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Water-use accounts in CPWF basins

Simple water-use accounting
of the Nile Basin

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1. ABSTRACT

This paper applies the principles of water-use accounts, developed in the first of the series, to the Nile River basin in Northeast Africa. The Nile and its tributaries flow though nine countries. The White Nile flows though Uganda, Sudan, and Egypt. The Blue Nile starts in Ethiopia. Zaire, Kenya, Tanzanian, Rwanda, and Burundi all have tributaries, which flow into the Nile or into Lake Victoria. Unique features are Lake Victoria and the Sudd wetland where White Nile loses about half of its flow by evaporation, and the Aswan Dam which controls flow in the lower part of the Basin and also is where 15-20% of the flow is lost to seepage and further evaporation.

Net runoff is minimal in many catchments of the Nile Basin, comprising 6% or less of the water available in 16 catchments of the Basin. In the remaining catchments, net runoff ranges from 9% (Panyango) to 34% (Gambella) of the available water.

Water use by grassland is important in all catchments where it comprises 13 to 76% of the water available, except in the Lower Basin, where it comprises only 7% or less of the available water. In upstream catchments, woodlands and forests are the major components of land-use, while in the Lower Basin catchments barren and sparsely vegetated land is the main land-use class.

Rainfed agriculture is the most important water use by volume in only four catchments, Kessie, Paraa, Panyango, and the Sennar Dam where it comprises 24%, 27%, 30%, and 38% of the available water. Nevertheless, it is a relatively important use of water in many of the catchments, using 10% or more of the available water in 14 catchments of the Basin. Irrigated agriculture is the least use of water by volume, using 4% or less of the available water in all catchments except the d/s of Jebel Aulia, the Sennar Dam, Thamaniyat, Hudeiba, Atbara, Naga Hammadi, El Ekhsase, and Estuary catchments. It is, however, the most important water use in the Estuary catchment, using 90% of the available water.

The effect of climate change on rainfall in the Nile Basin is very uncertain, but temperature is expected increase by about 2°C by mid-century. To show the possible effects, we increased potential evapotranspiration by 5%, and left rainfall unchanged. The flow at Aswan Dam declines by about 6%, and irrigated crop water use in the El-Ekhsase region increases by about 2%.

Keywords: Water use accounts, Nile basin, top-down modelling, basin water use.

2. INTRODUCTION

In this note, we describe a simple water-use account for the Nile Basin.

The Challenge Program on Water and Food (CPWF) aims to catalyse increases in agricultural water productivity at local, system, catchment, sub-basin, and basin scales as a means to poverty reduction and improving food security, health, and environmental security. The Basin Focal Projects of the CPWF works in several priority basins: the Indo-Gangetic Basin, the basins of the Karkheh, Limpopo, Mekong, Niger, Nile, São Francisco, Volta, and Yellow Rivers, and a collection of small basins in the Andes.

A useful output for each basin, and a key element of the understanding of basin function, is an overview water-use account. Water-use accounts produced in the same way for each basin would have the further benefit of making easier the development of syntheses of understandings from all the basins.

Water-use accounting is used at national (ABS 2004; Lenzen 2004) and basin (Molden 1997; Molden et al. 2001) scales to:

- Assess the consequences of economic growth;
- Assess the contribution of economic sectors to environmental problems;
- Assess the implications of environmental policy measures (such as regulation, charges, and incentives);
- Identify the status of water resources and the consequences of management actions; and
- Identify the scope for savings and improvements in productivity.

However, these accounts are static, providing a snapshot for a single year or for an average year. Furthermore, they do not link water movement to its use. In contrast to the static national and basin water-use accounts referred to above, our accounts are dynamic, with a monthly time step, and thus account for seasonal and annual variability. They can also examine dynamic effects such as climate change, land-use change, changes to dam operation, etc. The accounts are assembled in Excel spreadsheets, and are quick and easy to develop, modify, and run. We have applied this accounting method to several major river basins including the basins of the Murray-Darling, Mekong, Karkheh, and Limpopo Rivers (Kirby et al. 2006a; Kirby et al. 2006b). Here we describe the application to the Nile Basin.

As we will describe below, the account has been developed using existing data, and gives an overview of water uses within the Basin. The account can be improved with better data and calibration. We recommend that, should it be intended to use the account for any purpose beyond developing an understanding of the broad pattern of water uses in the Basin, effort be directed to obtaining better data.

2.1. OTHER MODELS

We have not reviewed other models of the Nile Basin, although we presume that there are several models.

3. BASIC HYDROLOGY AND OUTLINE OF SIMPLE WATER ACCOUNT

3.1. BASIC HYDROLOGY, IRRIGATION, AND LAND USE

The River Nile is the longest river in the world with a length of 6,650 km. Its Basin covers about 3,260,000 km^2 (Figure 1 and Table 1). The two sources of the River Nile are the White Nile, which rises in the catchments above Lake Victoria, and the Blue Nile, which rises in the mountains of Ethiopia. The flow of the Nile is influenced by Lake Victoria, a large wetland known as the Sudd, and several reservoirs of which the most important is Lake Nasser, held up by the Aswan Dam.

Table 1. Catchments in the Nile Basin with their areas

Catchment	Location	Area, km^2
Kagera	Rusumo	30,018
Kagera	Kyaka Ferry	31,070
Victoria Nile	Owen Reservoir	195,705
Victoria Nile	Paraa	76,582
Albert Nile	Panyango	74,720
White Nile (el Jabel)	Mongalla	77,016
Bahr El Jabal	Gambella	26,364
White Nile (el Jabel)	Gambella D/S*	172,345
Baro	Malakal U/S*	352,711
Sobat River	Malakal	398,362
White Nile (el Jabel)	Jebel Aulia Dam D/S	283,167
Blue Nile (Abbay)	Kessie	68,155
Blue Nile (Abbay)	Roseires Dam	123,209
Blue Nile (Abbay)	Sennar (dam *)	21,583
Nile	Thamaniyat (Tamaniat)	110,948
Nile	Hudeiba (Hassanab)	39,146
Tekeze	Embamadre (Amba Madre)	51,880
Atbara River	Atbara	184,639
Nile River	Near Merowe	126,279
Nile	Dongola (Dunqulah)	207,989
Nile	Aswan Dam U/S	225,889
Nile	Aswan Dam	109,842
Nile	Naga Hammadi	96,501
Nile	El Ekhsase	158,608
Nile	Mouth	20,275
Total		3,263,003

* U/S = Upstream; D/S = Downstream

* It is not clear where the site of the gauging station is in relation to the Sennar dam.

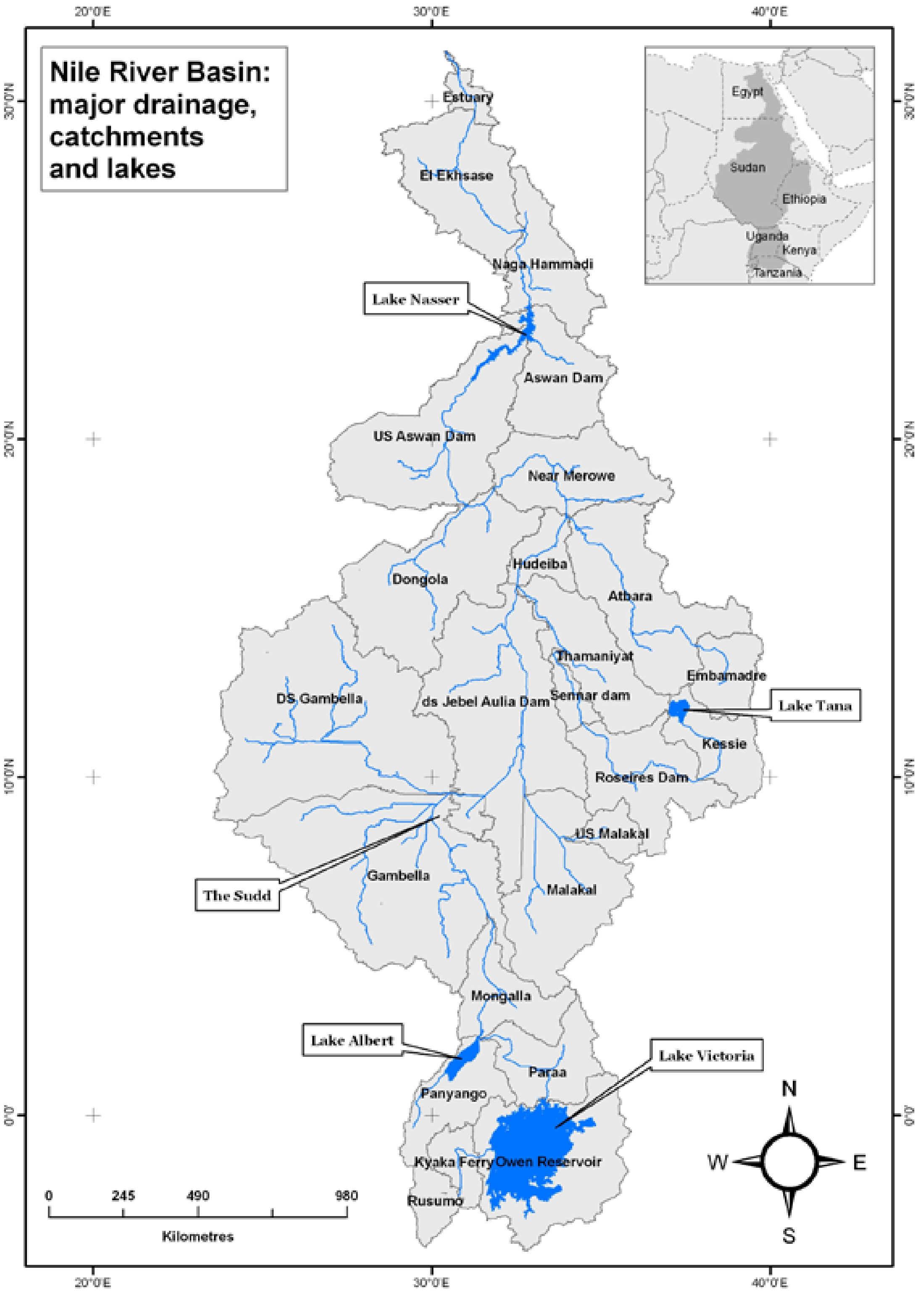

Figure 1. The Nile Basin, with the catchments used in the water-use account.

