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A water balance model of the Upper Blue Nile in Ethiopia

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Abstract This paper describes the development and validation of a water balance model of the Upper Blue Nile in Ethiopia. A major requirement of any modelling attempt is the availability of climatic and hydrological data. However, for the Upper Blue Nile, only a limited number of observation sites are available over a very large area. As a result, the model described here is a grid-based water balance model which requires limited data inputs, few parameters and runs on a monthly time-step. Climate is dominated by the influence of elevation in the river basin. Estimates of potential evapotranspiration (*PE*) and rainfall are predicted for 10-minute resolution grid cells for input to the model. These estimates are based on multiple regression models using latitude, longitude and elevation. In the basin, annual mean *PE* and rainfall range, with increasing elevation, from 1800 mm to 1200 mm and 924 mm to 1845 mm, respectively. In the model, vegetation cover is not explicitly treated and soil characteristics are spatially invariant. The model is calibrated to reproduce mean monthly runoff over a 37-year period (1953-1987), and validated by its ability to simulate sub-catchment runoff and historical variations in Blue Nile runoff. The key factor that determines model performance is the quality of the rainfall inputs, with the best results obtained with a time series comprised of long, good quality station data. Over a 76-year period the correlation between observed and simulated annual flows was 0.74 and the mean error was 14%, although fairly large errors occurred in individual years. Considering the paucity of data for the basin, these results are encouraging. The model is used to investigate spatial variability in the sensitivity of runoff to changes in rainfall and *PE*. The sensitivity is greatly affected by the runoff ratio of the model grid cells and it increases as grid cell runoff ratio decreases. The sensitivity is also affected by the seasonal distribution of rainfall. The paper ends with a discussion of the model's performance and its potential for future development.

Un modèle de bilan pour le bassin du haut Nil Bleu en Ethiopie

Résumé Cet article décrit le développement et la validation d'un modèle de bilan pour le bassin du haut Nil Bleu en Ethiopie. Dans toute tentative de modélisation il est avant tout nécessaire de disposer de données climatiques et hydrologiques. En ce qui concerne le haut Nil Bleu, il n'y a qu'un nombre limité de sites d'observation disponibles sur une vaste région. En conséquence, le modèle décrit ici consiste en un modèle de bilan d'eau sur un maillage dont les besoins en données sont modestes, qui possède peu de paramètres et qui fonctionne au pas de temps mensuel. Le climat du bassin est essentiellement influencé par l'altitude. Les estimations de l'évapotranspiration potentielle (*PE*) et de la hauteur des précipitations servant d'entrées au modèles ont été réalisées selon des mailles de 10 min. d'arc de côté. Ces évaluations ont été obtenues grâce à des modèles de régression multiple utilisant la latitude, la longitude et l'altitude. Dans le bassin, la moyenne annuelle moyenne de l'*PE* et des précipitations augmentent avec l'altitude et se situent respectivement dans des fourchettes allant de 1800 à 1200 mm et de 924 à 1845 mm. Dans le modèle la couverture végétale n'a pas été explicitement introduite et on a supposé que les caractéristiques du sol ne variaient pas spatialement. Le modèle a été calé en vue de reproduire le débit moyen mensuel (pendant une période de 37 ans, 1953-1987) et a été validé par sa capacité à simuler l'écoulement des sous bassins et les variations historiques de l'écoulement du Nil Bleu. Le facteur clé déterminant les performances du modèle est la qualité des données concernant les précipitations, les meilleurs résultats ayant été obtenus avec des séries chronologiques provenant de stations possédant de longues observations de bonne qualité. Pour une période de 76 ans la corrélation entre débits annuels observés et simulés est égale à 0.74, l'erreur

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moyenne étant de 14% bien que d'assez grandes erreurs aient été observées pour des années particulières. Compte tenu de la pauvreté des données dans le bassin, ces résultats sont encourageants. Le modèle est utilisé pour examiner la variabilité spatiale de la sensibilité de l'écoulement aux modifications de la hauteur des précipitations et de l'*PE*. Cette sensibilité est gravement affectée par la proportion de ruissellement au niveau de la maille du modèle et elle augmente lorsque la fraction ruisselée au niveau de la maille diminue. La sensibilité est également affectée par la distribution saisonnière de la hauteur des précipitations. L'article se termine par une discussion sur les performances du modèle et sur son potentiel de développement.

INTRODUCTION

The Blue Nile drains a large area of the Ethiopian Highlands and is the largest tributary of the Nile River, providing a vital source of freshwater to the downstream riparian users, Sudan and Egypt. To date, however, there have been very few published studies on the Upper Blue Nile. There are accounts of expeditions to the valley (Bruce, 1770; cited in Moorehead, 1969) and preliminary hydrological assessments (Hurst *et al.*, 1959). Several investigations have been carried out on Lake Tana (J. G. White Corporation, 1935; cited in United States Bureau of Reclamation (USBR), 1964a) mostly to assess the feasibility of increasing the storage capacity of the lake or diverting its waters into the Takeze, a tributary of the Atbara just to the north of the lake (Fig. 1). Indeed, apart from Lake Tana outflow records from 1923-1930 (Hurst & Philips, 1933), no published data existed for the whole of the Blue Nile in Ethiopia until the USBR carried out a major survey of the land and water resources of the Blue Nile basin between 1958 and 1963 (USBR, 1964a,b,c). Since then, other surveys on a smaller scale have almost certainly been commissioned by the Ethiopian Government, but these and their data are currently unavailable. To date, the USBR project represents the only such study of its kind on the Blue Nile. Virtually all recent literature on the Blue Nile has used the USBR study, directly or indirectly, as its source (Guariso & Whittington, 1987; Waterbury, 1988; Jovanovic, 1985; Collins, 1990; Tvedt, 1992; Johnson & Curtis, 1994).

More recently, Sutcliffe *et al.* (1989) and Dugdale *et al.* (1991) describe flood forecasting work on the Blue Nile using METEOSAT-derived rainfall estimates and a simple daily hydrological model. The World Bank has funded flood forecasting work on the Blue Nile undertaken by Delft Hydraulics, in association with the Soutanes Water Resources Department (Grimes *et al.*, 1993; El Amin El Nur *et al.*, 1993). An 11 region distributed model of the Blue Nile was developed, based on the Sacramento Watershed model (Grijsen *et al.*, 1992). Similar work is also in progress at the National Oceanic and Atmospheric Administration in Washington, USA, in association with the Egyptian Ministry of Public Works, who are developing a comprehensive model of the Nile river in order to predict the inflows to the High Aswan Dam reservoir (Barrett, 1993; Schaake *et al.*, 1993; Johnson & Curtis, 1994; Todd *et al.*, 1995). Johnson & Curtis (1994) describe the application of a monthly water balance model to a number of sub-catchments in the Blue Nile basin with available data. Both of these projects are constrained by the availability of data – particularly sub-catchment runoff data to develop a distributed hydrological model and gauge estimates of daily rainfall to calibrate the METEOSAT-derived estimates of rainfall. Simple modelling studies on the Blue Nile have been undertaken by

Gleick (1991) and Strzepek *et al.* (1996) as part of climate change impact assessments on the Nile river. The model described here has also been used for climate change impacts studies by Conway & Hulme (1996) and in a modified form by Conway *et al.* (1996).

