between 1956 and 1978. For this period the model was able to reproduce historical fluctuations in lake levels using over-lake precipitation, tributary inflows and lake evaporation (Figure 4).

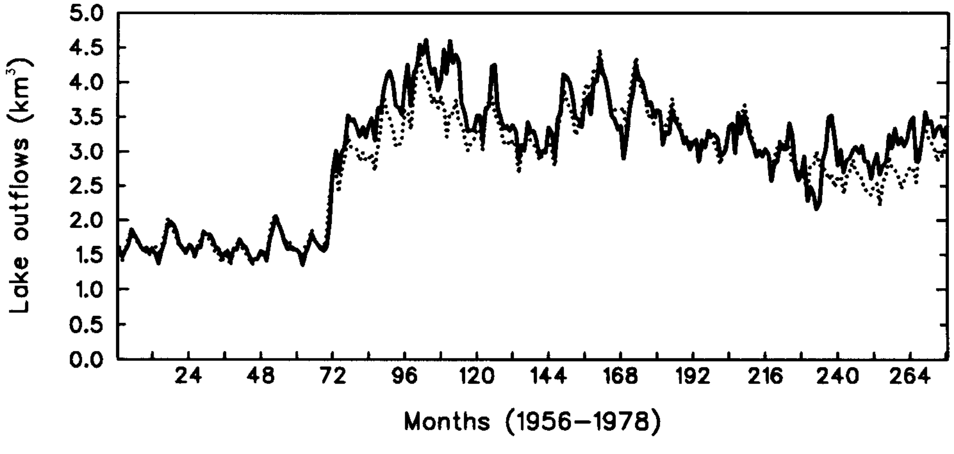

Figure 4. Observed (bold line) and simulated (dashed line) Lake Victoria outflows, 23-year period, 1956–78.

Future Climate Change

Climate Scenarios from General Circulation Models

GCMs are the most sophisticated method currently available for estimating the future effects of increasing greenhouse gas concentrations on climate (Carter *et al.*, 1995). Coupled ocean-atmosphere GCMs can calculate the time evolution of temperature plus humidity, wind, soil moisture, ice and other variables for the land surface and atmosphere. Model calculations are based on the laws of physics and executed at widely spaced points of a three-dimensional grid at a resolution of approximately 5° by 5° latitude and longitude (some GCMs now operate at 2.5° by 3.75° resolution). Control experiments are run to simulate current climate ($1 \times CO_2$) and two methods can be used to estimate the response of future climate to greenhouse gas forcing: equilibrium response and transient response. The equilibrium response of climate will be discussed here since only a few transient experiments have been conducted to date, and their results are less widely available and their use in impact studies is associated with some awkward methodological problems (Carter *et al.*, 1995). In equilibrium mode, the GCM is run with an abrupt increase in CO_2 concentrations, usually a doubling from 300 ppm to 600 ppm ($2 \times CO_2$). The difference between the $1 \times CO_2$ and the $2 \times CO_2$ climate at each grid point is then used to represent the equilibrium climate change to a doubling of atmospheric CO_2 (or CO_2 equivalent).

Climate scenarios from GCMs are *not* predictions. GCMs operate at various resolutions, use different representations of physical processes and hence produce different control climates and responses to increased CO_2. Control run simulations fail to reproduce accurately various features of current climate, particularly at regional scales and particularly with some precipitation regimes. There is also uncertainty about the role of feedback mechanisms, such as clouds or sea ice, in the response of the climate system to increases in greenhouse gases. Furthermore, assumptions need to be made that land cover does not change in the future and also, for example, that ocean circulation does not change. The GCM scenarios presented here are therefore no more than plausible estimates of the direction and magnitude of future climate change. The level of uncertainty in such results is, however, considerably less for temperature than for precipitation.