Rainfall in the source regions varies from 1000-1500 mm per year, falling to almost nothing in the lower parts of the Basin. The wet season in July and August is pronounced in Ethiopia, whereas the Lake Victoria region has a less pronounced and more prolonged wet period from October to May. The potential evapotranspiration (PET) varies from about 1500 mm per year in the source regions, to about 2000 mm in the lower parts of the Basin. This pattern of rainfall, together with the influence of Lake Victoria, results in the River Nile deriving all its flow from the source regions, with an even flow in the upper parts of the White Nile, which is enhanced by peak flows from tributaries below Lake Victoria. The Blue Nile has a very pronounced peak flow with little base flow. Below the confluence of the White and Blue Niles, the River Nile has pronounced peak flows with a modest base flow. In the lower reaches of the River Nile, much water is lost to evaporation in Lake Nasser, and peak flows are substantially reduced by the operation of the Aswan Dam.

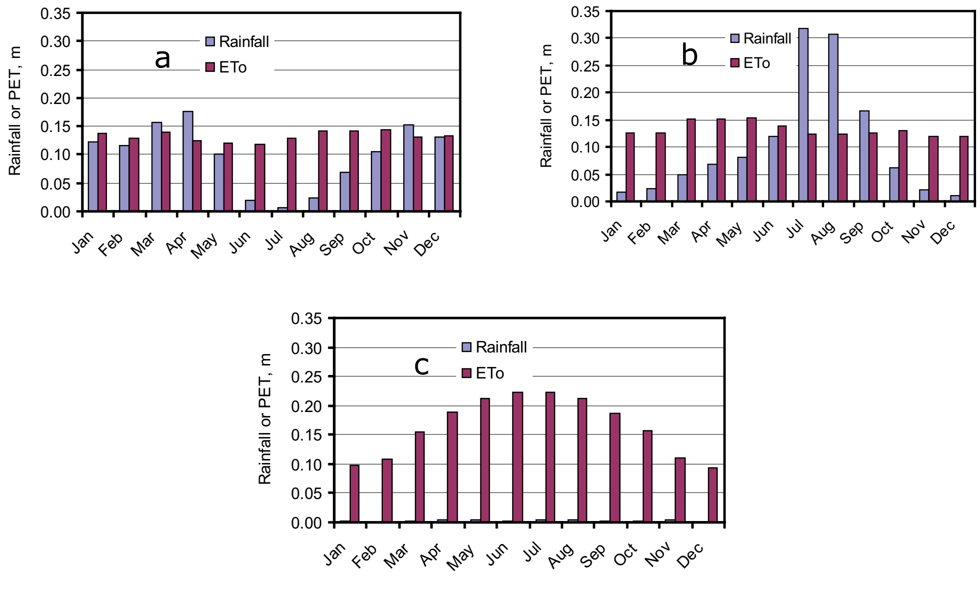

Figure 2. Monthly average rainfall and potential evapotranspiration in the Nile Basin. a). Rusumo, above Lake Victoria; b). Kessie, in the headwaters of the Blue Nile in Ethiopia; and c). Aswan Dam in Upper Egypt.

3.2. SIMPLE WATER ACCOUNT

The simple water account has two parts:

- A hydrological account of the water flowing into the basin, flows, and storages within the basin, and water flowing out of the basin (primarily as evapotranspiration and discharge to the sea); and
- A further partitioning of the evapotranspiration into the proportion of evapotranspiration accounted for by each vegetation type or land use, including evapotranspiration from wetlands and evaporation from open water.

The simple hydrological account is based on a monthly time step, which we consider adequate for our purpose.

The account is a top-down model (Sivapalan et al. 2003), based on simple lumped partitioning of rainfall into runoff and infiltration into a generalised surface store. This is done at the catchment level, with no attempt to model the spatial distribution of hydrological processes and storages within a catchment. Evapotranspiration from the total catchment is estimated from potential evapotranspiration and water supply from the surface store, and partitioned between rainfed and irrigated land uses based on the ratio of their areas. The rainfed component of evapotranspiration is further partitioned between land uses/vegetation types (agriculture, forest/woodland, grassland, other) based on the ratio of their areas and using crop coefficients to scale their evapotranspiration relative to other land uses.

Runoff flows into the tributaries and then into the River Nile, with downstream flow calculated by simple water balance. We assume that the base flow in a catchment comes from a notional groundwater store whose monthly discharge is a fraction of the quantity of water it contains. Deep drainage to the groundwater store is estimated as a proportion of the surface water store. For more details see Kirby et al. (2009). During high flows, some of the flow is stored in the river channels. Channel storages and losses from the river are estimated as functions of flows. Inflows are stored in reservoirs, and are balanced by evaporation and discharge at the dam. Water is spilled if the capacity of the dam is exceeded.

Diversions for irrigation are based on crop water requirements calculated from cropped areas, crop coefficients, potential evaporation and irrigation efficiencies. Maximum irrigated areas are defined based on land-use data, but the area irrigated may be reduced in any one year to match supply if the volume stored in the reservoir at the beginning of the season is insufficient to meet crop water requirements. If reservoir storage becomes insufficient to meet crop demand during the season, irrigation applications are reduced to match supply.

The model is described in detail in a companion report *Water-use accounts in CPWF basins: Model concepts and description* (Kirby et al. 2010). Here we describe only that part of the model that differs from the general set of equations. The behaviour of, and equations for, Lake Victoria and Aswan Dam/Lake Nasser are unique to the Nile Basin.

3.2.1. UNITS

Rain, evapotranspiration and potential evapotranspiration are given in mm.

River flows and storages, and lake storage, are given in mcm (million cubic metres). 1 mcm is equivalent to one metre over one square kilometre. 1000 mcm = 1 bcm (billion cubic metres) = 1000 m over 1 km^2 = 1 km^3.

3.3. LAKE VICTORIA

Lake Victoria is a natural lake, which in 1952 was further impounded by a hydropower dam built across the natural outlet. It has an area of about 69,000 km^2 and a volume of about 275,000 mcm. It receives flows from several rivers with a total catchment area of about 260,000 km^2. The flow into the lake shows considerable month to month variation with peak flows on top of a strong base flow. The discharge from the lake generally has less pronounced peaks and a larger base flow than the contributing rivers. The discharge is governed by an agreement amongst the countries that share the Nile that specifies the discharge (and hence the power generation), as shown in Figure 3.

Figure 3. Release curve for Lake Victoria.

The change in storage of Lake Victoria, S_{LV}, in any one month is:

$$S^{t}_{LV} = S^{t-\Delta t}_{LV} + Q_i - Q_o - E_{LV} + R_{LV} \qquad (1)$$

where E_{LV}, the evaporation, and R_{LV}, the rainfall, are given by equations in Water-use accounts in CPWF basins: *Model concepts and description* (Kirby et al. 2010); and

Q_o, the outflow, is given by the curve in Figure 3.

3.4. LAKE NASSER AND THE ASWAN DAM

The first Aswan Dam was constructed in 1902. The modern Dam was constructed from 1960 to 1970, and Lake Nasser reached its full capacity of 111,000 mcm in 1974. From the mid 1970s, the discharge from the reservoir has generally been between about 4,000 mcm/month in January and 7,000 mcm/month in July. The area of Lake Nasser is about 5,000 km^2 and the evaporation is about 10,000 mcm per year.

We modelled the discharge, Q_o, of the reservoir as:

$$Q_o = C_3 \qquad S + Q_i - C_3 \leq S_{\max} \tag{2a}$$

$$Q_o = C_3 + \left(S + Q_i - S_{\max}\right) \qquad S + Q_i - C_3 > S_{\max} \tag{2b}$$

where Q_i is the sum of the inflows from upstream;
S is the storage in the reservoir;
S_{max} is the maximum storage; and
C_3 is a constant.

Equation 1b gives a flood spill when the storage capacity of the reservoir is exceeded.

The change in storage of the lake, S_{LV}, in the month is:

$$S^t_{LV} = S_{LV}^{t\text{-}\Delta t} + Q_i - Q_o - E_{LV} + R_{LV} - D \tag{3 }$$

where E_{LV}, the evaporation, R_{LV}, the rainfall, and D, the irrigation diversion, are given by equations in *Water-use accounts in CPWF basins: Model concepts and description* (Kirby et al. 2010).

4. DATA SOURCES

The datasets used in this water-use account were all readily available on the internet.