The use of physically-based (conceptual) water balance models is perhaps the most appropriate method for simulating Blue Nile riverflow. The problems involved with developing even the simplest models lie primarily in data availability. Most established hydrological models are data intensive, yet the Blue Nile has limited raingauge coverage, few long term temperature records, few gauged subcatchments, and very scarce daily data. The size and complexity of the Blue Nile, together with the lack of data, is therefore a severe constraint to the application of sophisticated hydrological models. The development of less complex grid-based water balance models which require limited data inputs and run on monthly time steps is, however, feasible for the Blue Nile. Grid-based hydrological models may be integrated with Global Climate Model (GCM) land surface schemes and can easily utilize gridded remotely sensed data for model development and GCM results for climate sensitivity studies (Conway & Hulme, 1996).

The model developed here is an attempt to model in a distributed way the runoff from the Upper Blue Nile in Ethiopia using limited inputs of climate data on a monthly time step. The first part of this paper reviews the previous studies of the Upper Blue Nile and the physical characteristics of the river basin. The next parts deal with the generation of climate inputs to the model and its physical structure. Empirical relationships, based on the strong influence of elevation on temperature, potential evapotranspiration (*PE*) and rainfall in the basin, are used to construct multiple regression models to predict these variables at a grid cell resolution of 10 minutes. The following part describes the calibration and validation of the model which is then used to study spatial variation in the sensitivity of runoff to hypothetical changes in climate. The paper ends with a discussion of the model's performance and its potential for development based on new sources of data.

PHYSICAL DESCRIPTION

The Blue Nile River flows down through the upland plateau of the Ethiopian Highlands from its exit at Lake Tana (1780 m a.m.s.l.) to where it enters Sudan (500 m), a distance of roughly 940 km (Fig. 1). The river course is from humid to semiarid conditions and there is usually little additional runoff north of Roseires in the Sudan except for the two tributaries, the Dinder and the Rahad. These join downstream of Roseires and also have their headwaters in the Ethiopian Highlands. In this analysis, the contributing basin is taken to be the headwater regions of the Blue Nile, excluding the Rahad and Dinder tributaries (an area of roughly 176 000 km^2). Rainfall in the region is highly seasonal and the Blue Nile possesses a highly seasonal flood regime with over 80% of annual discharge occurring in the four months from July to October. The highland plateau has been deeply incised by

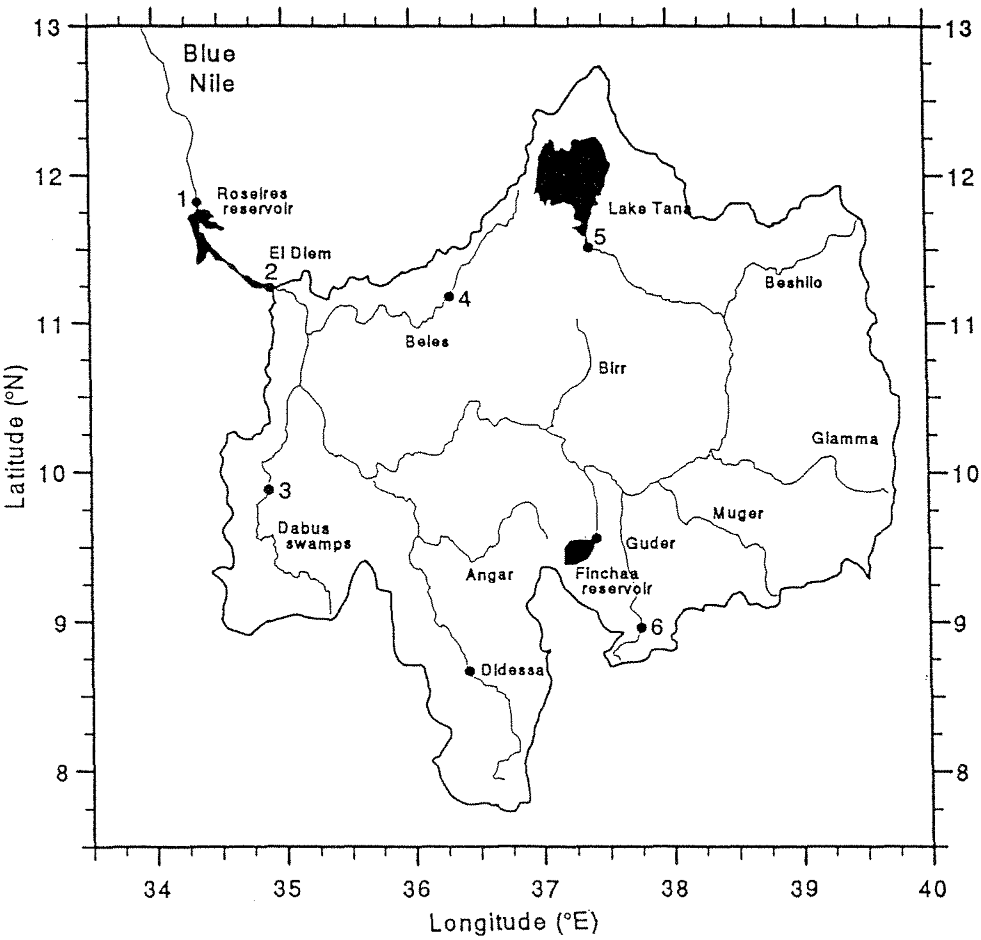

Fig. 1 Major tributaries of the Upper Blue Nile and location of river gauges used in the study: 1. Roseires, 2. El Diem, 3. Dabus, 4. Beles, 5. Lake Tana, 6. Upper Guder.

the Blue Nile and its tributaries and has a general slope to the northwest. Much of the plateau is above 2600 m and reaches its highest point at 4620 m in the Simen mountains (Mount Ras Dashen) northeast of Lake Tana. There are several other peaks above 4000 m on which snow sometimes falls, but it is not permanent and does not contribute significantly to Blue Nile runoff (Hurst, 1950). The plateau country is not flat, but rather hilly with grassy downs, swamp valleys and scattered trees. In places, the Blue Nile flows 1300 m below the level of the country on either side. At the foot of the plateau the plain slopes gradually westwards down into Sudan from a height of about 700 m.

The original natural vegetation was altitudinally zoned, but has now been greatly affected by agriculture and deforestation. At the time of writing, Hurst (1950) stated that the plateau was not thickly wooded, although forest often occurred on the slopes of river valleys. It is very difficult to assess exactly how land use and vegetation have changed before and since the USBR survey in the early 1960s because there is no detailed information or maps on land use and land cover in the Upper Blue Nile. At one time roughly 37% of Ethiopia was forested (~400 000 km^2) and the high plateaux were almost completely vegetated. However, the growth of population during the present century has devastated these areas and only about 40 000 km^2 of forest remain. In the 1960s closed forests were being cut in a slash-and-burn type agriculture and in 1964 the USBR found many areas where decreases in forest size were noticeable since 1957-1958 aerial photography surveys. Since then, forest depletion has continued, with woodland being replaced by scrub trees or bush, although some replanting (mainly *Eucalyptus globulus*) has occurred (Pohjonen & Pukkala, 1990). Although it is not possible to quantify the extent of land cover change during the last century, what evidence there is suggests that it has been substantial. Such changes, coupled with soil erosion problems, are likely to have had a significant impact upon the runoff regime (El-Swaify & Hurni, 1996).

Throughout the basin the soils are generally vertisols or latosols. The drainage system is well defined, and the gradient of most tributaries is steep. Flood waters quickly collect in the drainage channels (Hurst *et al.*, 1959; USBR, 1964b) and the loss to overflowing on flood plains or to evaporation is small over much of the basin. Because of the sparse growth of trees, steep slopes, and the shallow and often denuded soil, runoff is rapid and a relatively small amount of rainfall is retained by deep percolation or absorption (USBR, 1964b). Many of the Blue Nile tributaries often dry up in the dry season.