Future Climate Scenarios for the Blue Nile and Lake Victoria Sub-basins

The results from three equilibrium GCM experiments were used for this study. The Geophysical Fluid Dynamics Laboratory (GFDL; Weatherald & Manabe, 1986) and Goddard Institute for Space Studies (GISS; Hanson *et al.*, 1984) were chosen as examples of 'dry' and 'wet' cases, respectively to highlight the inter-model differences in precipitation changes. The third case was a composite scenario generated from seven different GCM experiments using a method originally developed by Santer *et al.* (1990) (see also Hulme, 1994). The Composite precipitation scenario was generated from a weighted mean of seven equilibrium GCM change fields (Hulme, 1994). Each GCM was given a weighting based on its ability to simulate current precipitation. The temperature changes were given equal weights in the composite scenario. In order to introduce time dependency into equilibrium GCM results the method developed by Santer *et al.* (1990) was used. The $2 \times CO_2 - 1 \times CO_2$ differences are divided

Table 1. Absolute change in temperature and percentage change in precipitation for three scenarios based on a 1°C increase in global mean temperature

	Temperature (°C)					Precipitation (%)				
GCM	DJF	MAM	JJA	SON	ANN	DJF	MAM	JJA	SON	ANN
Blue Nile:										
Composite	1.1	1.0	0.9	1.0	1.0	4.0	−1.1	2.6	3.6	2.2
GFDL	0.7	0.7	0.7	0.7	0.7	−3.0	−2.1	−1.1	−2.4	−1.9
GISS,	1.0	0.9	0.6	0.9	0.8	12.0	14.4	6.4	1.9	7.4
Lake Victoria:										
Composite	0.9	0.8	1.0	0.8	0.9	3.0	7.0	6.0	5.0	5.0
GFDL	0.6	0.7	0.6	0.7	0.7	3.0	−3.0	5.0	−3.0	−1.0
GISS	1.0	1.0	0.6	0.9	0.8	1.0	6.0	36.0	4.0	5.0

Note: Annual and seasonal (December–February DJF, March–May MAM, June–August JJA, September–November SON) changes are shown. Changes are shown for two grid points (Blue Nile, mean 37.5°E, 12.5°N & 37.5°E, 7.5°N Lake Victoria, 32.5°E, 2.5°S), and have been standardized by each climate model sensitivity (see Hulme, 1994).

by the overall climate sensitivity of each GCM (e.g. 4.2° GISS and 4.0° GFDL) to produce a standardized change in temperature/precipitation per degree Celsius change in global-mean temperature. The climate sensitivity is a term used to describe the equilibrium global-mean temperature change for a doubling of atmospheric CO_2—a figure that varies considerably between GCM experiments. For this study a rise of 1°C in global-mean temperature was chosen to represent the realized temperature rise by the year 2025 with respect to the present (defined as the average of 1961–90). This increase is comfortably within the range of temperatures estimated using a range of emissions scenarios, climate sensitivities and ignoring the cooling effect of sulphate aerosols (Hulme & Viner, 1996).

Table 1 lists the seasonal (December–February DJF, March–May MAM, June–August JJA, September–November SON) and annual absolute temperature and percentage precipitation changes produced by the three scenarios for the mean of two grid boxes overlying the Blue Nile (37.5°E, 7.5°N; 37.5°E, 12.5°N) and one grid box overlying Lake Victoria (32.5°E, 2.5°S) (see Figure 1). All three scenarios show increases in temperature in all four seasons. The GCMs produced a much less homogeneous set of changes in seasonal and annual precipitation. Changes in annual precipitation ranged from −2% (GFDL) to +7% (GISS) over the Blue Nile. The significant differences of magnitude, and direction of change, for precipitation highlight the well-known disparities between GCM simulations of precipitation (e.g. Gates *et al.*, 1992). For the grid box overlying Lake Victoria (32.5°E, 2.5°S) temperature changes were similar in magnitude to those in the Blue Nile Basin, with GISS slightly warmer than GFDL. The dry scenario (GFDL) only produced a decrease in precipitation in MAM and SON and an overall annual decrease of 1%.

Impacts on Runoff in the Blue Nile and Lake Victoria Basins

GCM Scenarios

To generate climate change fields for input to the Blue Nile model, the GCM

Table 2. The percentage change in Blue Nile and Lake Victoria mean annual runoff

		% change in annual runoff	
GCM	Changed climate inputs	Blue Nile Basin	Lake Victoria
Composite	PET and precipitation	+ 0.7	+ 6.9
GFDL	"	− 8.6	− 9.2
GISS	"	+ 15.3	+ 11.8
Composite	PET only	− 6.0	− 9.2
GFDL	"	− 4.1	− 6.9
GISS	"	− 3.9	− 8.8
Composite	Precipitation only	+ 6.9	+ 16.2
GFDL	"	− 4.5	− 2.3
GISS	"	+ 19.7	+ 20.9