4.1. RAINFALL

The rainfall and other climate data were taken from the Climate Research Unit at the University of East Anglia (specifically, a dataset called CRU_TS_2.10). They cover the globe at 0.5° (about 50 km) resolution, at daily intervals for 1901 to 2002. The dataset was constructed by interpolating from observations. For recent decades, many observations were available and the data show fine structure. For earlier decades, few observations were available and the data were mostly modelled and lack fine structure. We sampled the rainfall and other climate surfaces for each catchment within the Basin, to calculate catchment area-means of rainfall and potential evapotranspiration for each month. The method is described in more detail in Kirby et al. (2010).

4.2. FLOWS

Reach flows were taken from a dataset called ds552.1, available on the internet (http://dss.ucar.edu/catahtmllogs/free.) (Dai and Trenberth 2003). The dataset also gives contributing drainage areas for each flow gauge. Flow records were not available for all the catchments, and no flow records were available for the D/S Gambella, U/S Malakal, Atbara, Near Merowe, U/S Aswan dam, and Estuary catchments.

4.3. LAND USE

Land use was taken from the 1992-3 AVHRR dataset (IWMI 2006), which has more than 20 land-use classes, many of which have similar patterns of water use. The land-use classes were therefore aggregated into rainfed agriculture, irrigated agriculture, grassland, and woodland and other. The aggregated class of grassland contains important areas of other land uses including shrubland and barren land. Additional information on irrigation areas was taken from the GIAM dataset (http://www.iwmigiam.org/info/gmia/default.asp).

In addition, for the major irrigation areas of the lower Nile Basin, a basic cropping calendar was based on FAO (1997), with two overlapping crops per year: a winter crop from December to May and a summer crop from May to October.

5. COMPONENTS AND RESULTS IN DETAIL

5.1. FLOW

The Nile shows different flow patterns in various parts of the Basin. We describe the flow in sub-basins with similar flow characteristics and, for brevity, do not show every catchment.

5.1.1. THE LAKE VICTORIA CATCHMENT

The discharge of the Kagera River into Lake Victoria at Kyaka Ferry, and the spatially-averaged rainfall of the catchment for 1951-1955 are shown in Figure 4. Despite a dry period each year with nearly no rainfall, the river has a base flow of approximately half the peak flow. Futhermore, there are two rainfall peaks each year, but only one weak flow peak. This implies that the rainfall is partitioned primarily to evapotranspiration and recharge of a base flow storage (presumably shallow groundwater), with little direct runoff.

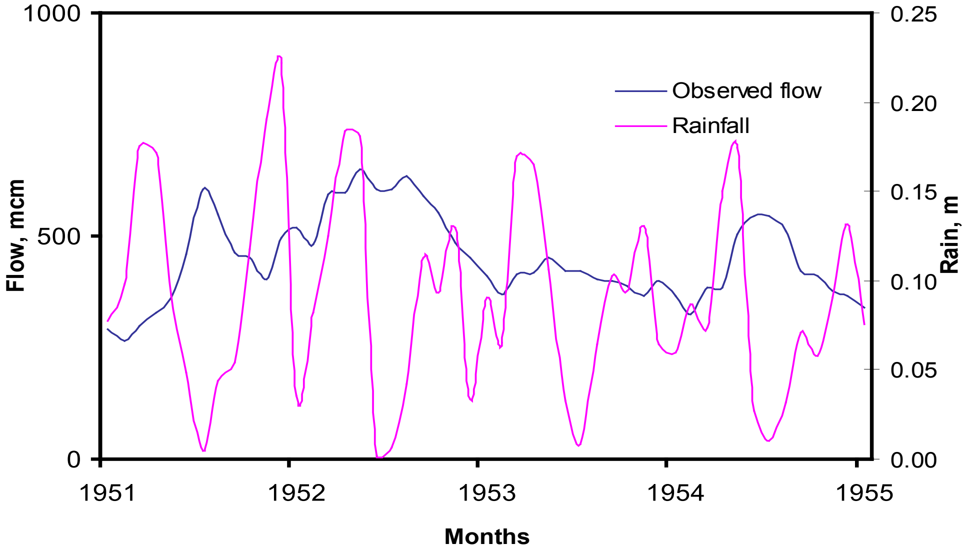

Figure 4. Discharge of the Kagera River into Lake Victoria at Kyaka Ferry, and the spatially-averaged rainfall of the catchment for 1951-1955.

We modelled the flow of the catchments into Lake Victoria using the model given in Kirby et al. (2010), with groundwater and surface runoff parameters set such that there is little direct runoff, and large recharge to groundwater with subsequent base flow discharge. The observed and modelled flows at Rusomo and Kyaka Ferry on the Kagera River are shown in Figures 5 and 6. The flows at Rusomo are not particularly well modelled, while those at Kyaka Ferry are modelled better.

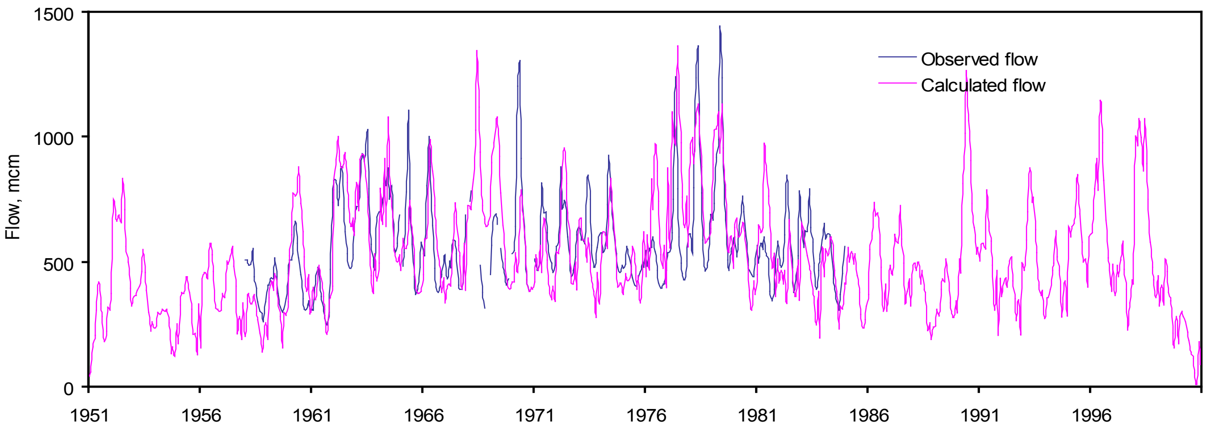

Figure 5. Observed and modelled flow at Rusomo.

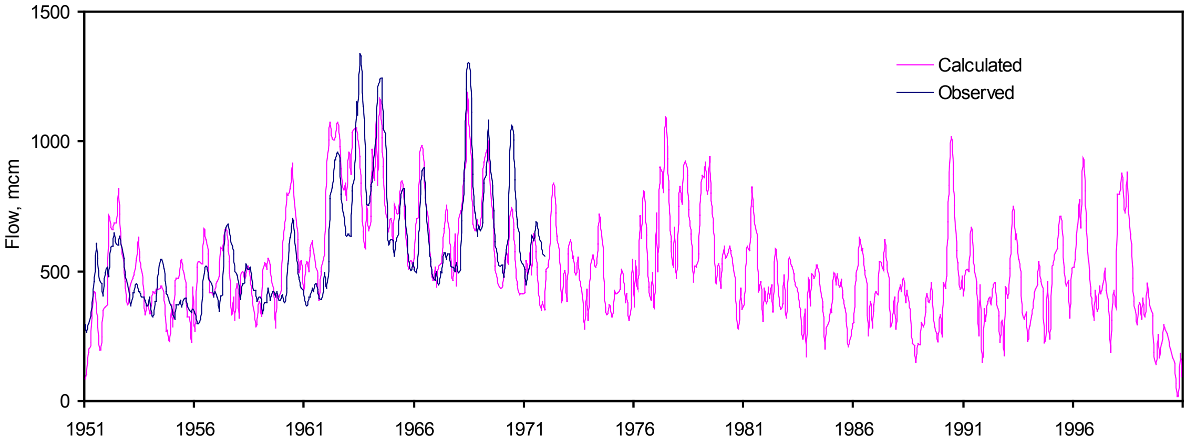

Figure 6. Observed and modelled flow at Kyaka Ferry.

The flow from Lake Victoria is modelled using equation (1) and the release curve shown in Figure 3 above, and the result is shown in Figure 7. The detail for the period for which we have flow records is not reproduced particularly well, but the overall pattern is reproduced.

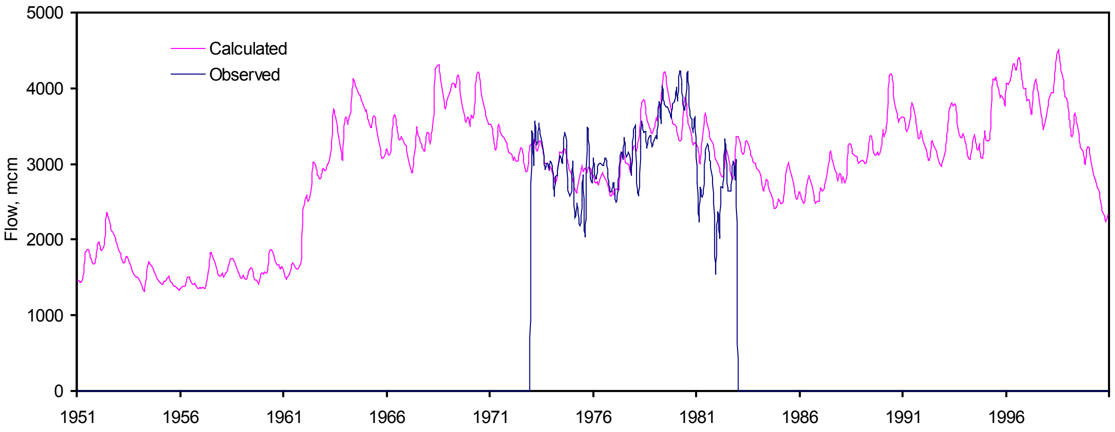

Figure 7. Observed and modelled flow at Owen Falls, the outlet from Lake Victoria. The increase in outflows from about 1962 appears to be related to the increase in inflows at about the same time and hence to an increase in the long-term rainfall at about this time.