Two areas of special hydrological interest exist within the basin: Lake Tana and the Dabus swamps. The surface area of Lake Tana (3 000 km^2) is large in relation to its contributing area (roughly 20% of it) and because of the large storage capacity and the restriction at its outlet, the lake outflows peak (September) two months after maximum rainfall (July) and one month after maximum flows at Roseires (August). There is a slow decline in wet season flows that extends into the dry season. The Dabus swamps are located in the headwaters of the Dabus River, have an area of approximately 900 km^2 out of the 8030 km^2 total area upstream of the swamp outlet and there are large losses of water from the swamp to evaporation and transpiration (USBR, 1964b). The swamp has a considerable smoothing effect on the monthly distribution of runoff and the Dabus River contributes relatively little runoff to the peak flows of the Blue Nile in August and much higher proportions in low flow months, reaching a maximum in March.

Climate in the highlands is strongly influenced by the effects of elevation which makes the basin ideal for estimating climatic variables based on empirical relationships with elevation. The climate is generally temperate at higher elevations and tropical at lower elevations. Traditional classifications of climate in the Basin use elevation as a controlling factor and recognize the following three regions:

1. the *Kolla* zone below 1800 m has mean annual temperatures in the range 20-28°C;
2. the *Woina Dega* zone between 1800-2400 m has mean annual temperatures in the range 16-20°C; and
3. the *Dega* zone above 2400 m has mean annual temperatures in the range 6-16°C.

RUNOFF DATA AND CLIMATE DATA INPUTS

Runoff data

Good quality long runoff records for the Blue Nile are available only for river gauges in Sudan. Data from two such gauges are used here: Roseires and El Diem. The data for Roseires were obtained from *The Nile Basin* (Volume IV and supplements 1-11, Hurst & Philips, 1933) from 1912 up to 1977 and the data for El Diem (further upstream) were taken from World Bank (1989). The two records were combined (Roseires for 1912-1963, before construction of the Roseires dam, and El Diem for 1964-1987, subsequently) to provide a continuous time series of Blue Nile discharge (1912-1987). There is good agreement between annual runoff at both gauges during their period of overlap (annual correlation = 0.97, 1964-1977). A slight decline in flows has occurred since the 1960s up to the late 1980s (Demessie, 1990; Conway & Hulme, 1993). There are very few hydrological data for tributaries upstream of the El Diem gauge in Ethiopia. Runoff data are limited because of the remoteness of many of the catchments, lack of economic resources and infrastructure to build and maintain monitoring sites, and the concentration of urban development and population east of the Blue Nile in the Awash river basin and, consequently, less need for data on the Blue Nile itself. In some cases, more data may exist within Ethiopia, but these are difficult to obtain because of their sensitive nature and their perceived political and strategic value, particularly to the downstream riparian users.

The earliest records within Ethiopia are the Lake Tana levels and outflows between 1921 and 1932 (Hurst & Philips, 1933). The USBR (USBR, 1964b) report contains monthly flow data for a number of river gauges recorded between late 1959 and early 1963. Most of these gauges, however, were probably operational for only one or two years. Short series of riverflow data for a couple of sites were also obtained from Gamachu (1977) and the Global Runoff Data Centre (Koblenz, Germany). The quality of these data is unknown, although cross referencing between sources allowed limited verification. In addition, because the records are so short it is unlikely that they are representative of the long term mean conditions. For this study, data were used from the following sites: Lake Tana outflows (1921-32); Dabus River (1961/62); Upper Guder (1961); Didessa (1961) and Beles (1962) (Fig. 1).

Climate data

The primary data set used for this analysis was obtained from the Food and Agriculture Organization (FAO) *Agroclimatological Data Africa* vol. 1 (FAO, 1984). This contains monthly mean estimates of important agroclimatic variables, including rainfall and temperature. Observations are available for over 100 sites in Ethiopia and, as such, the data set represents easily the best spatial coverage of rainfall and *PE* observations available for the Blue Nile and provides enough samples to construct and independently check methods of prediction. Unfortunately, there is no indication of the quality of these data and the estimates are based on meteorological observations for unknown, and probably non-uniform, periods. A second data set was also used to estimate rainfall which consisted of raingauges inside and close to the Blue Nile basin for which monthly time series data were available. The data set is primarily the same as that used by Eklundh & Pilesjö (1990) with historical additions from the FAO Famine Early Warning System, Fantoli (1965) and the Ethiopian Meteorological Service. The length of record varies considerably, from 67 years to only four years at a number of gauges, with a mean length of about 15 years.

Climate inputs

To provide distributed climate inputs to the model, estimates of monthly mean *PE* and rainfall at 10 minute resolution were generated using multiple regression models based on latitude, longitude and elevation. To generate the *PE* estimates, all sites located inside and outside the basin within the region bounded by 33.5°-42.0°E and 6.5°-13.0°N were used. The total number of sites (67) was split randomly into a set for calibrating (34) and a set for validating (33) the alternative methods of estimation. The sites were evenly distributed over the Blue Nile basin but most concentrated between 7° and 9°N around Addis Ababa and in the Awash river basin (adjacent and southeast of the Blue Nile basin). A comparison of Thornthwaite and Penman estimates for a limited number of sites with both showed Thornthwaite underestimated Penman by roughly 35% in the dry season and 25% in the wet season (Conway, 1993). Because of the greater number and reliability of sites with temperature data (and hence Thornthwaite *PE*), a number of regression models were tried to predict monthly Penman *PE*. Four combinations of variables were used to predict monthly Penman: (i) Thornthwaite only; (ii) elevation only; (iii) latitude, longitude and elevation; and (iv) latitude, longitude and Thornthwaite. The results of monthly regression relationships for the two best combinations of predictor variables

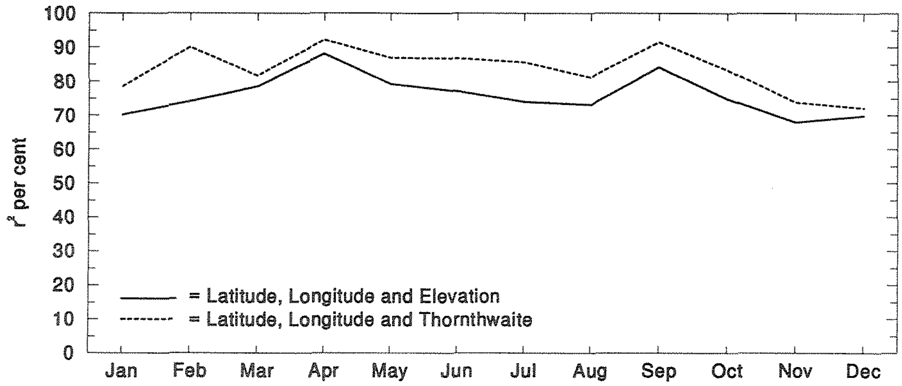

Fig. 2 R^2 values for multiple regression predictions of monthly Penman based on combinations of Thornthwaite, elevation, latitude and longitude (n = 43).

are shown in Fig. 2. The regression models accounted for over 70% of the variance in Penman in all months and produced monthly root mean square errors (RMSE) for the independent validation set of less than 10% of the observed values. It was decided to use the multiple regression model based on latitude, longitude and Thornthwaite to predict grid cell *PE* in the model. The resulting estimates of mean annual *PE* ranged from 1200 mm in the highest cells to 1800 mm in the lower lying grid cells in the Blue Nile gorge.