Note: Three climate scenarios, with different combinations of PET and precipitation changes applied, each assuming a 1° global mean warming.

changes from eight adjacent grid boxes (30°E–45°E; 0°N–20°N) were interpolated to a 10-minute resolution using a Gaussian space-filtering method. The gridded fields of seasonal changes in precipitation and temperature were used to drive the Blue Nile model. The model was run for 24 months to simulate mean monthly runoff for the calibration period and the first 12 months of the simulation were discarded to allow soil moisture and lagged runoff to adjust to the new climate. Seasonal changes were applied to each month in their respective seasons. Simulations were performed with both PET and precipitation changed, with only PET changed, and with only precipitation changed. The method of converting temperature changes into percentage changes in PET was derived by Budyko (1982) as used by Nash & Gleick (1991). The relationship assumes a 4% change in PET per 1° change in temperature. A similar approach was followed for the Lake Victoria model. For each scenario the seasonal changes in temperature and precipitation for the grid box overlying Lake Victoria were applied to all years in the lake-level simulation.

The differences between the observed runoff and the runoff under a perturbed climate were calculated and are listed in Table 2 expressed as percentage changes in annual runoff. As expected, for both sub-basins, the dry and wet GCM scenarios produce decreases and increases in outflows, respectively. For the Blue Nile and Lake Victoria with the composite scenario the losses due to increased temperature were offset by the increase in precipitation. Figure 5 shows the optimized and perturbed mean monthly runoff for the Blue Nile after applying the PET and precipitation changes from the three GCM scenarios. The largest changes occurred in July, August and September but there were no significant changes in the annual cycle of monthly runoff. There was also no significant change in the seasonality of outflows from Lake Victoria (Figure 6). The results with only PET and only precipitation changed highlight an interesting difference between the two sub-basins: changes in PET have a greater impact on runoff in Lake Victoria than in the Blue Nile model owing to the large expanse of open water in the lake sub-basin.

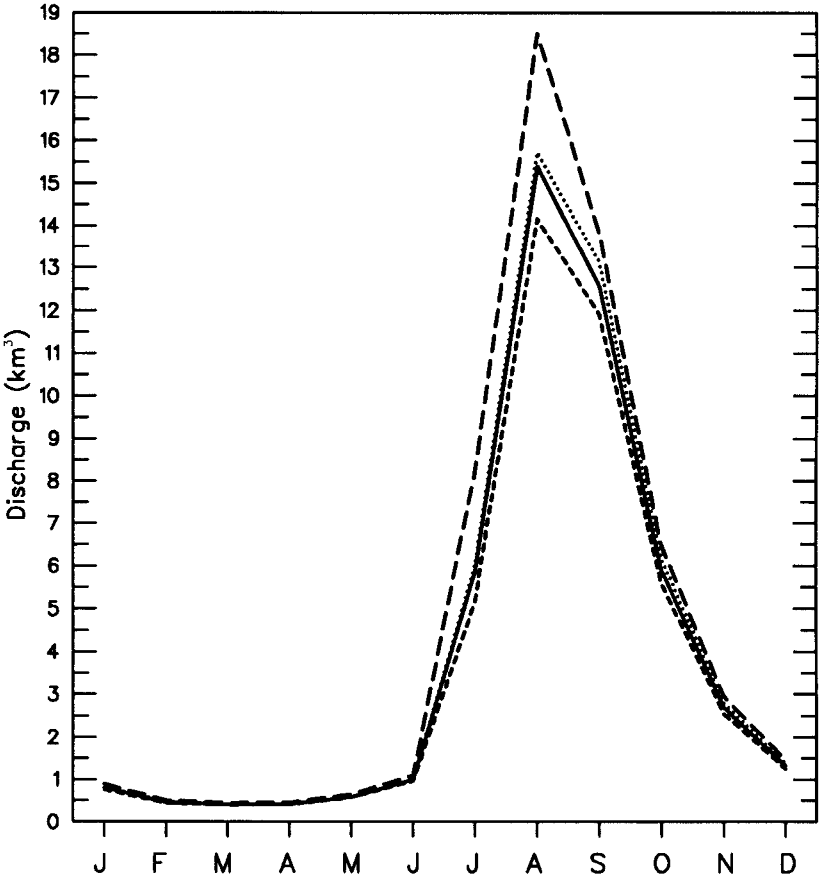

Figure 5. Optimized and GCM scenario mean monthly runoff for the Blue Nile based on 1951–87 runoff at El Diem: —— optimized; · · · · composite; - - - - GFDL; – – – GISS.

