Assessing the Hydrological Performance of the Nile Forecast System in Long Term Simulations

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Abstract

This paper presents an assessment of the performance of the Nile Forecast System (NFS) hydrological component with regard to long-term simulations for the purpose of using the NFS to assess the impact of climate change on the river flow. This assessment used available daily and monthly rainfall and runoff data within the NFS database for the period 1940-1999. Simulated flow series were compared to observations at 7 key locations on monthly time step basis. A set of 6 performance criteria measuring the different aspects of flow (peak flow, low flow, etc.) were calculated for the monthly series. The best performance was achieved for the Blue Nile and the Atbara sub-basins (R^2 was between 0.79 and 0.67 through the whole period) followed by Lake Victoria basin (R^2 = 0.48). Performance was not satisfactory for the Sobat, the Equatorial Lakes below Victoria, and Bahr El-Jabal sub-basins. The variable performance depended mainly on the quality of rainfall data in addition to discrepancies in the area of some sub-basins. This evaluation points to the key areas that need further work in order to improve the performance of the NFS..

Key words: Nile Basin, Hydrologic Models, Flow Forecasting, Climate Change Impacts

1. INTRODUCTION

It is widely accepted that Global Circulation Models (GCMs) are the best physically-based means for describing the future climate (Bárdossy, 2000). They are able to reproduce the global and continental scale climate fairly well (Hewitson and Crane, 1996) but they fail to reproduce local and, sometimes, regional climate features required by hydrological (catchment scale) and national (country scale) impact studies. The main reason for this gap between the spatial scale of GCM output and that needed for impact studies is the coarse spatial resolution of GCMs (typically several hundreds of kilometres). This restricts their usefulness at the grid-size scale and smaller (Wilby and Wigley, 1997). Other reasons include inadequate parameterization of several processes regarding cloud formation and land-surface interactions with the atmosphere.

Hydrological processes are parameterised in GCMs using land surface schemes (LSSs) which simulate the partitioning of energy and moisture at the land-atmosphere interface. Errors in heat and moisture fluxes result from the inadequate representation of some land surface features (e.g. wetlands and large lakes that characterize the Nile basin) and the derivation of effective surface parameters for the large heterogeneous GCM grids from point observations. In addition, the hydrologic cycle is too simplified in most GCMs with no lateral transfer of water between grid cells within the land phase. These features are, to a large extent, consequences of the spatial scale gap described above. Therefore, to assess the impacts of climate change on river flow, hydrological models forced with the output of GCMs are often used in preference to direct GCM runoff output. However, the performance of such hydrological models has to be evaluated, and necessary calibration might be conducted before these models can be used in climate change impact studies. In addition, well calibrated hydrological models can be used to assess the performance of LSSs and GCMs in terms of hydrology.

In this study, the performance of the Nile Forecast System (NFS) is evaluated in long-term simulations for the purpose of using the NFS in climate change impact studies and performance assessment of LSSs. The performance of the NFS is evaluated by comparing simulated and observed flow series at 7 key locations along the river. The study uses a set of 6 performance criteria that measure the different aspects of the monthly flow hydrograph (base flow, peak flow, etc.) utilizing available daily and monthly rainfall and discharge data within the NFS database over the period 1940-1999. The next section gives a brief overview of the NFS, the datasets used and reviews previous evaluations of its performance. A discussion of the used performance indicators is then provided before assessing the performance of the NFS. A discussion of the results is finally presented

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2. THE NILE FORECAST SYSTEM (NFS)

The NFS is a real-time distributed hydro-meteorological model designed for forecasting Nile flows at designated key points along the Nile. Of major interest is the inflow of the Nile into the Aswan High Dam in order to plan the annual water resources in Egypt. The system is hosted at the Nile Forecasting Center (NFC) of the Ministry of Water Resources and Irrigation (MWRI), Giza, Egypt, which kindly provided a copy of the NFS software (version 4.1 - Nile Forecast Center, 2002) for this study. In summary, the NFS is composed of 6 main components that perform the following functions: Rainfall Estimation, Hydrological Simulation, River Flow Forecasting, Assimilation, Data Collection and Management (NBHIS), GIS Functions.

The core of the NFS is a conceptual distributed hydrological model of the whole Nile system (Figure) including soil moisture accounting, hillslope and river routing, lakes, wetlands, and man-made reservoirs within the basin. The hydrological component of the NFS is defined on the quasi-rectangular grid of the METEOSAT from which the system receives satellite imagery to estimate rainfall. Each grid cell (pixel) imitates a small basin with generalized hillslopes and stream channels. Inputs to each grid cell are precipitation and potential evaporation. This input is applied to the water balance model of the grid cell. Based on the moisture deficit in the cell, the water balance model computes the actual evaporation and the surface and subsurface runoff components from the pixel. This model was introduced by Koren and Schaake (1992) and was further developed by Schaake et al. (1996) as the Simple Water Balance (SWB) model that was used to analyze FIFE data (Chen et al., 1996). Surface and subsurface runoffs are subsequently input to the pixel's hillslope routing model, simulating the transfer of water towards the main channel. Then water is routed through this channel to the downstream pixel according to a pre-defined connectivity sequence (established via GIS). Different treatment is applied to pixels falling within Victoria, Kyoga, and Albert lakes and the Sudd and Machar swamps, as they do not fit the distributed approach. Basically, rainfall and PET are differenced over those pixels and water balance models are then applied in a lumped sense to the whole lake or swamp area where the specific rating curves for lakes are applied. In addition, the NFS takes care of the operation of reservoirs at Roseries, Sennar, and Gabal-Awlia and abstractions for irrigation in Sudan. For more details about the NFS, refer to Nile Forecast Center (1999) and Elshamy (2006).