Mean annual rainfall was also predicted using multiple regression models based on gauge elevation, latitude and longitude. This method was adopted in order to incorporate the significant effects of elevation and is an expansion of the approach used for Ethiopia by Eklundh & Pilesjö (1990). The best results were obtained with a sub-set of the time series data set. Long term annual mean rainfall was calculated for 25 gauges located within 33.5°-42.0°E and 6.5°-13.0°N, and which possessed at least 16 years of data inside the 37 year period between 1951 and 1987. The model accounted for 63% of the variance in mean annual rainfall. Monthly regression models were not robust enough to predict monthly rainfall. For each cell, therefore, the mean annual rainfall was partitioned according to the corresponding standardized monthly distribution taken from the overlying 0.5° grid cell from the Legates & Willmott (1990) global rainfall data set. Mean annual rainfall ranged from 924 mm in the lowest cells to 1845 mm in the highest cells, with a gradual decrease from the southwest to the northeast, across the Blue Nile basin.

THE MODEL

The Blue Nile model is a combination of the Thornthwaite water balance approach (Thornthwaite & Mather, 1957) and the large scale hydrological modelling approach used for the Amazon and Zambezi rivers by Vorosmurty *et al.* (1989, 1991, respectively). The Blue Nile basin is divided into 10 minute (longitude and latitude) grid cells. Elevation data were available at this resolution and estimates of rainfall and *PE* were generated from observational data sets as previously described. Grid cell runoff is calculated using a simple water balance: for runoff (r) to occur, rainfall (p) must exceed *PE* and satisfy a soil moisture deficit (*SMD*). A small proportion (α) becomes direct runoff before the water balance is calculated. This component represents direct rainfall onto areas of surface water and saturated land in the catchment in order to generate runoff in months when rainfall is too low to satisfy the *SMD* and *PE*.

In the months in which rainfall exceeds *PE* and the *SMD* is satisfied, the excess is added to storage runoff (sr_{i-1}) left over from the previous time-step ($i - 1$) and the result is used to calculate the available runoff (ar_i) for that time step:

$$ar_i = (p_i - \alpha \times p_i) + sr_{i-1} - PE_i + SMD_{i-1} \qquad (1)$$

A parameter (β) is used to determine the instantaneous runoff which is added to the direct runoff to give total runoff:

$$r_i = (\beta \times ar_i) + \alpha \times p_i \qquad (2)$$

The remainder is held over into the following time step and the *SMD* is set to zero. This storage component represents the lagged response of subsurface runoff and generates baseflow after the wet season:

$$sr_i = (1 - \beta) \times ar_i \qquad (3)$$

When rainfall is too low to satisfy both the *PE* demand and the *SMD*, soil moisture is removed:

$$SMD_i = SMD_{i-1} + (p_i - \alpha \times p_i) - AE_i \qquad (4)$$

As the soil dries, it becomes progressively harder to deplete moisture through evaporation:

$$AE_i = K \times PE_i \qquad (5)$$

Soil moisture is depleted at the potential rate for the first 25 mm after which the rate (*K*) decreases linearly down to one half of the potential rate when a certain fraction ($\chi = 0.5$) of the soil water holding capacity (*SWHC*) has been lost:

$$K = 1.0 \text{ if } SMD_{i-1} > -25 \text{ mm} \qquad (6)$$

$$K = 0.5 + 0.5 \times (\chi \times SWHC + SMD_{i-1})/(\chi \times SWHC - 25) \qquad (7)$$

After this point, actual evapotranspiration (*AE*) drops to one tenth the rate of *PE*:

$$K = 0.1 \text{ if } SMD_{i-1} < -0.5SWHC \qquad (8)$$

In this case runoff is simply the direct runoff component plus any left-over storage runoff:

$$r_i = \alpha \times p_i + \beta \times sr_{i-1} \qquad (9)$$

For this study, *SWHC* has been assumed to be constant for all grid cells due to the lack of detailed information on the depth and characteristics of soils in the region. Since there is very little information available on flow times along the channel networks in the catchment and because the instantaneous runoff parameter is spatially invariant and tuned to reproduce the monthly distribution of runoff, no flow routing scheme is used in the model. Finally, in order to reproduce dry season flow, it was necessary to attribute to the grid cells in the two hydrologically special areas (Lake Tana and the Dabus swamps) with separate parameter values. Cells in both catchments were given 0 mm *SWHC* and much lower instantaneous runoff parameter values (β) to represent the increased storage and response times in these hydrological systems.

RESULTS

Model calibration

Runoff from each cell within the catchment (or subcatchment) is summed to produce an estimate of overall mean monthly runoff for the whole Blue Nile Basin (and for the Dabus swamps and Lake Tana). The model parameter values are optimized to simulate observed monthly mean runoff for the whole basin (1951-1987, the period of best data availability although observations were only available for 1961/62 for the Dabus swamps and 1921-1932 for Lake Tana). For calibration purposes, the model was run for two years using the baseline climate input data and the first year's results discarded to initialize the soil moisture conditions for January in the second year. Separate calibrations were performed to simulate the observed runoff for the Dabus swamps and Lake Tana due to their different characteristics. The final choice of parameter values was made based upon certain assumptions of their likely magnitude (based on similar studies and *a priori* information) which were then optimized within physically meaningful ranges to produce the best model fit (Table 1). Figure 3(a) shows the observed and simulated mean monthly runoff for the whole Blue Nile with optimized parameter values. Table 2 lists the observed and simulated runoff volumes, the RMSE and per cent error for the whole Blue Nile basin, the Dabus swamps and Lake Tana.

The mean annual runoff for the period between 1951 and 1987 expressed as mm depth over the basin is 371 mm. Mean annual rainfall for the same period averaged over the basin was 1590 mm and so the long term runoff ratio is 23%. Simulated mean annual discharge is equal to the observed long term mean (1951-1987) and the monthly distribution of runoff is reproduced very closely. The monthly RMSE is

Table 1 Optimized monthly grid cell parameter values for instantaneous runoff (β), proportion of direct runoff (α), and Soil Water Holding Capacity (*SWHC*). Values are spatially invariant except for grid cells in the hydrologically special areas, the Dabus swamps and Lake Tana.

Parameter	Normal cells	Dabus swamp cells	Lake Tana cells
β:			
January-April	0.61	0.37	0.50
May	1.00	0.37	0.50
June	1.00	0.37	0.15
July	0.95	0.37	0.15
August	0.70	0.37	0.15
September	0.61	0.37	0.35
October	0.61	0.45	0.35
November	0.61	0.37	0.35
December	0.61	0.37	0.35
α	0.035	0.090	0.000
SWHC	345	0	0

Table 2 Calibration results based on optimized parameter values to simulate mean monthly runoff for 1951-1987.

	Whole Blue Nile		Dabus swamps		Lake Tana	
Calibration	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
Mean annual discharge (km^3)	47.37	47.37	4.67	4.22	3.90	4.06
RMSE (km^3)	-	0.427	-	0.003	-	0.050
Mean error (%)	-	9.6	-	25.2	-	24.2