Sensitivity of Runoff to Climate Change: Hypothetical Changes in PET and Precipitation

A range of hypothetical changes in PET and precipitation were used to drive the sub-basin models to examine their sensitivity further. PET was changed by ± 4% and precipitation changed in 5% steps from − 25% to + 25%. The anomalies were applied equally to all months. The results, expressed as percentage change in annual runoff, are shown for the Blue Nile in Figure 7. Changes in precipitation produce larger changes in runoff than changes in PET. The runoff response is greater than the precipitation anomaly: a 10% increase in precipitation causes a 34% increase in runoff and a 4% decrease in PET causes an 8% increase in runoff. The relationship between change in precipitation and change in runoff is roughly linear (but not 1:1) down to a 10% reduction in precipitation. A 25% increase in catchment precipitation caused a 90% increase in runoff and a 25% decrease caused a 70% reduction in run-off. In contrast, for Lake Victoria (not shown) a 10% increase in precipitation causes a 31% increase in runoff and a 4% increase in PET causes an 11% decrease in runoff. This greater sensitivity

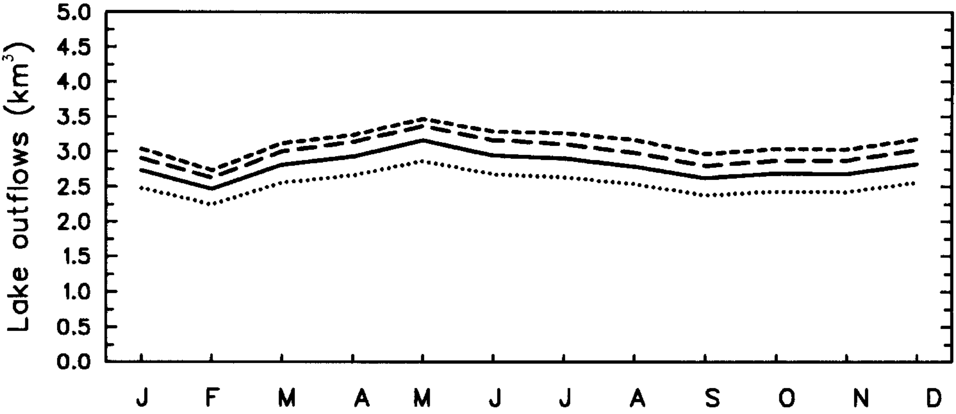

Figure 6. Observed and GCM scenario mean monthly Lake Victoria outflows based on 1956–78: —— observed; – – – composite; · · · · GFDL; - - - - GISS.

of runoff to changes in precipitation than to changes in PET has also been found in other modelling studies (for example Nemec & Schaake, 1982) and theoretically by Wigley & Jones (1985).

Implications of Natural Variability and Future Climate Change for Water Resources in Egypt

Impact of 'Natural' Variability on Water Supply

Fluctuations in decade-mean Main Nile discharge of up to ±20% have occurred during this century (Conway & Hulme, 1993). This 'natural' variability in the discharge of the Main Nile has had important consequences for water resource management in Egypt (Abu-Zeid & Abdel-Dayum, 1992). This section presents an analysis of the availability of water and demand for water in Egypt projected for the year 2025. Two Nile flow scenarios are used; one based on the long-term mean Nile discharge (1900–59) currently used for water resource management, and an extreme low-flow case based on the decade-mean discharge (1981–90).

Three projections of future water availability and demand for water were drawn up by the Egyptian Ministry of Public Works and Water Resources as part of a long-term water resource management plan. The mid-case is used here (S3, see Abu Zeid & Hefny, 1992). Table 3 shows a breakdown of current (1990) and projected (2025) water availability and demand in Egypt under this projection which is based on the following assumptions:

- completion of the Jonglei canal;
- increases in groundwater extraction;
- increased reuse of agricultural drainage water;
- field-irrigation efficiency improved to 65%;
- potable water-use efficiency improved to 80% (currently 50%);
- improved control of water transport and distribution;
- the 1959 Nile Waters Agreement to provide the legal basis for water planning;
- no allowance for potential increases in abstractions from the upstream riparians.