5.1.2. THE VICTORIA NILE, THE ALBERT NILE AND THE WHITE NILE TO UPSTREAM OF MALAKAL

Downstream of Lake Victoria, the Nile is known as the Victoria Nile. It is joined by several tributaries, of which the largest are the catchment of Lake Albert, after which it is known as the Albert Nile. After its confluence with the Aswa River, the Albert Nile becomes the White Nile. From there it continues its northward journey to the Sudd, Africa's largest wetland, where the White Nile loses about half its flow to evaporation. The rainfall shows an increasingly distinct wet season - dry season pattern as the White Nile flows northwards, and a slight annual high flow - low flow signal becomes apparent on top of the base flow signal, as shown in Figures 8 and 9.

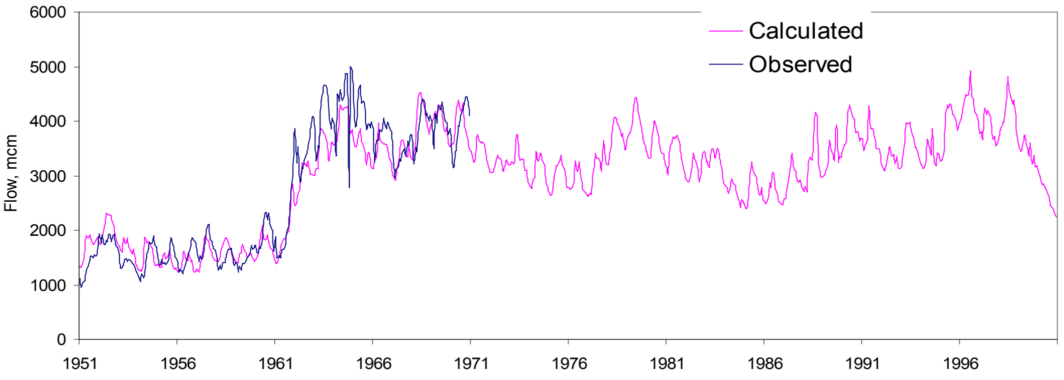

Figure 8. Observed and modelled flow at Paraa.

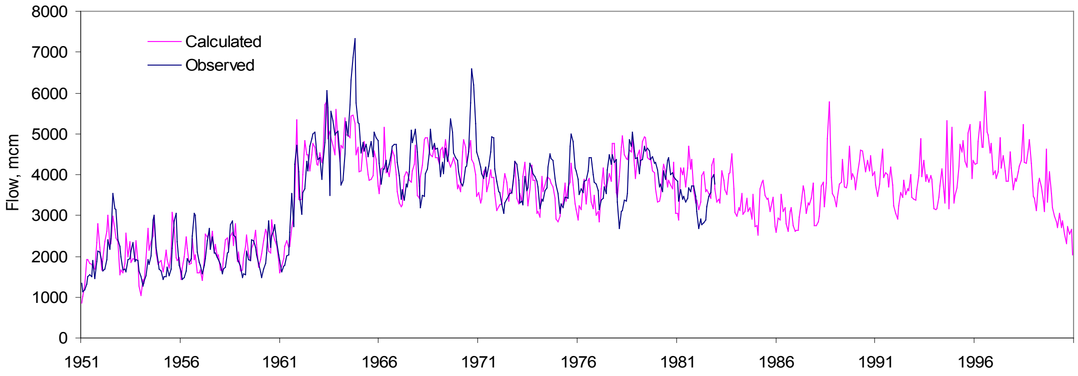

Figure 9. Observed and modelled flow at Mongalla.

5.1.3. THE SOBAT, THE BLUE NILE, AND THE ATBARA

From upstream of Malakal to Atbara, the White Nile is joined by three tributaries draining the Ethiopian highlands, the Sobat, the Blue Nile (after the confluence with which it becomes simply the River Nile), and the Atbara. The rainfall in the source areas of these tributaries has distinct wet and dry seasons, and all three rivers have strongly seasonal flows with large peaks and little base flow. The flows in the Sobat are shown in Figures 10 and 11, the flows in the Blue Nile in Figures 12 and 13, and the flows in the Atbara in Figures 14 and 15. The Sobat is largely ungauged, although four years of flow records from 1976 indicate that the calculated flows are reasonable. The Atbara is also largely ungauged.

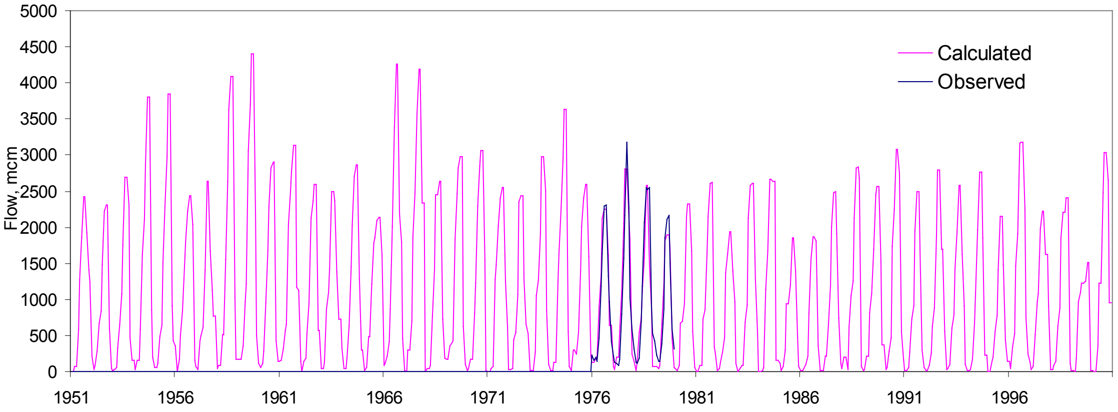

Figure 10. Observed and modelled flow of the Baro Wenz (a tributary of the Sobat) at Gambella.

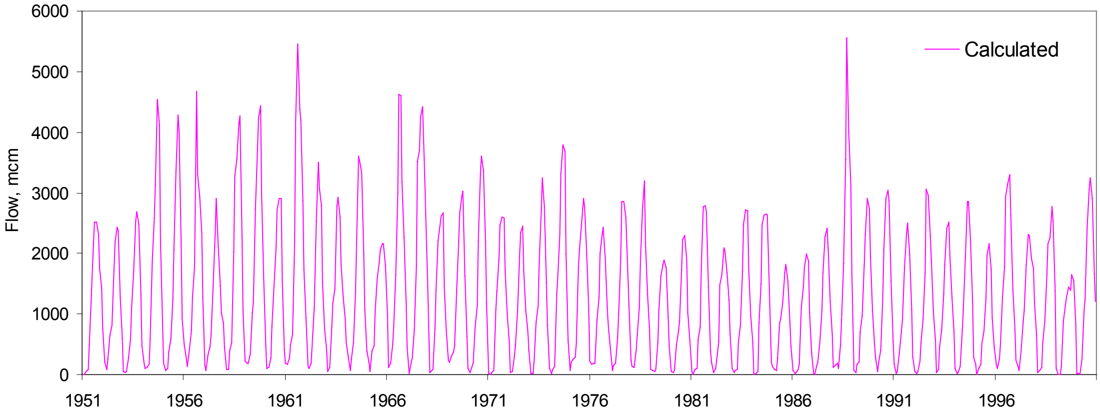

Figure 11. Observed and modelled flow of the Sobat downstream of Gambella.

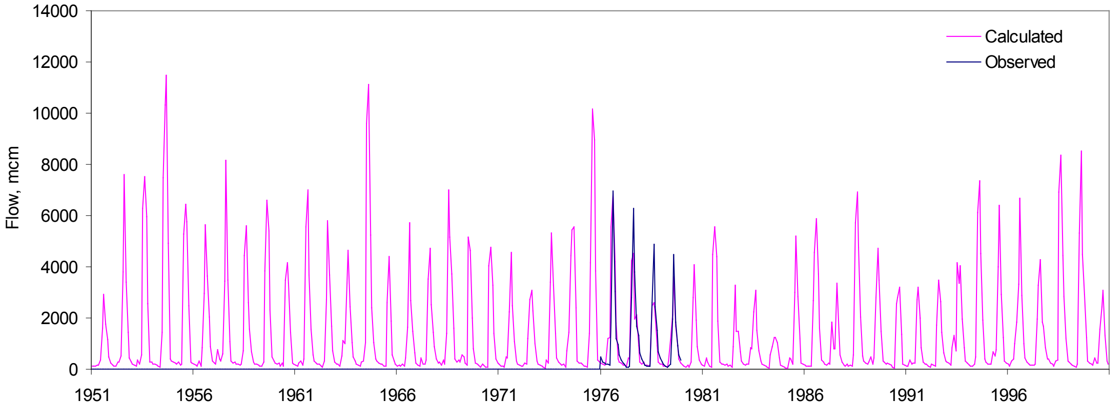

Figure 12. Observed and modelled flow of the Blue Nile at Kessie.