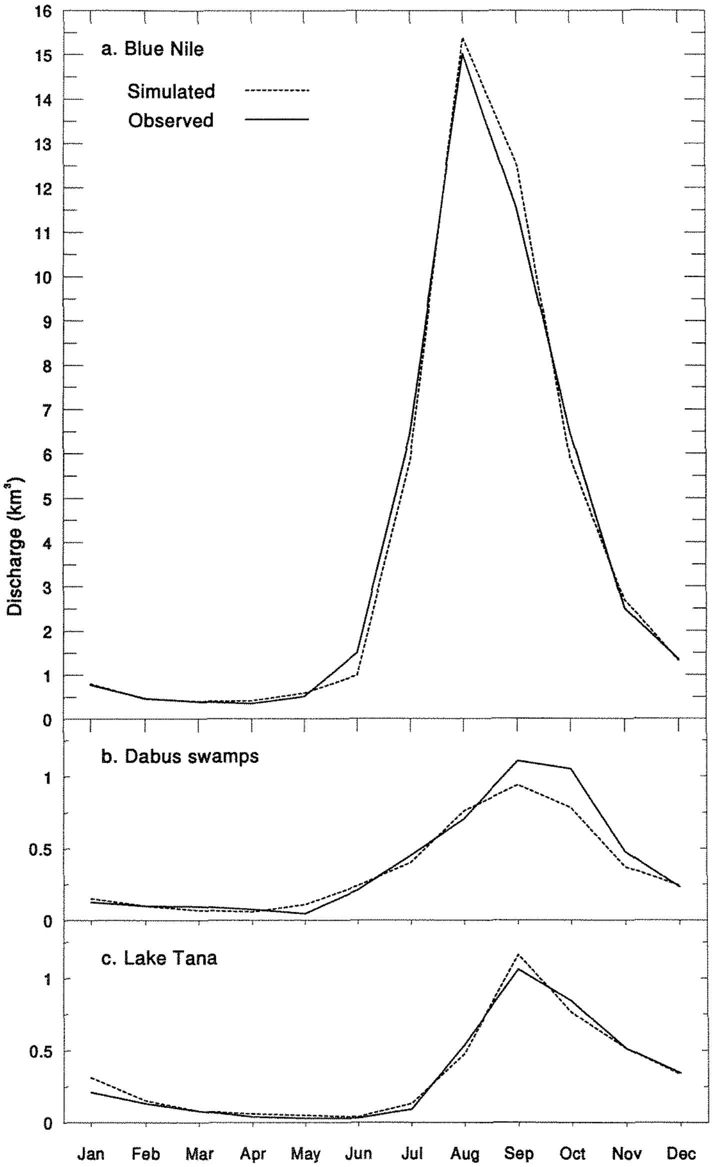

Fig. 3 Simulated (1951-1987) and observed (different periods) mean monthly runoff for calibration period: (a) the whole Upper Blue Nile (1951-1987); (b) Dabus swamps (data only available for 1961/62); and (c) Lake Tana (data only available for 1921-32). Note different vertical scales.

0.43 km^3 and the monthly mean percentage error is just under 10% of the observed runoff. The largest errors occur in June, August and September. Direct runoff (α) for the normal catchment grid cells was set at 3.5% which is comparable to other studies (Alley, 1984). The instantaneous runoff parameter (β) had to be changed in different months to reproduce the seasonal pattern of runoff (Table 1). For normal grid cells these values are high considering the large size of the Blue Nile catchment. This is partly a result of the steep slopes and rapid runoff response of many of the tributaries in the Basin which has been observed by Hurst (1950). The high value of β in May and June, at the onset of the main rains, is primarily to offset the delaying effect due to the storage capacity of the soil which has to be filled before runoff occurs in the model. It logically follows that lag times will vary through the year, being shorter during the wet season when the ground is saturated and rivers fast flowing and longer during dry months when there is a *SMD* and many tributaries dry up.

Figure 3(b) shows the observed (1961-1962) and optimum simulation of mean monthly runoff (1951-1987) for the Dabus swamps. Observed annual runoff was underestimated by 9.6% (Table 2) and two values of β were required to reproduce the seasonal runoff pattern (Table 1). These low values reflect the delayed runoff response to rainfall in the swamp catchment and the high flows in October and November. The mean percentage error was quite high (25.2%), although a large proportion of these errors occur in the dry season and so in terms of volume it is very low (*RMSE* = 0.003 km^3). Although observed annual runoff is slightly underestimated the seasonal pattern of runoff is well reproduced. Figure 3(c) shows that optimized mean monthly runoff (1951-1987) reproduced both the distribution and volume of observed runoff from Lake Tana for the period 1921-1932. As in the Dabus swamps, the instantaneous runoff parameter (β) had to be set very low due to the delayed response of lake outflows to rainfall. Three different values were required: very low values in the early wet season, slightly higher in the late wet season, and highest between January and May. Runoff in the dry season was wholly generated by stored runoff and so no direct runoff component was required. The high percentage error is due to differences between simulated and observed monthly runoff in the dry season (January, August and October) but these errors are very low in terms of volume (*RMSE* = 0.05 km^3).

Model validation

The model is validated in two ways: first, by assessing its ability to simulate sub-catchment runoff; and second, by using the model to simulate historical Blue Nile discharge using time series of rainfall anomalies derived from various combinations of raingauges with monthly time series data.

Sub-catchment runoff Three sub-catchments with runoff data were chosen for independent validation: the Didessa, upstream of the confluence with the Angar; the Beles, west of Lake Tana; and the Upper Guder, southeast of the Finchaa reservoir. Monthly runoff from all grid cells inside (wholly and partially) each catchment boundary was summed to produce the mean monthly hydrographs shown in Figs 4(a)-(c), together with the observed runoff for limited periods for visual comparison. For the Didessa observed runoff was significantly underestimated, by roughly half, in all months (Fig. 4(a)). Observed annual runoff was almost twice the simulated volume (6.86 km^3 compared to 3.75 km^3) mainly due to the model underestimates in July and October. Runoff for the Beles was significantly underestimated in the months with maximum runoff. August and September results

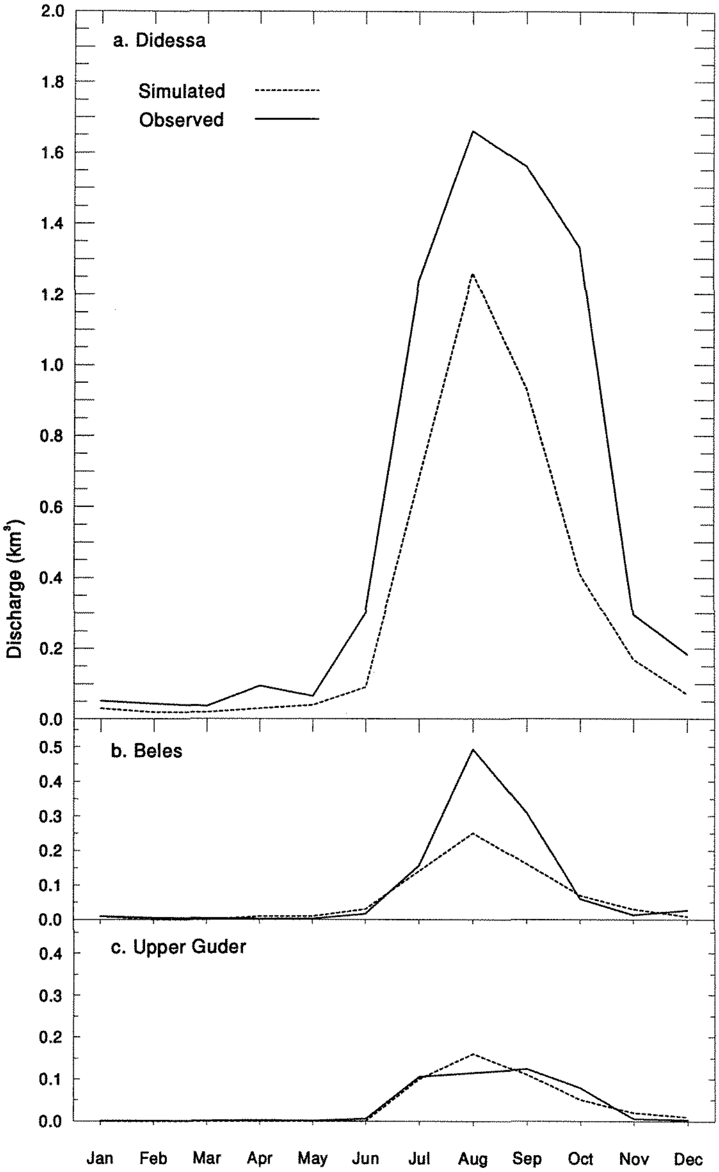

Fig. 4 Simulated (1951-1987) and observed (different periods) monthly runoff: (a) Didessa (1961); (b) Beles (1962); and (c) Upper Guder (1961). Note different vertical scales.

were less than half the observed values which led to the significant underestimate of annual runoff (observed 1.10 km^3; simulated 0.72 km^3). There was better agreement between observed and simulated runoff through the rest of the year (Fig. 4(b)). The model simulated observed runoff in the Upper Guder reasonably well (observed 0.44 km^3; simulated 0.45 km^3). The largest monthly error occurred in August for which the observed discharge (Fig. 4(c)) appears to be slightly anomalous. August is expected to be the month with maximum runoff in a headwater catchment of this size with neither lakes nor areas of swamp. Nevertheless, in this example both the timing and magnitude of runoff were simulated well.