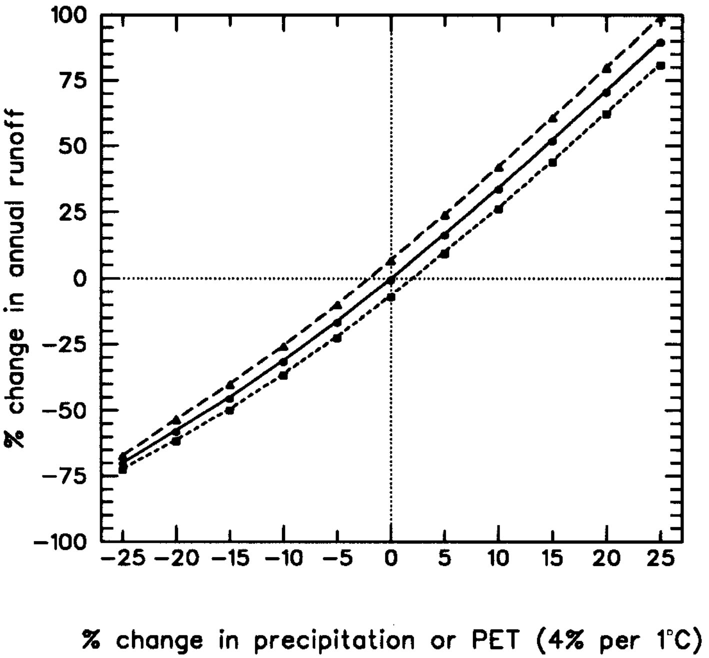

Figure 7. Change in mean annual Blue Nile runoff with a range of hypothetical PET and precipitation changes: —— PET 0%; - - - - PET + 4%; – – – PET − 4%.

Two assumptions about climate are implicit in the projection of water availability:

- a return to the mean annual flow volume based on the period between 1900 and 1959;
- no change in availability or demand (±) as a result of climate change due to increasing concentrations of greenhouse gases (or, indeed, any other cause).

The first two columns in Table 3 show that there will be a fine balance between the future availability of water and demand for water. It should be noted that some of these projections are based on assumptions that will not necessarily hold true and the estimates of future demand are rather conservative. If the land reclamation policy is fully implemented it will lead to a shortfall in supply of 0.9 km^3 by 2025 (based on a demand of 1 km^3 per 67 000 ha; Abu Zeid & Hefny, 1992). It is clear therefore that the proportion of water now allocated for agricultural purposes will have to decrease as non-agricultural demands increase in the future.

Table 4 shows the division of water between Egypt and Sudan according to the Nile Waters Agreement of 1959, based on a mean annual flow of 84 km^3 for the period 1900–59. Also shown is an equivalent breakdown based on the mean flow for the period between 1981 and 1990. A revision of water availability and demand projections based on these figures makes the current level of demand exceed availability (see figures in bold, first column of Table 3). With regard to 1990 there is a water surplus of 4.3 km^3 based on the 1900–59 mean annual

Table 3. Current (1990) and projected (2025) water availability and demand scenarios for Egypt (km^3)

	Current climate		Changed climate		
			Scenarios for 2025		
	1990	S3	Comp (T only)	GFDL (T only)	GISS (T only)
Water sources:					
River Nile	55.5	55.5	56.4 (51.5)	50.1 (52.7)	64.7 (52.7)
	49.9	49.9	50.7 (46.3)	45.0 (47.4)	58.3 (47.3)
Jonglei Canal	—	2.0	Completion is not certain		
Deep groundwater	0.5	3.5	Unlikely to be affected on this timescale		
Nile Valley and Delta groundwater	2.6	3.6	Aquifier recharge rates may change. Salt water incursion in the Nile Delta		
Agricultural drainage water	4.7	5.0	Direct CO_2 effects on crop water use. Higher irrigation water losses due to increased PET		
Treated sewage water	0.2	2.0			
Total	63.5	71.6	72.5 (67.6)	66.2 (68.8)	80.8 (68.8)
	57.9	66.0	66.8 (62.4)	61.1 (63.5)	71.4 (63.4)
Water demand:					
Agriculture (present area)	49.7	46.6	Likely to increase		
Municipal and industrial	7.7	10.8	"		
Navigation	1.8	0.3	"		
Total	59.2	57.7	57.7	57.7	57.7
Water surplus/deficit:	4.3	13.9	14.8 (9.9)	8.5 (11.1)	23.1 (11.1)
	−1.3	8.3	9.1 (4.7)	3.4 (5.8)	16.7 (5.7)
Water demand for desert reclamation	5.2	14.3	14.3	14.3	14.3
Water surplus/deficit	−0.9	−0.4	0.3 (−4.4)	−5.8 (−3.2)	8.8 (−3.2)
	−6.5	−6.0	−5.2 (−9.6)	−10.9 (−8.5)	2.4 (−8.6)