The observed rainfall data set have been taken from the NBHIS as gridded daily and monthly raingauge fields for the period 1940-1999. Although the NBHIS contains also satellite-based rainfall data, this evaluation only used gauge data for consistency as satellite data started in 1992. These gridded fields were created by interpolating daily and monthly (as available) rain gauge data to the quasi-rectangular METEOSAT grid (about 5x5 km2) using the Nile Inverse Distance (NID) interpolation (Cong and Schaake, 1995) technique. The NID is a variant of the inverse distance method, where rainfall at an ungauged location is estimated as the weighted average of rainfall at the surrounding gauges (weights are the inverse distance between the gauges and the ungauged location. The NID blends that estimate with the long-term mean rainfall at the ungauged location to increase the influence of climatic characteristics for locations far from gauges. This is similar to the climatologically aided interpolation (CAI) technique of Willmott and Robeson (1995). The NFS requires daily rainfall inputs which are obtained using a simple disaggregation scheme from monthly data when daily data is unavailable.

The NFS uses monthly potential evapotranspiration (PET) in the form of 12 long-term average maps as an input to the hydrological model. The source or averaging period of these data could not be traced from the available documentation. However, comparisons of the annual PET map with a map based on reference crop ET data from the FAO CLIMWAT database (FAO, 2000) revealed close resemblance (LNDFC, 2005). This is expected as the FAO was involved in the NFS development. The inter-annual variability is not considered and the daily values are simply deduced by dividing the monthly total (for each pixel) by the number of days in a month. The insensitivity of hydrological performance to PET variability has generally been reported for several hydrological models (e.g. Oudin et al., 2005). However, inter-annual variability of PET may be important for lakes and swamps.

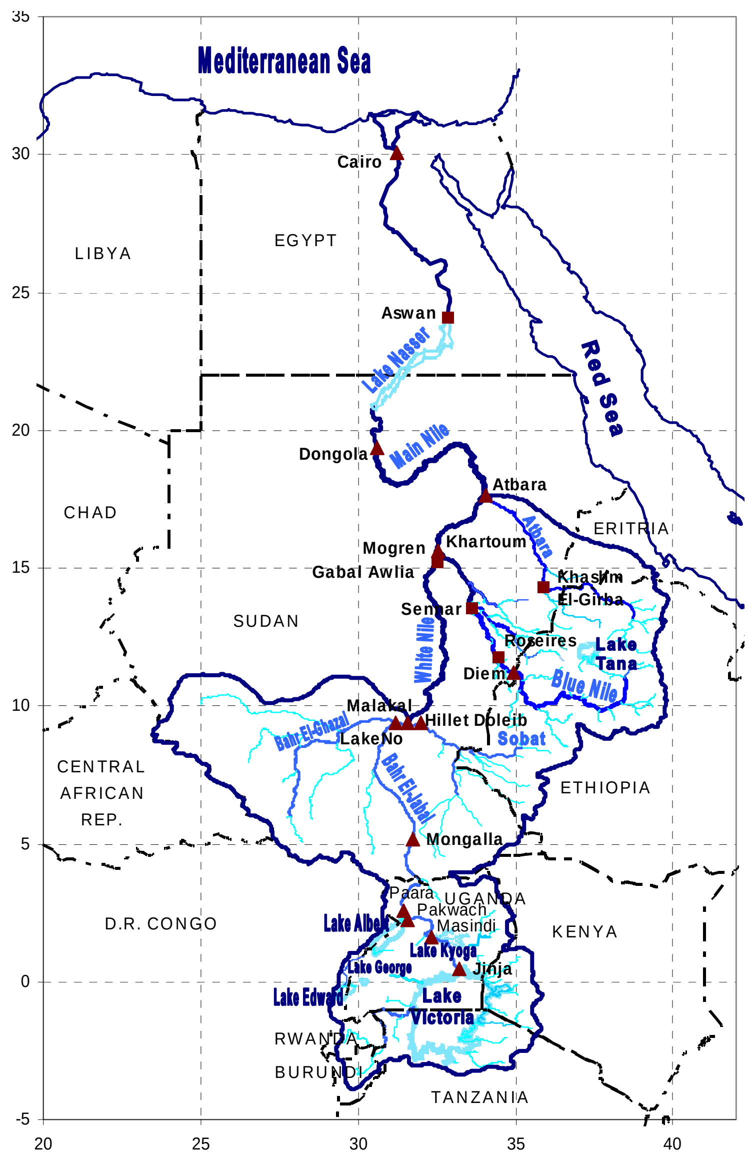


Figure 1 Key Sites and tributaries of the Nile Basin
(triangles indicate river gauges, squares indicate dam sites)

The performance of the NFS in providing accurate forecasts is readily assessed by comparing the issued forecasts (internally published by the NFC for different departments in the MWRI) with observed flows as soon as they become available and is generally judged as satisfactory (NFC, personal communication, 2004). However, as the assimilation procedure changes the rainfall inputs and model states, the comparisons do not provide an assessment of the hydrological performance of the system.