Care must be taken in the interpretation of this sub-catchment validation exercise for the following reasons. Firstly, the periods used for comparison are not uniform. Model simulations represent mean monthly runoff (1951-1987) whereas observed data are available only for one or two years. The catchment boundaries and areas have been estimated from the main map in USBR (USBR, 1964a) and the gauge positions digitized from Fig. III.8 (from USBR, 1964b: p. 10). The accuracy of this method cannot be better than ±10% (USBR, 1964a) and is likely to be worse because of errors in delineating and digitising the catchment boundaries. Errors such as these will affect

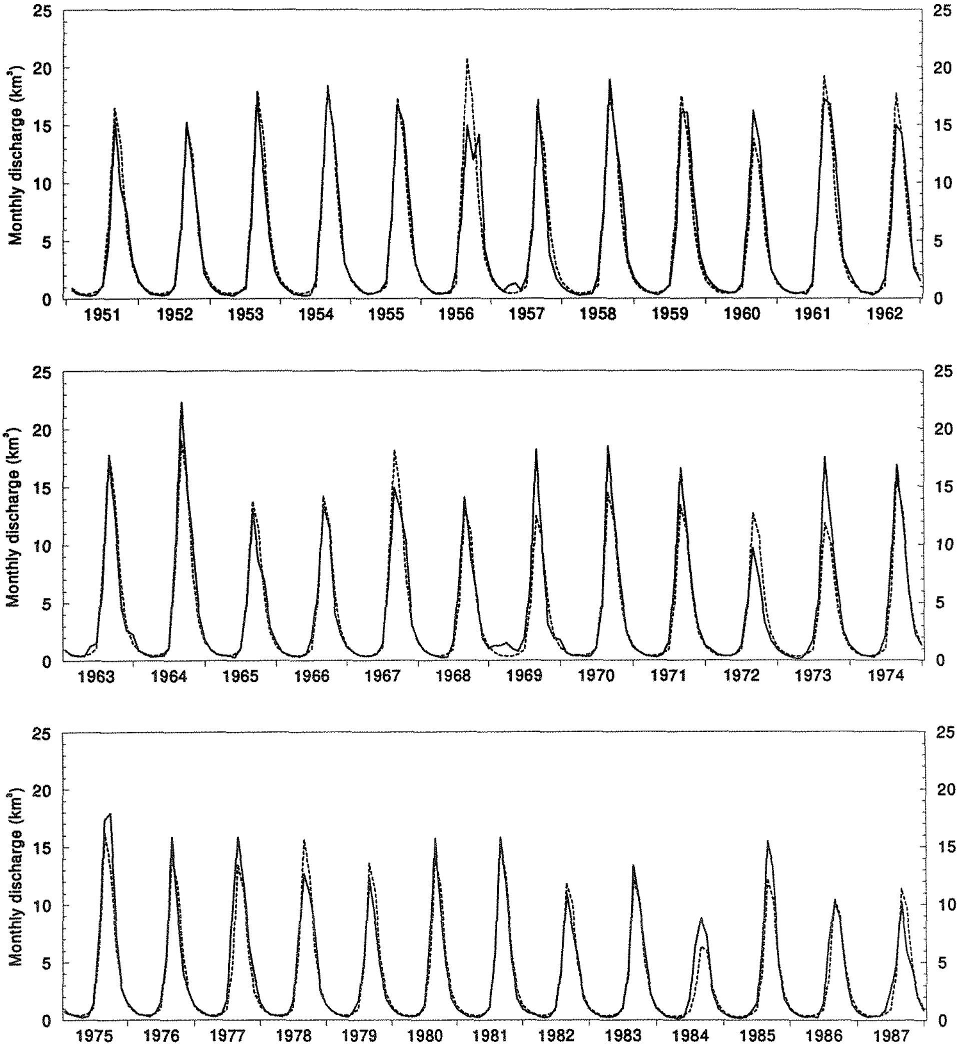

Fig. 5 Observed (bold line) and simulated (dashed line) Blue Nile monthly discharge between 1951 and 1987.

the total volume of runoff calculated for the sub-catchments. In the upper part of the Didessa catchment there are some small areas of swamp not accounted for in the model which may affect the timing and volume of observed runoff. The USBR flow data for the Upper Guder and Didessa are from 1961, which may well be higher than the long term mean runoff because in that year a very high rainfall anomaly occurred over East Africa (Conway & Hulme, 1993). Additional runoff data for the Beles in 1965-1967 (Gamachu, 1977) are similar, although for the Upper Guder in 1978-1980 (Global Runoff Data Centre), they are considerably lower. Probably the most important source of error is the rainfall estimate and this is considered in the discussion.

Interannual variability A time series of annual rainfall anomalies expressed as percentages was applied to the long term (1951-1987) estimates of mean monthly grid cell rainfall used in the optimized model simulation. The time series was derived from 30 gauges within the region bounded by 30-43° E and 5-14° N and covered a 76-year period (1912-1987). The annual percentage anomaly was applied to the standard monthly distribution of each cell so that the monthly runoff distribution was the same in all years. Model performance was assessed by five criteria: comparison of the simulated and observed volumes of annual runoff; monthly and annual RMS error expressed both as a volume and a percentage of the observed; maximum monthly and annual errors; and monthly and annual correlation coefficients (listed in Table 3). Over the 76-year period the mean error in simulated annual runoff was 6.8 km^3 (14%) with an annual correlation of $r = 0.74$ between observed and simulated annual runoff. Monthly correlation coefficients (calculated from standardized departures from the long term monthly means to allow for the strong seasonality) were considerably lower, although still statistically significant, due to the increased noise in the monthly data. The monthly RMSE were low in terms of volume although when expressed as percentages they are quite high. Errors were also calculated using the 76-year rainfall anomaly series over the 37-year calibration period and these were similar to those generated over the whole 76-year record. Figure 5 shows the reproduction of historical runoff between 1951 and 1987 in which there are a few months with very large residuals, for instance 1956. However, there is no bias in the model performance with low and high flow years equally well simulated.

Table 3 Validation results of time series simulation. Monthly correlation coefficients are calculated from standardized departures from the long term monthly means.