Note: S3 is future demand without climate change. Climate change scenarios taken from this study; see text. Normal figures are based on the mean for 1900–59, figures in bold are based on the extreme low decade-mean discharge between 1981 and 1990. T only = temperature change only.
Source: Adapted from Abu Zeid & Hefny (1992, p. 45).

discharge, and a surplus of 13.9 km^3 projected for 2025. When the availability figure is based on the 1981–90 mean, current demand exceeds availability by 1.3 km^3 and the projected surplus for 2025 is reduced to 8.3 km^3. This deficit has so far been met by stored water in the HAD reservoir and additional water from Sudan's allocation which has not been fully utilized. Currently, there is no clear evidence to suggest that a return to higher rainfall in the Sahel of Africa, and by association Blue Nile flows, is any more likely than a continuation of the present conditions (Hulme & Kelly, 1993). Recent Nile flows have, however, returned to nearer the long-term mean and, following a wet year, the 1994 flood level was higher than average and HAD reservoir levels surpassed the level of 173 m for the first time since 1987 (Anon, 1993). Nevertheless the magnitude of 'natural' fluctuations in discharge clearly has very important consequences for water resource management regardless of future climate change.

Table 4. Allocation of water according to the Nile Waters Agreement 1959, based on the original mean annual flow (1900–59) and the recent decade-mean (1981–90)

	Volume (km^3) 1900–59	%	Volume (km^3) 1981–90
Egypt	55.5	75	49.9
Sudan	18.5	25	16.6
HAD reservoir evaporation	10.0	—	10.0
Mean flow (km^3)	84.0	—	76.5

Implications of Climate Change due to the Enhanced Greenhouse Effect for Main Nile Discharge

Against the background of high 'natural' variability and a fine balance between future water availability and demand, climatically induced changes in Main Nile discharge will further increase the uncertainty of this vital natural resource. The impacts of climate change on runoff have been calculated for the two largest contributing Nile sub-basins ($>70\%$ of Main Nile discharge). In order to translate these changes in terms of Main Nile discharge a number of assumptions about the response of the other sub-basins were made based on their characteristics and their similarities to either the Blue Nile or Lake Victoria sub-basins. These are described in Conway *et al.* (1996), and summarized in Table 5. Annual mean discharges (based on the period 1900–59 to allow comparison with the scenarios in Table 3) were calculated for all sub-basins that contribute to the Main Nile. The percentage changes in mean runoff produced by the models in each of the climate scenarios were then applied to these discharge volumes in the manner described in Table 5. To assess the implications of these changes for Egypt the resulting Main Nile discharges were calculated and divided according to the Nile Waters Agreement (see Table 4). After subtracting 10 km^3 for evaporation at Aswan the total was split 75% for Egypt and 25% for Sudan to represent their allocations of water under a future flow scenario. Table 3 lists the resulting flow allocations for Egypt together with potential impacts on the other water sources in Egypt and potential increases in demand for water for land reclamation.

The three climate-change scenarios produced changes in Main Nile discharge and hence Egypt's allocation of Nile water of $+0.9$ km^3, -5.4 km^3, and $+9.2$ km^3 (composite, GFDL, GISS, respectively, Table 3 top figures in last three columns) by 2025. Without the water requirements for land reclamation none of the scenarios leads to an estimated deficit between water availability and demand by 2025. With land reclamation, however, the GFDL scenario produces a water deficit, and if the 1981–90 flows are now typical of the 'natural' background flow in the absence of greenhouse gas-induced climate change then substantial deficits appear for both the composite and GFDL scenarios (figures in bold). With only changes in PET applied (results shown in parentheses, Table 3), all scenarios produce fairly substantial reductions in discharge. These reductions are on the conservative side because no allowance has been made for increased losses to evaporation from river and reservoir surfaces in the semi-arid and arid parts of Sudan. In addition to this a 1°C increase in temperature in Upper Egypt would increase losses to evaporation from the HAD reservoir by