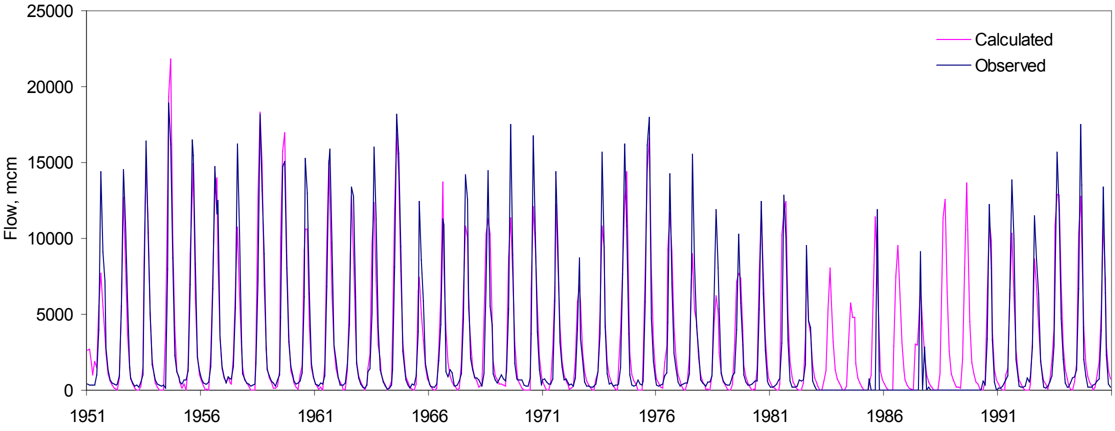

Figure 13. Observed and modelled flow of the Blue Nile at Sennar Dam.

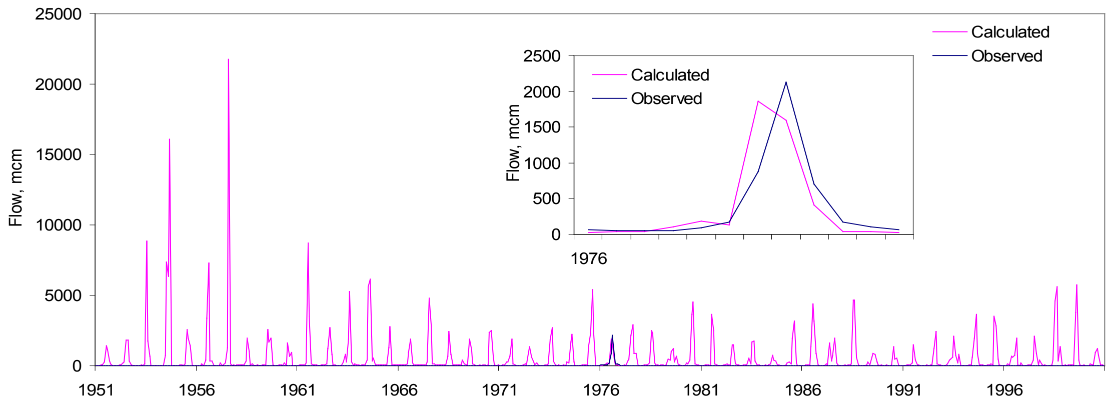

Figure 14. Observed and modelled flow of the Tekeze, a tributary of the Atbara, at Embamadre. The flow during the one year of recorded flow is shown in the insert.

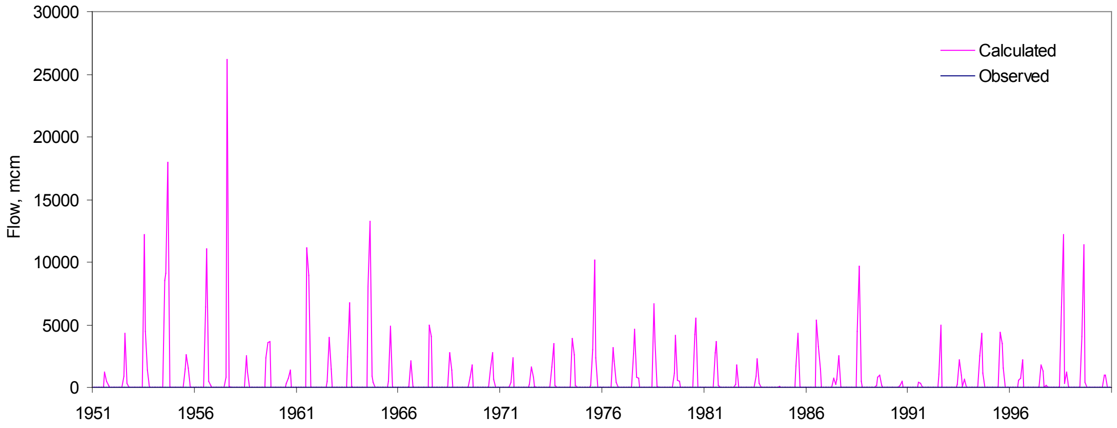

Figure 15. Observed and modelled flow of the Atbara, at Atbara.

5.1.4. THE WHITE NILE TO KHARTOUM AND THE NILE TO DONGOLA

The flow of the White Nile from Malakal to Khartoum and the River Nile from there to Atbara is increasingly dominated by the peak flows from the the Sobat and the Blue Nile, as shown by Figures 16 to 19. The modelling of the releases from the Jebel Aulia dam is poor; we have not yet modelled the irrigation demand in the Gezira and other areas downstream, and hence the release pattern of this dam.

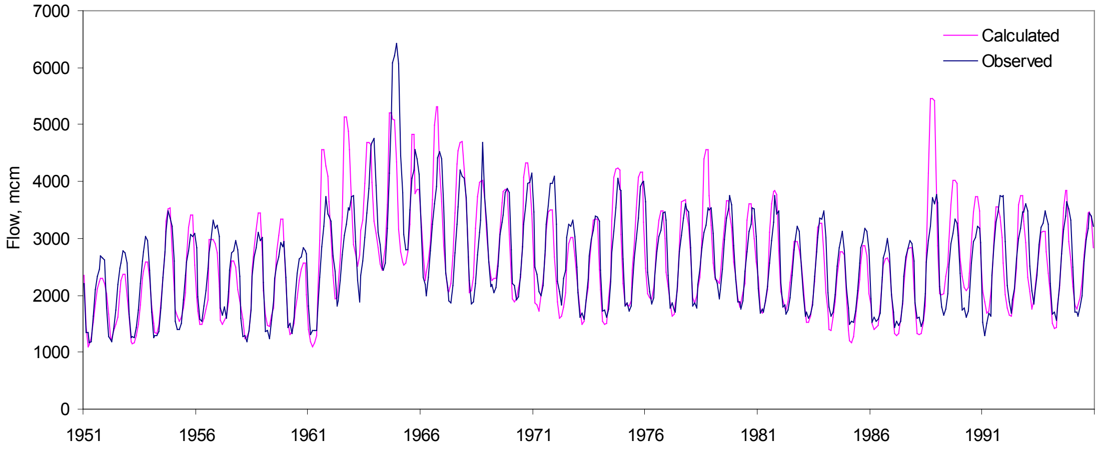

Figure 16. Observed and modelled flow in the White Nile at Malakal, after its confluence with the Sobat.

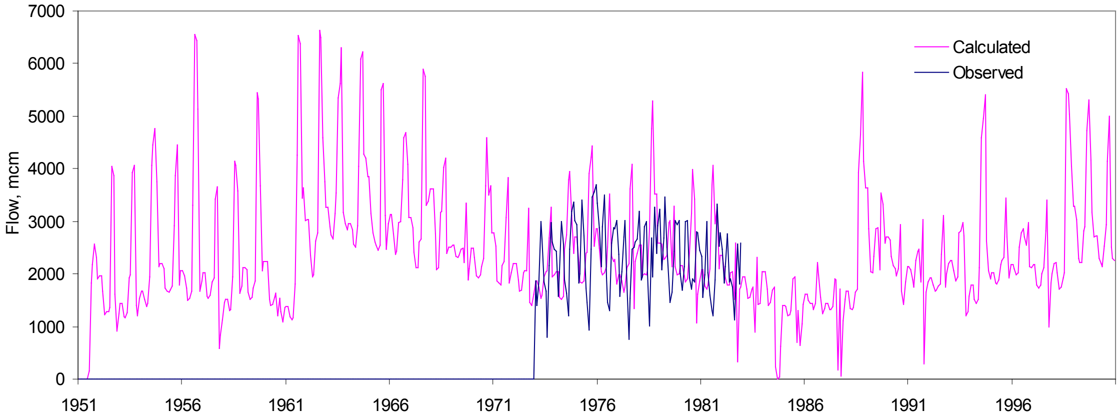

Figure 17. Observed and modelled flow in the White Nile at the Jebel Aulia Dam.