	Mean annual discharge (km^3)		RMSE (km^3)		% RMSE		Max. error (km^3)		Correlation coefficient	
	Obs.	Sim.	Ann.	Mon.	Ann.	Mon.	Ann.	Mon.	Ann.	Mon.
1. 76 years (1912-1987)	48.5	49.7	6.8	1.4	14.0	39.7	-19.8	-9.3	0.74	0.38
2. 37 years (1951-1987)	47.4	46.2	5.8	1.3	12.2	34.5	-12.1	-9.3	0.79	0.40

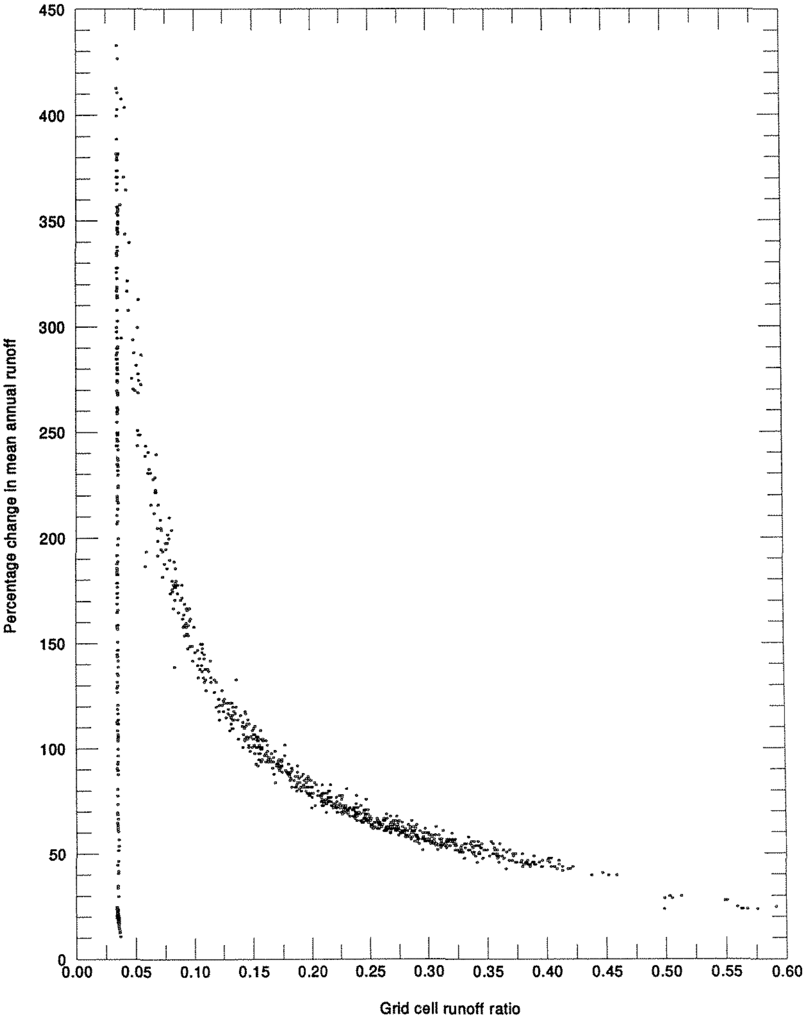

Fig. 6 The percentage change in mean annual runoff against Blue Nile grid cell runoff ratio for a 20% increase in rainfall in all months.

DIFFERENCES IN THE SENSITIVITY OF RUNOFF TO CHANGES IN CLIMATE

In order to show a potential application of the model the sensitivity of runoff to changes in climate was investigated by driving the model with hypothetical changes in rainfall and *PE*. Figure 6 shows the change in annual runoff against the runoff ratio for all model grid cells in the region of the Blue Nile (1287 or 39 x 33 10-minute cells) after applying a 20% increase in rainfall to all months. There is a linear relationship between change in annual runoff and grid cell runoff ratio for runoff ratios from 60% to roughly 25%. The percentage change in annual runoff increases exponentially for runoff ratios below 25%, up to roughly 400% of original runoff due to the 20%

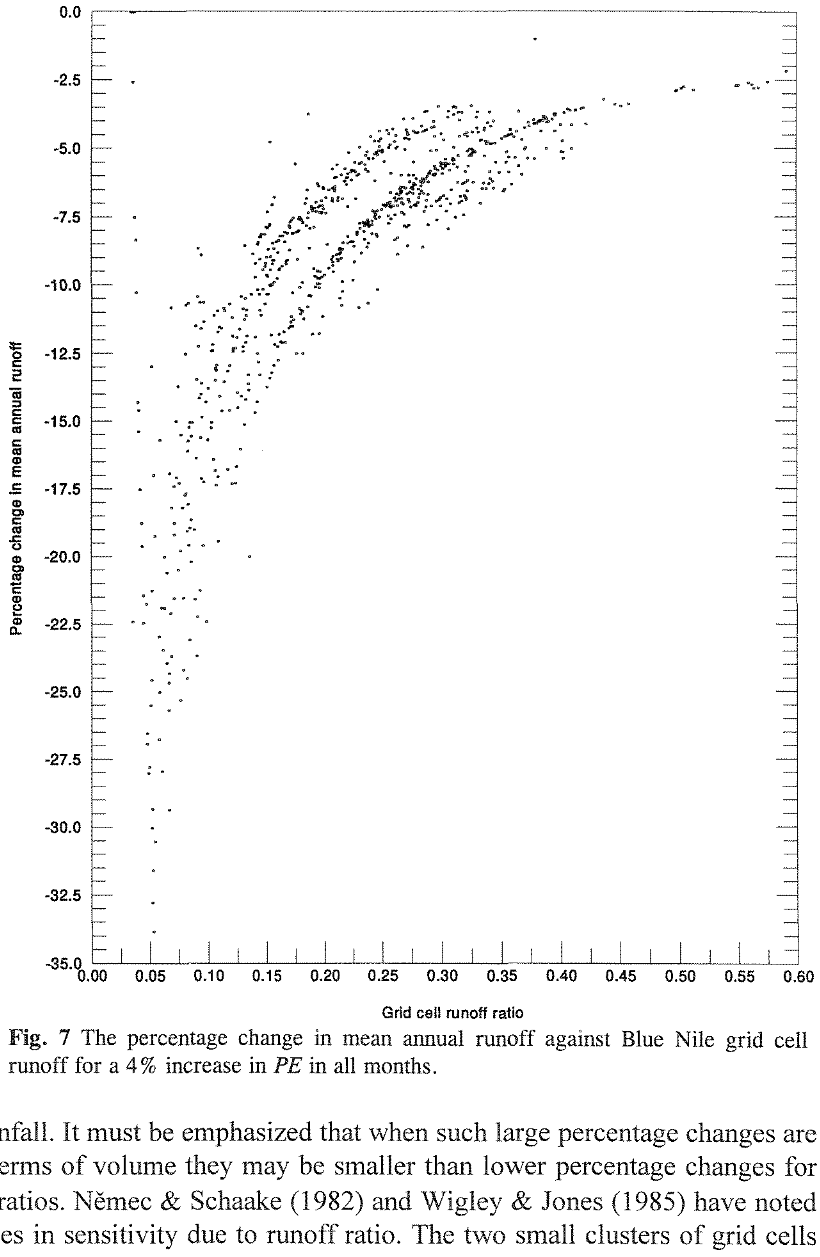

Fig. 7 The percentage change in mean annual runoff against Blue Nile grid cell runoff for a 4% increase in *PE* in all months.

increase in rainfall. It must be emphasized that when such large percentage changes are expressed in terms of volume they may be smaller than lower percentage changes for higher runoff ratios. Němec & Schaake (1982) and Wigley & Jones (1985) have noted such differences in sensitivity due to runoff ratio. The two small clusters of grid cells with runoff ratios over 50% are the cells in the Dabus swamps and Lake Tana with zero *SWHC*. Finally there are many grid cells that generate only direct runoff and therefore have the same runoff ratio, 3.5% (determined by α).