Table 5. Annual mean discharges and losses to evaporation for the Nile sub-basins (km^3)

Sub-basin	Volume of water contribution or loss 1900–59 (km^3)	Perturbation applied
Lake Victoria	+20.78	% change produced by Lake Victoria model
Equatorial Lakes	+5.99	No change
Sudd	−12.60	The percentage historical loss is used (−47.1%) See Sutcliffe & Parks (1987)
Bahr el Ghazal	0.00	No change
Sobat	+13.48	% change produced by Blue Nile model is applied to half the Sobat discharge
Central Sudan	−3.15	No change
Blue Nile (El Diem)	+50.22	% change produced by Blue Nile model
Blue Nile (Khartoum):		
Evap.	−2.45	No change
Dinder	+1.09	% change produced by Blue Nile model
Rahad	+2.99	% change produced by Blue Nile model
Atbara	+12.43	% change produced by Blue Nile model
Northern Sudan	−3.00	No change
Total	85.78	Scaled to 1900–59 mean discharge; 84.00

Note: All means based as far as possible on the period 1900–59 used for the Nile Waters Agreement. The treatment of each sub-basin in order to calculate the impact of climate change on Main Nile discharge is summarized.

0.4 km^3 (assuming annual losses to be 10 km^3 and a 4% change in PET per degree change in temperature).

Conclusions

This paper has described the application of methods to assess the potential impacts of climate change on runoff in the Nile Basin. Hydrologic models of the Blue Nile and Lake Victoria sub-basins were driven with future climate scenarios derived from a number of GCM experiments and a range of hypothetical climate changes. Three scenarios were chosen for the climate sensitivity study: a ‘dry’ case (GFDL), a ‘wet’ case (GISS) and a composite case generated from a weighted mean of seven GCM experiments. Both PET and precipitation changes were applied and also PET changes alone because of the higher uncertainty associated with the precipitation changes. The climate perturbations were applied to the model simulations of mean monthly runoff (no consideration in this study was given to changes in interannual climate variability). The three scenarios with both PET and precipitation changes applied (PET only) produced the following changes in annual runoff: Blue Nile −8.6% (−4.1%), +15.3% (−3.9%), and +0.7% (−6.0%) with the dry, wet and composite scenarios, respectively; Lake Victoria −9.2% (−6.9% with only PET changed), +11.8% (−8.8%), and +6.9% (−9.2%) for the dry, wet and composite scenarios, respectively. Sensitivity analysis showed that runoff was slightly less (more) sensitive in the Lake Victoria Basin to changes in precipitation (PET) than runoff in the Blue Nile Basin. Changes in PET had a greater impact in Lake Victoria than in the Blue Nile, although they were not as significant as changes in precipitation.

To discuss how these findings relate practically to Egyptian water management it is first necessary to review the uncertainties in the analysis:

- It is not yet possible to predict future climate change with a known degree of confidence. There are large uncertainties in the climate scenarios derived from GCMs, particularly in the precipitation changes. The scenarios presented here are therefore *not* predictions and to highlight the uncertainties examples of dry and wet futures have been used. It is therefore not yet possible to produce reliable estimates of future Nile discharge taking into account the effects of climate change; a range of possibilities must be considered.
- Because of their different hydrologic characteristics the Nile sub-basins will have varying responses to any given change in climate. Because of the lack of data for some sub-basins simple assumptions have been made about their response to climate-change scenarios based on historical evidence and their similarity to either the Blue Nile or Lake Victoria sub-basins.
- The hydrologic models are being used for conditions for which they were not calibrated; the models do not incorporate changes in vegetation or soil properties that may change in response to climate change; they also do not account for changes in stomatal resistance which will affect the water-use efficiency of vegetation; the climate inputs to the models are based on empirical relationships (temperature and PET) that may no longer be valid in a changed climate; and alternative hydrologic models may produce different responses to the same changes in climate because of differences in their structure and parameter values (Leavesley, 1994). For these reasons, some of the sensitivity obtained here may therefore be an artefact of the model itself rather than a realistic response to climate change.
- There is uncertainty concerning the future availability of water from non-Nile sources and a high level of uncertainty in forecasting socioeconomic change in demand for water.