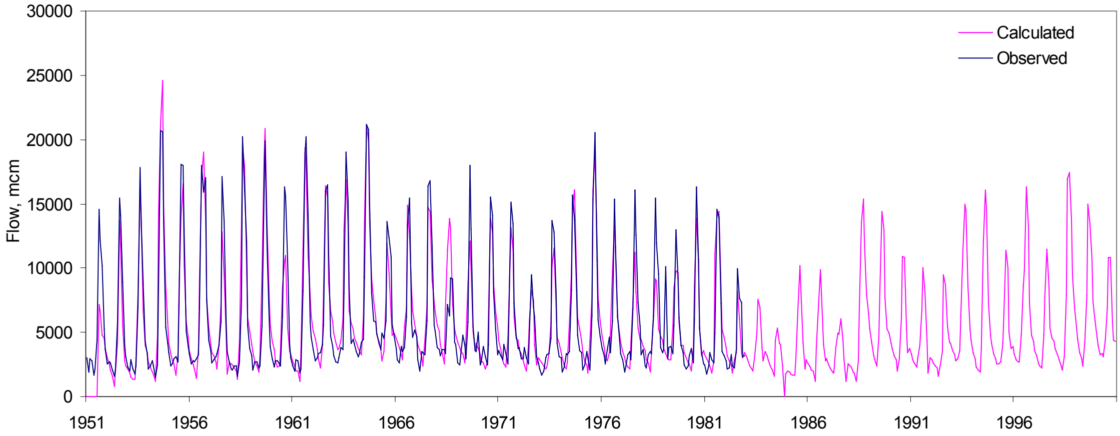

Figure 18. Observed and modelled flow in the River Nile at Thamaniyat, after the confluence of the White Nile with the Blue Nile.

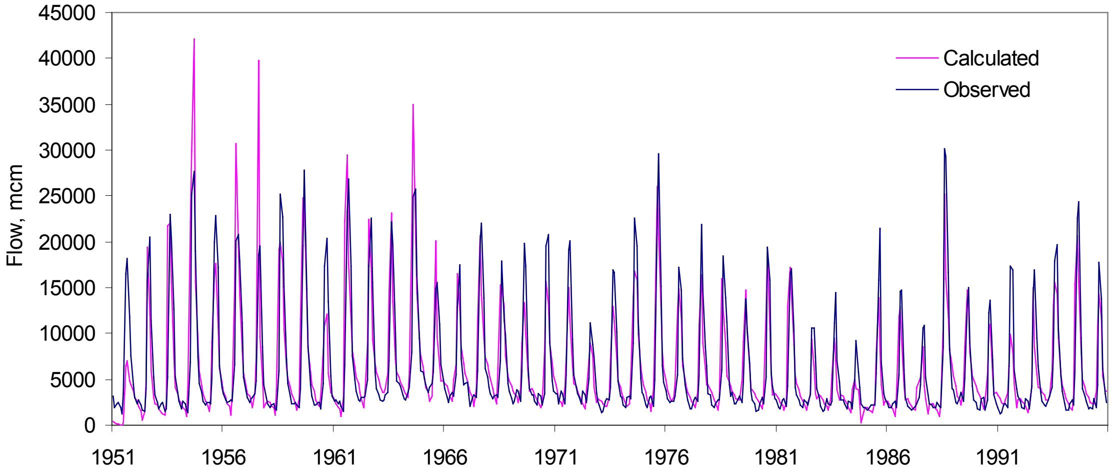

Figure 19. Observed and modelled flow in the River Nile at Dongola, after its confluence with the Atbara.

5.1.5. THE LOWER NILE FROM THE ASWAN DAM TO THE MOUTH

The main feature of the Lower Nile is the Aswan Dam and Lake Nasser. The first Aswan Dam was constructed in 1902, and subsequently increased to a storage of 50,000 mcm. The Aswan High Dam was constructed from 1960 and completed in 1970, with complete filling of Lake Nasser in 1976. The Dam is operated both for irrigation supply to areas downstream and to provide hydropower. Lake Nasser loses substantial volumes of water, perhaps amounting to 10-15% of the flow, to evaporation and seepage. The Dam modifies the flow of the River Nile substantially, as shown in Figure 20. The flow is further reduced downstream by irrigation diversion (Figure 20).

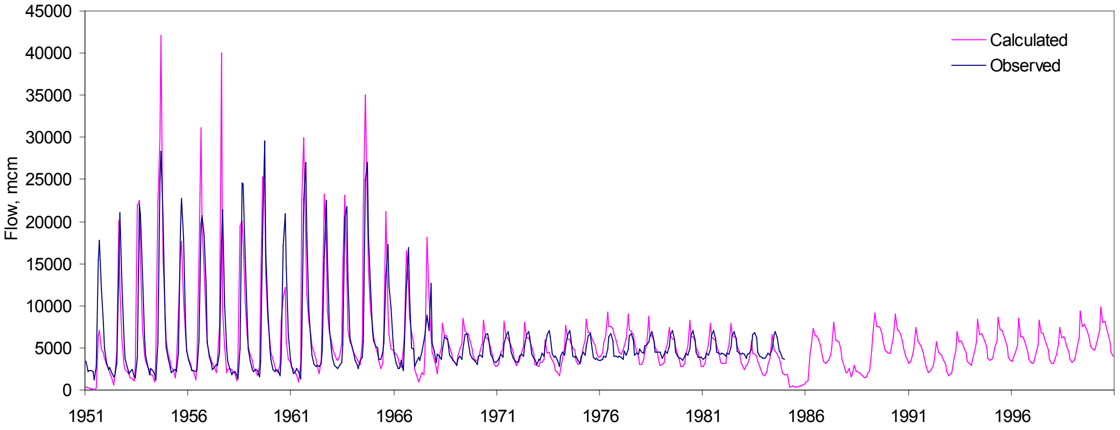

Figure 20. Observed and modelled flow in the River Nile at downstream of the Aswan Dam.

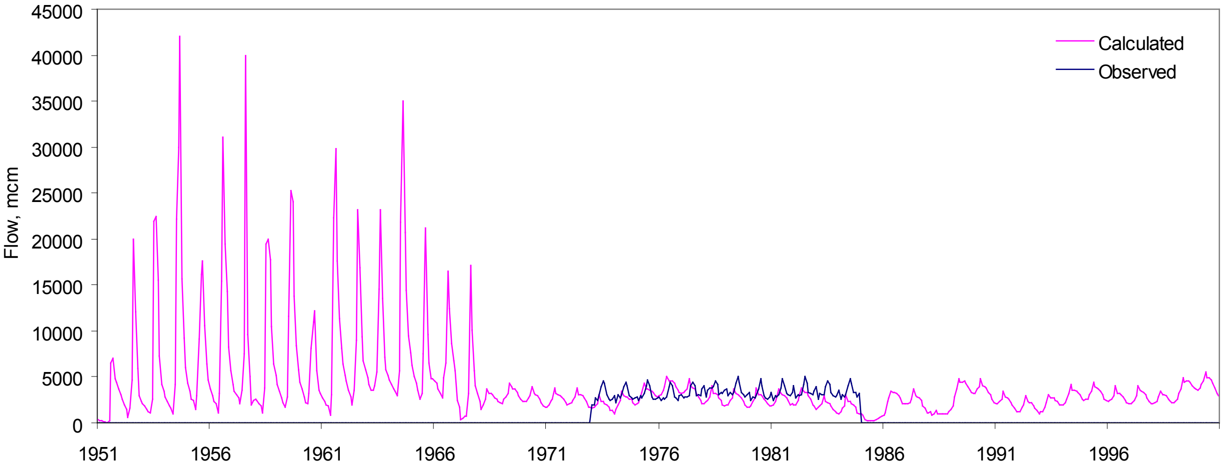

Figure 21. Observed and modelled flow in the River Nile at El Ekhsase.

5.1.6. BASIN RUNOFF

Annual runoff and precipitation for the whole Nile Basin show similar trends through time from 1951 to 2000 (Figure 22), with peaks in annual rainfall generally resulting in peaks in runoff. Annual average runoff is 161,500 mcm, but runoff shows large temporal variation ranging from 110,500 mcm in 1984 and 234,500 mcm in 1964.

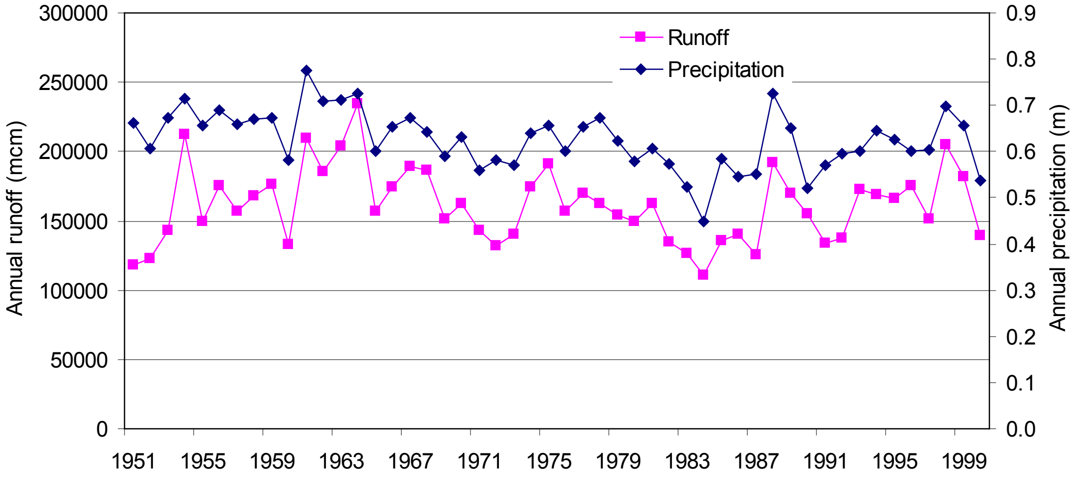

Figure 22. Annual precipitation and runoff for the whole Nile Basin from 1951 to 2000.