Figure 7 shows the percentage change in annual runoff against runoff ratio after applying a 4% increase in *PE*. As with the rainfall changes, the sensitivity of runoff to changes in *PE* also increases as the runoff ratio decreases. Interestingly, however, there are two response curves and more scatter in these relationships than the changes that occur with increased rainfall. The curves represent different responses to changes in *PE* for any given runoff ratio. This effect is caused by the seasonality of rainfall which varies considerably over the basin. Cells with greater sensitivity to *PE* possess bimodal rainfall regimes (peaks in April and July) where a 4% increase in *PE* causes a larger impact upon runoff than the same increase in a unimodal regime.

DISCUSSION

Model performance

The key determinant of the model's performance is the accuracy of the rainfall inputs. The area of the catchment is vast (176 000 km^2) making it difficult to obtain a representative estimate of "actual" catchment rainfall with so few gauges. In addition, gauges may be in non-representative areas, e.g. rain shadow regions or areas where rainfall is evaporated or delayed such as Lake Tana and the Dabus swamps. This problem is compounded by the high spatial variability of rainfall due to the complex topography and the convective nature of rainfall. In the time series simulations there were a number of years containing large errors (positive and negative), particularly in the wet season months. The cause of this may be that the magnitude of the rainfall anomalies are too large, possibly due to the low number of gauges used to estimate rainfall over such a large area. The model is driven by catchment-wide rainfall anomalies which will tend to make it over-sensitive because it is unrealistic to have homogeneous rainfall anomalies over such a large area.

The reliability of the measured variables is uncertain. The runoff records at El Diem and Roseires can be considered accurate to at least ±10% (World Bank, 1989), but the reliability of the rainfall estimate is more questionable. Raingauges are subject to a number of under catch and reading/data entry errors. Since as many gauges as possible were used to generate the time series, however, the influence of such errors has been minimized. It is also possible that certain physical characteristics of the catchment, not incorporated in the model, may smooth out responses to large rainfall anomalies. For instance, the lake and swamp areas may expand and increase losses to evaporation in wet years and the opposite may occur in dry years. Likewise, streams and rivers may overflow their banks and increase transmission losses in wet years. This is probably not the case in the Blue Nile since flood waters quickly collect in the drainage channels and the loss to overflowing on flood plains or to evaporation is small according to Hurst *et al.* (1959) and USBR (1964b). Conversely, it is just as likely that in wet years saturated areas will expand, the runoff response will be more rapid and so transmission losses lower. Without much more detailed information of the physical characteristics of the basin, it is impossible to determine how important these factors may be in affecting the historical variations in runoff.

Potential for developing the model

Distributed parameter values Except in the two sub-catchments all grid cell parameter values were spatially invariant. Due to the lack of information about the variability and characteristics of soil types, vegetation and land use these factors were not treated explicitly in the model. There are advantages and disadvantages to adopting a distributed parameter approach. On the positive side it makes the model truly distributed and increases its physical realism. However, such an undertaking in the Upper Blue Nile would require more information about the characteristics and spatial distribution of soil and vegetation than is currently available. Due to spatial variability at grid scale and subgrid scales, the large catchment size, and the remote and difficult terrain, a field sampling strategy would be prohibitively expensive. Remote sensing may be used to obtain information on surface conditions and vegetation characteristics in the basin, although estimation of soil parameters and other important variables is problematic (Bathurst & O'Connell, 1992). To date, there have been very few published attempts to utilize remotely sensed data in the Blue Nile region and the Nile Basin as a whole. Three other potential developments in the model: reducing the time step; increasing the spatial resolution; and incorporating time series of temperature anomalies have not been performed in this study due to the lack of suitable data.

Improving the rainfall estimate There are two published studies that use remote sensing techniques to estimate rainfall in the Blue Nile region. One of these was a brief study by Riehl *et al.* (1979) and the other forms part of an on-going study by the Tropical Applications of METEOSAT (TAMSAT) group at the University of Reading, UK, (Sutcliffe *et al.*, 1989; Dugdale *et al.*, 1991). Their work on the Blue Nile and Atbara attempted to simulate the flood event that devastated Khartoum in August 1988. A three month simulation was presented that used average daily Cold Cloud Duration (CCD) input (not rainfall) to a fairly simple hydrological model, calibrated over the same period, which reproduced daily flows reasonably well. The method ideally requires calibration of CCD with raingauge data. Unfortunately the relationship between CCD and raingauge catch is not straightforward. Cloud type, season and regions may affect the relationships and the calibration in Ethiopia is also highly dependent on orography and affected by height above sea level, slopes and rain shadows. Todd *et al.* (1995), however, show that marked improvements in rain-area classification may be obtained using an optimum infrared rain/no-rain threshold temperature variation. The method does represent probably the best means available of deriving a spatially distributed time series of rainfall for the Blue Nile basin. Ideally, detailed knowledge of sub-catchment characteristics and response times is required to forecast floods accurately in such a large and diverse basin. The method has great potential, but it is not a panacea - stable, robust calibrations have yet to be obtained between CCD and raingauge data and much remains to be discovered about the hydrological characteristics of the basin upstream of Roseires and El Diem.

CONCLUSIONS

Because of the vast size of the basin and the sparsity of data it is difficult to apply complex hydrological models without making many assumptions about parameter values and without using a monthly time step. For this reason an approach was chosen based on the original water balance concept by Thornthwaite & Mather (1957), with modifications from Alley (1984), and a large-scale gridded approach from Vörösmarty *et al.* (1989). Runoff is generated using three parameters and from the outset it was decided to keep grid cell parameter values invariant, apart from the two special areas (Lake Tana and the Dabus swamps). This was because of the lack of information and the difficulties of calibrating and interpreting such large numbers of parameter values. However, in order to reproduce the seasonal distribution of runoff it was necessary to alter the instantaneous runoff parameter on a monthly basis.

The model was calibrated to reproduce mean monthly runoff based on the period between 1951 and 1987. Gridded estimates of *PE* and rainfall (based on the multiple regression models) were used to calculate a water balance for each grid cell. The model was tested by its ability to simulate sub-catchment runoff and historical runoff. In three sample sub-catchments the seasonal distribution of runoff was reproduced reasonably well, although the volume of runoff in two of the cases was significantly underestimated. In order to simulate historical runoff the model was driven with a time series of rainfall anomalies. A 76-year time series produced a reasonable simulation of interannual variability, although some of the annual errors were still large relative to the observed values. Nevertheless, the results obtained here compare favourably with other similar studies, particularly considering the amount and quality of the rainfall input data.

In a sensitivity analysis the response of runoff to changes in *PE* and rainfall was greatly affected by the runoff ratio of the grid cell. The sensitivity increased as grid cell runoff ratio decreased. The percentage change in annual runoff with a 20% increase in annual rainfall for the 1287 grid cells in the region was linear for runoff ratios from 25% to 60%. These magnitude runoff ratios are typical for temperate river basins. For grid cells with lower runoff ratios (less than 25%) the response increased exponentially up to 400%. Similar results were obtained for changes in annual *PE*, although interestingly two separate response curves resulted due to differences in the seasonal distribution of rainfall (unimodal and bimodal regimes).

To improve the model further, longer times series of sub-catchment runoff and more information on the characteristics of the lake and swamp catchments are required. Improved rainfall estimates may be derived from remote sensing which may also provide information on land cover characteristics to incorporate vegetation in the model. The results obtained here show that it is feasible to develop and apply a simple hydrological model for the Upper Blue Nile that requires limited data inputs and runs on a monthly time step. The prospects of future remotely sensed data sets and the potential for coupling catchment-wide hydrological models to climate models emphasizes the need for flexibility in the structure of hydrological models. The physical basis and simple structure of grid-based water balance models equips them to meet these objectives and also provides an easy means of studying the sensitivity and interactions of runoff to a whole range of environmental conditions.

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