Notwithstanding these uncertainties the results of this analysis highlight the following:

- ‘Natural’ variability is critical for water supply in Egypt because the balance between the availability of water and demand for water is very fine. It is important to define the baseline Nile flows since these vary considerably depending upon which period they are taken from. It is shown here that, based on the recent low-flow decade-mean flows of the Nile, Egypt’s current water use actually exceeds current availability. This water deficit has only been maintained by extra water from Sudan’s unused allocation and storage in the HAD reservoir. Such a situation cannot continue indefinitely if Nile flows remain at their present level and would at some stage call for an updating of the 1959 agreement based on mean discharge for, say, the 1961–90 period.
- Population in Egypt is expected to double by 2025 (50 million in 1987 to 99 million in 2025) and the per capita quota of freshwater which was 922 m^3 in 1990 is expected to fall to 337 m^3 by 2025. The potential for future climatically-induced changes in supply could exacerbate this situation. Using the Blue Nile

and Lake Victoria models, together with some simple assumptions about the other Nile sub-basins, the following changes in Egypt's allocation of Nile water were obtained: $+0.8$ km^3 (-3.6 km^3), -4.9 km^3 (-2.6 km^3) and $+8.4$ km^3 ($+2.6$ km^3) with both PET and precipitation changes (PET only) applied from the composite, GFDL and GISS GCM scenarios, respectively. These runoff scenarios are for 2025, based on mean annual Nile flows for the period 1900 to 1959, and assume a 1° global mean warming with regard to 1961–90.

- Historical evidence and the low runoff ratios of the Blue Nile Basin and most of the other Nile sub-basins suggest that runoff will have a fairly high sensitivity to changes in precipitation and temperature. The results from water balance models of the Blue Nile and Lake Victoria confirm this expectation. None of the scenarios suggested any changes in the seasonal distribution of runoff. The hydrologic model results show that changes in temperature are more important in the Lake Victoria sub-basin than in the Blue Nile sub-basin owing to the large expanse of open water.
- With the vast areas of swamp and open water in the Upper White Nile Basin and the semi-arid conditions and prevalence of irrigated agriculture on the part of the downstream riparians, changes in temperature and PET would have a major impact upon sub-basin runoff and may well be more critical than the direct impacts of changes in precipitation.

It is at least prudent for water resource planners to consider the potential of climatically induced changes in water availability, whatever their direction. 'Natural' fluctuations in Nile flows are already a problem for water management and future changes may well worsen the problem. Research into how to deal with fluctuations is necessary and Egypt's policy towards facing low flows is very important. At present, forecasting of flows is entirely based on discharge data at upstream gauges (Abu-Zeid & Abdel-Dayem, 1992). A new forecasting system is being developed in association with the USA using satellite estimates of precipitation in the headwater catchments (Schaake *et al.*, 1993). This will aid water management decisions (primarily releases from the HAD reservoir) on a year-to-year basis.

Future policy towards the management and development of water resources is also important. The planned land reclamation scheme will require a heavy commitment of water that will reduce flexibility of supply in other areas. This is at a time when the incorporation of flexibility in planning is important. Abu-Zeid & Hefny (1992) suggest that new sources of water are likely to be treated wastewater and agricultural drainage water. One other option is demand management based on improved allocation and economic pricing of water (LeMoigne *et al.*, 1992). Whittington & McClelland (1992) reviewed the economic rate of return on investment in land reclamation and found that it was probably significantly overestimated. As future demand for water for non-agricultural uses increases it will become increasingly necessary for water to be transferred from the agricultural sector and for food production to be substituted for imports. Egypt has moved from self-sufficiency in food during the 1970s to a position where roughly half the country's food requirements are imported (Onyeji & Fischer, 1994).

Finally, it is very likely that the upstream riparians will increase abstractions which will place a further constraint on water supply downstream in the midto long-term future (Abate, 1994). Historically the legal and institutional aspects of water management between the Nile Basin countries have been strained and subject to much controversy (Waterbury, 1987). Future water resource development and the potential of climatically induced changes in supply will increase the need for cooperation and coordinated planning. At present cooperation and communication in the Nile Basin is being promoted through a series of international conferences, started in 1993 in Aswan, to be held once a year in each member country (Shady *et al.*, 1994). Such measures now are vital to ensure that the increasing pressure on water resources in the future can be met with a planned and efficient solution rather than by crisis management.

Acknowledgements

This paper originated as part of a PhD thesis funded by the Stockholm Environment Institute.

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