5.2. WATER USE

The mean annual input by precipitation to the Nile Basin totals about 2,043,000 mcm. Figure 23 summarizes how this water is partitioned amongst the major water uses in the Basin. Net runoff comprises the runoff remaining after all the water uses in the Basin have been satisfied, and includes all other storage changes and losses. Net runoff from the Basin is about 256,000 mcm or 12% of the total precipitation input. The aggregated class grassland which includes shrubland and barren land, is the most extensive land use, covering 51% of the Basin. Its water use is correspondingly high, with a mean annual water use of 937,000 mcm, or 45% of the water used in the Basin (Figure 23).

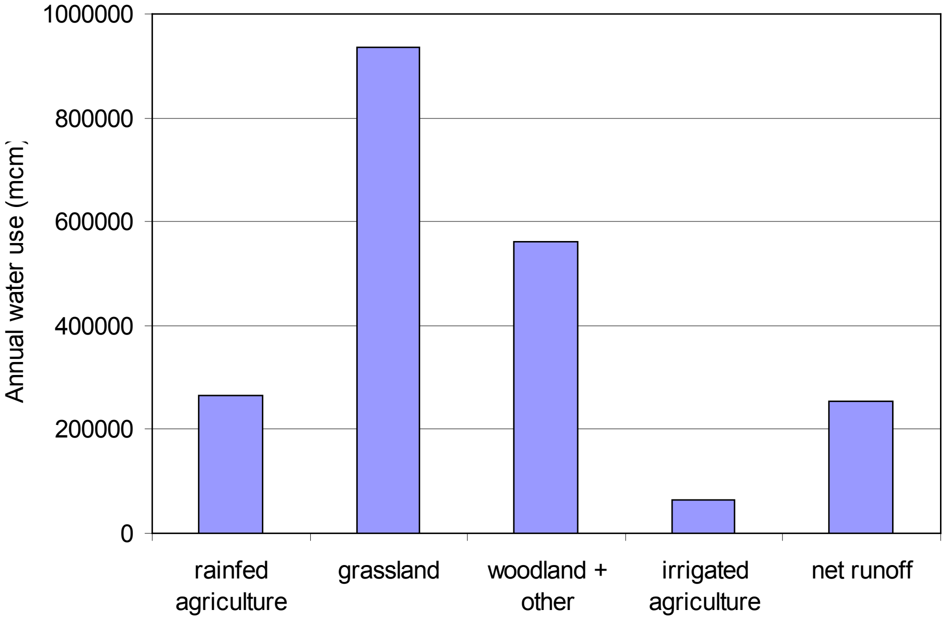

Figure 23. Summary of major water uses in the Nile Basin. Grassland includes shrubland and barren land (see Section 4.3).

The 'woodland + other' land use class includes woodlands, forests, wooded wetlands, urban land, bare ground, barren land, and sparsely vegetated land. This land-use class covers 36% of the Basin and uses about 562,000 mcm or 27% of the available water. Rainfed agriculture covers 7% of the Basin, but uses 13% of the water in the Basin (264,000 mcm). Irrigated agriculture is the least important of the major land uses in the Basin covering less than 2% of the area, and using 3% of the total available water (65,000 mcm).

Figure 24 depicts the uses of water in each catchment, and the distribution of water uses across the Basin. Note that the figure does not represent the water balance at a basin level, since water represented as net runoff in the upper basin may be used in downstream catchments. For example, runoff from upper basin catchments may contribute to irrigation in downstream catchments, and thus is double counted at the basin level. The figure reveals a notable heterogeneity in water availability across the Basin. There is a marked contrast between catchments in the Lower Basin where there is very little water available (Hudeiba, Near Merowe, U/S Aswan, Aswan Dam, Naga Hammadi, El Ekhsase, and Estuary catchments), and many of the catchments upstream that have much greater water availability. This results from the large decrease in rainfall on moving from the south to the north of the Basin.

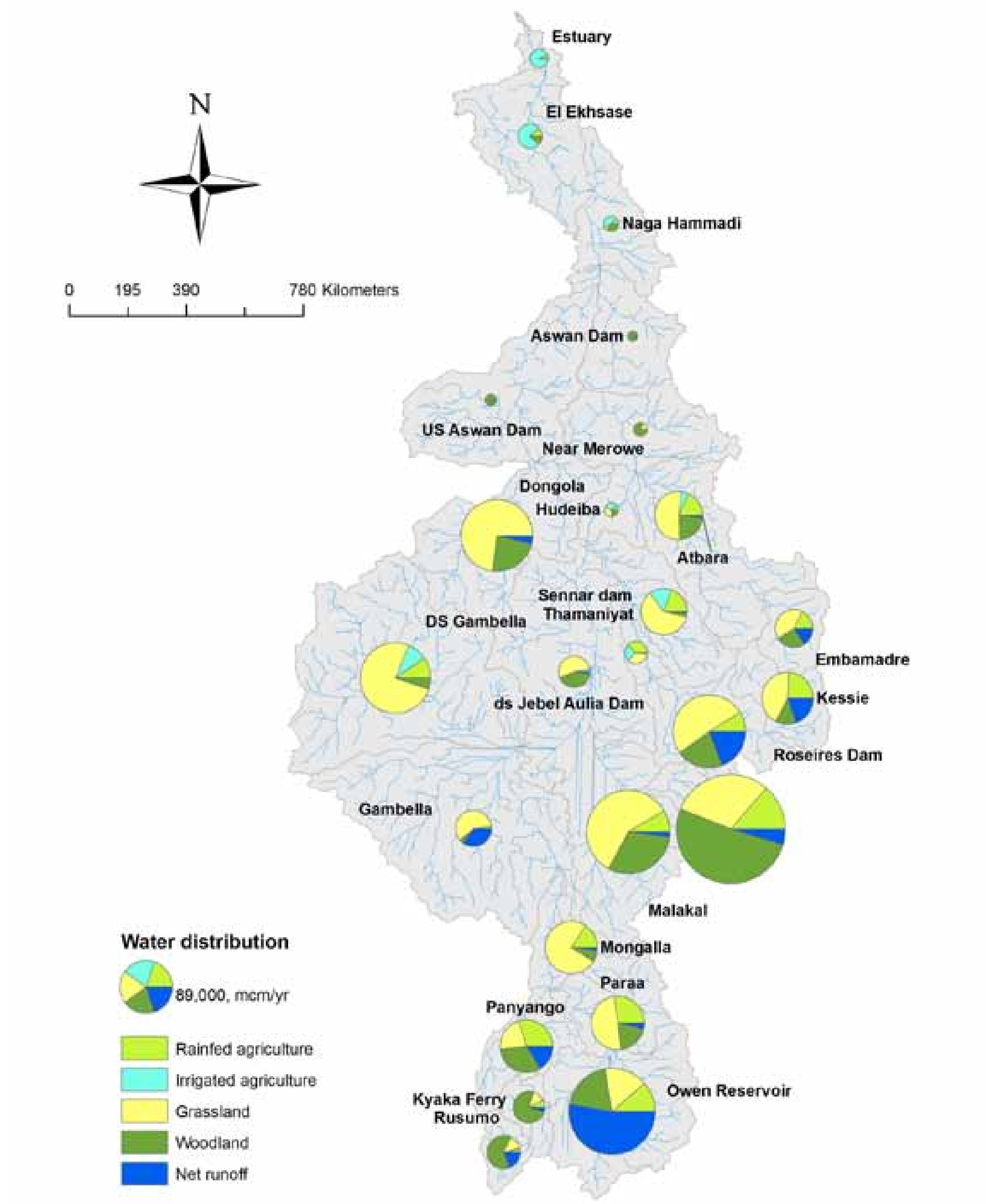

Figure 24. Spatial distribution of major water uses across the catchments of the Nile Basin. Grassland includes shrubland and barren land (see Section 4.3).

The land-use classes presented here are an amalgamation of a broader range of land-use classes determined by remote sensing.The relative size of each of the major water uses varies for different catchments. Net runoff is minimal in many catchments of the Nile Basin, comprising 6% or less of the water available in 17 catchments of the Basin. In the remaining catchments (Rusumo, Owen Reservoir, Panyango, Gambella, Kessie, Roseires Dam, Embamadre, and Aswan Dam), net runoff ranges from 16% (Embamadre) to 53% (Owen Reservoir) of the available water.

Water use by grassland is important in all catchments except for the U/S Aswan Dam, Aswan Dam, El Ekhsasae, and Estuary catchments in the Lower Basin, where it comprises 6% or less of the available water. It is the most important use of water in the Para, Mongalla, Gambella, D/S Gambella, Malakal, D/S Jebel Aulia Dam, Kessie, Roseires Dam, Thamaniyat, Embamadre, Atbara, and Dongola catchments, where it comprises 41 to 76% of the water available. The ‘woodland and other’ land-use class is the most important water use in the Rusumo, Kayaka Ferry, Pamyamgo, U/S Malakal, Malakal, Near Merowe, Dongla, U/S Aswan Dam, Aswan dam, and Naga Hammadi catchments, where it ranges from 31% to 91% of the available water. In upstream catchments, woodlands and forests are the major components of this land-use class. In Lower Basin catchments (Near Merowe, U/S Aswan Dam, Aswan Dam, and Naga Hammadi) barren and sparsely vegetated land form the major component of the land-use classes.

Rainfed agriculture is the most important water use in only three catchments, Paraa, Panyango and Sennar Dam, where it comprises 27%, 30%, and 38% of the available water. It is a relatively important use of water in many of the catchments, using 10% or more of the available water in 14 catchments of the Basin. Irrigated agriculture is the least important use of water, using 3% or less of the available water in all catchments except the Sennar Dam, Naga Hammadi, El Ekhsase, and Estuary catchments. It is the most important water use in the Estuary catchment, using 90% of the available water.

5.3. CATCHMENT AND BASIN HYDROLOGICAL CHARACTERISTICS

Selected hydrological characteristics will be useful for comparing the hydrological function of the Nile Basin and its vulnerability with those of other basins under study in the Challenge Program. Some of these hydrological characteristics are outlined briefly below.

Runoff characteristics for different basins may be compared by comparing their annual percentage runoff ratios (total basin runoff/total basin precipitation). The runoff ratio for the Nile Basin is 8 (i.e. mean annual runoff is 8% of mean annual precipitation). Similarly, differences in runoff characteristics for the different catchments in the Basin can be seen by comparing their annual runoff ratios (Table 2). The runoff ratio of 34 % for Gambella is almost certainly an overestimate. However, a smaller and more likely value of, say, 2 % (the value for the adjacent catchment of Mongalla), generates far less runoff than is actually observed in the gauge and hence the river modelling cannot reproduce the known gauge values (Figure 10). Thus, in this catchment there is an inconsistency in the measured data which should be investigated

Table 2. Annual percentage runoff ratios (runoff/precipitation) for catchments in the Nile Basin.

Catchment	Location	Runoff ratio (%)
Kagera	Rusumo	18
Kagera	Kyaka Ferry	6
Victoria Nile	Owen Reservoir	12
Victoria Nile	Paraa	2
Albert Nile	Panyango	9
White Nile (el Jabel)	Mongalla	2
Bahr El Jabal	Gambella	34
White Nile (el Jabel)	Gambella D/S*	1
Baro	Malakal U/S*	5
Sobat River	Malakal	2
White Nile (el Jabel)	Jebel Aulia Dam D/S	3
Blue Nile (Abbay)	Kessie	20
Blue Nile (Abbay)	Roseires Dam	19
Blue Nile (Abbay)	Sennar Dam	4
Nile	Thamaniyat	10
Nile	Hudeiba	19
Tekeze	Embamadre	16
Atbara River	Atbara	6
Nile River	Near Merowe	2
Nile	Dongola	5
Nile	Aswan DamU/S	4
Nile	Aswan Dam	3
Nile	Naga Hammadi	0
Nile	El Ekhsase	0
Nile	Estuary	0
Whole basin		8

*D/S = Downstream; U/S = Upstream

When annual runoff from each catchment is expressed on a unit area basis, runoff may be plotted as a function of annual precipitation for catchments of the Basin (Figure 25). For catchments with annual precipitation between nil and 700 mm, annual runoff is low, and there is little response in runoff to increasing precipitation. In contrast, annual runoff tends to increase with annual precipitation for catchments with annual precipitation greater than 700 mm.

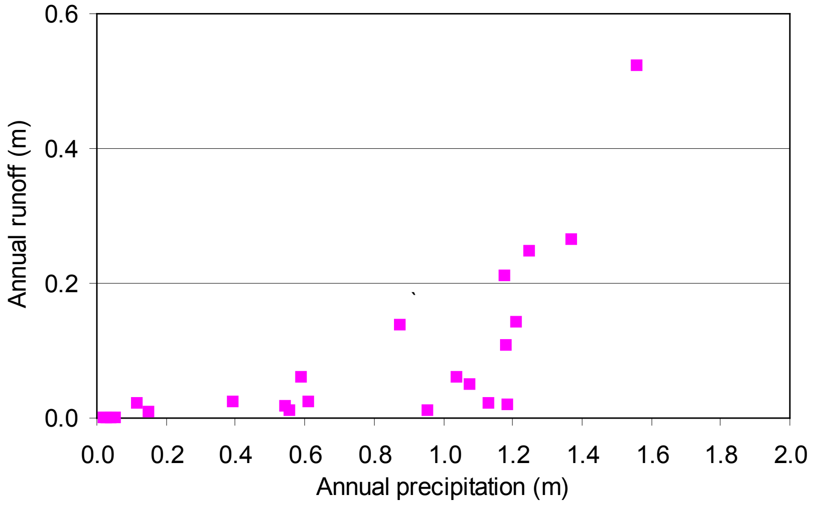

Figure 25. Annual runoff/area as a function of precipitation for catchments of the Nile Basin.

As shown above (Figure 22) total annual runoff from the Basin reflects the annual variation in rainfall from 1950 to 2000. A single function may be used to quantify the relationship between whole basin annual runoff and precipitation (Figure 26). The relationship may be used as a first estimate of the impact of changing rainfall under climate change scenarios. If potential evaporation were to change significantly under climate change, the rainfall-runoff relationship may also be expected to change.

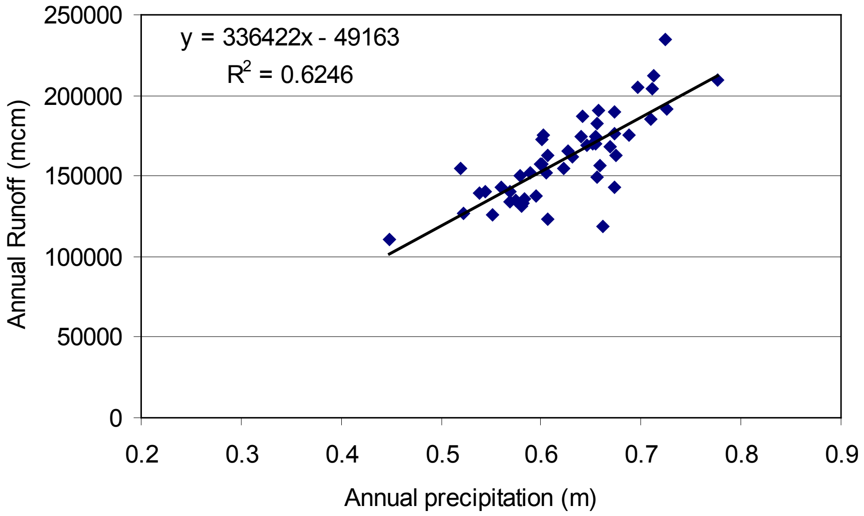

Figure 26. Whole basin annual runoff as a function of annual precipitation for the Nile Basin.

6. EXAMPLE USE

As an example use of the spreadsheet to model the impact of change, we examined the impact of a scenario for climate change in the Basin.

The impact of climate change on rainfall in the Nile Basin is very uncertain, both in direction and magnitude (Conway 2005). Predictions of temperature change are more certain, with an expected increase of perhaps 2°C by mid-century. For demonstration purposes, we used a simple uniform increase of 5% in potential evapotranspiration, and with rainfall unchanged. We emphasise that the scenario is not a prediction; rather it is a demonstration of the use of the spreadsheet. The consequence for reduced flow at Aswan is shown in Figure 27. The annual average flow is predicted to decline from 67,000 mcm/yr to 63,000 mcm/yr. At the same time, evapotranspiration increases, as does irrigation demand with predicted irrigation water use in the El-Ekhsase region increasing from about 13,200 mcm/yr to 13,500 mcm/yr.

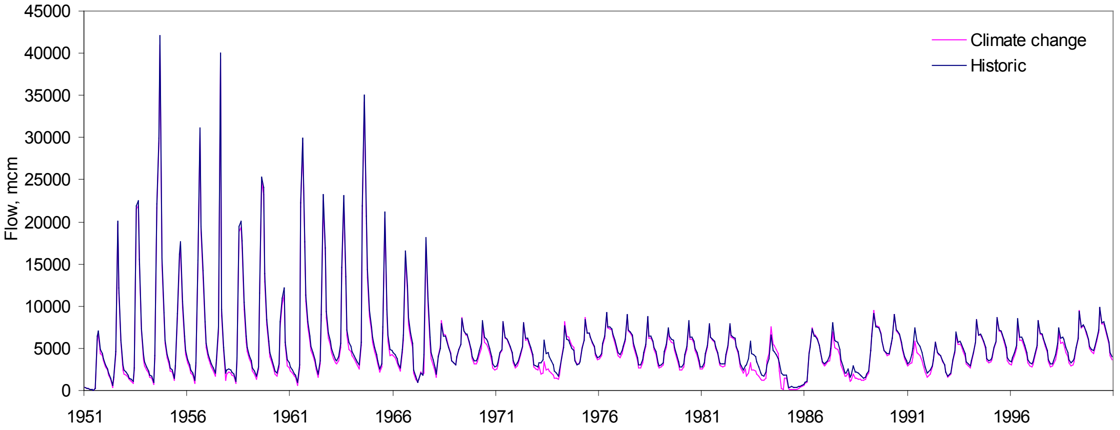

Figure 27. Observed and modelled flow in the River Nile downstream of the Aswan dam with a 5% increase in potential evapotranspiration caused by climate change .

7. CONCLUSIONS

Although currently incomplete, a very simple spreadsheet model with a few adjustable parameters has produced plausible runoff and river flow behaviour in many parts of the Nile Basin. It must be further developed to complete the flow and irrigation diversion description, and to give a better representation of water use by different land uses.

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