A recent evaluation of the NFS hydrological component was conducted by Sayed and Saad (2002) for a short period (1997-2002). This evaluation focused on Diem and Dongola stations and compared simulated and observed daily flows showing a generally good agreement (93% and 90% of the observed daily variance explained by the simulation) but indicated that errors are larger during the Ethiopian rainy season in the period May to September. The performance of the NFS hydrological component with regard to long-term simulations was also recently assessed for the purpose of conducting climate change scenarios (van der Weert, 2003). This assessment used available monthly rainfall and runoff data within the NBHIS for the period 1940-1995 and compared simulated and observed flow series at 7 key locations within the basin. The results showed variable performance for different locations and time periods with strong linkages to the quality of monthly rainfall grids. The following assessment is similar to that of van der Weert (2003) but extends the simulation period to

1999. In addition, an attempt to use daily rainfall grids as much as available has been made and a more detailed analysis of the results is presented. Although flow records at several key stations started earlier than 1940, the period 1940-1999 is selected as the rainfall grids are only available since 1940.

3. PERFORMANCE CRITERIA

Performance of mathematical models in general and hydrological models in particular, is evaluated statistically by calculating one or more performance criteria, also known as “goodness-of-fit” measures. The most commonly used measures in hydrologic applications are the Root Mean Squared Error (RMSE) and the Nash-Sutcliffe (coefficient of) Efficiency (Nash and Sutcliffe, 1970) calculated for either daily or monthly runoff/stream flow (as the evaluation variable). The Nash-Sutcliffe efficiency (R2) is particularly appealing because it is dimensionless, and thus can be used to compare results for different locations/variables irrespective of the actual values of the simulated quantity. It is also easy to interpret as the percentage of the observed variance explained by the model and has the special zero value at which the mean of the observations is as good as the used model.

However, R2 and RMSE are sensitive to outliers (Legates and McCabe, 1999) and give more weight to flow peaks and peak timing (Gupta et al., 2003) because they involve squaring of the errors. Therefore, other measures have been developed by many researches. These include the Heteroscedastic Maximum Likelihood Estimator (HMLE) (Sorooshian and Dracup, 1980) and the index of agreement (Willmott, 1981). Boyle et al. (2000) assessed the simulation of the different parts of the hydrograph (peak, rising and recession limbs, base flow) by partitioning it into three segments and calculating the RMSE separately for each segment from all time steps belonging to that segment. This attempts to extract more information from the same dataset (Wagener et al., 2001). Hogue et al. (2003) used a squared log error criterion to give more weight to errors at low flows.

To enable comparison of performance at different locations, absolute error measures (e.g. RMSE and BIAS) can be put in relative form via normalization by the mean observed annual or monthly total of the studied variable. In the following analysis, the error measures listed in Table will be used for model assessment. These measures include the commonly used RMSE and R2 focusing on peak values and timing, the BIAS and MAE that focus on the volume balance, and the MLE and MSLE that focus on low values. These measures give a complete picture about the performance, despite having some redundancies (e.g. the R2 is the RMSE normalized by the observed variance).

Table 1 Performance criteria definitions

Criterion	Symbol	Equation	Range & Best Value	Emphasis
Root Mean Squared Error	*RMSE*	$\sqrt{\frac{1}{N_p}\sum_{N_p}(Z_s - Z_o)^2}$	$0 - +\infty$ 0 (Minimize)	Peak values Timing of peaks
Nash Sutcliffe Efficiency	R^2	$1-\frac{\sum_{N_p}(Z_s - Z_o)^2}{\sum_{N_p}\left(Z_o - \overline{Z_o}\right)^2}$	$-\infty - 1$ 1 (Maximize)	Peak values Timing of peaks
Mean Error	*BIAS*	$\frac{1}{N_p}\sum_{N_p}(Z_s - Z_o)$	$-\infty - +\infty$ 0	Volume balance
Mean Absolute Error	*MAE*	$\frac{1}{N_p}\sum_{N_p}\lvert Z_s - Z_o\rvert$	$0 - +\infty$ 0 (Minimize)	Volume balance

Mean Log Error	*MLE*	$\frac{1}{N_p}\sum_{N_p}\left(Ln\left(Z_s\right)-Ln\left(Z_o\right)\right)$	$-\infty - +\infty$ 0	Baseflow
Mean Squared Log Error	*MSLE*	$\frac{1}{N_p}\sum_{N_p}\left(Ln\left(Z_s\right)-Ln\left(Z_o\right)\right)^2$	$0 - +\infty$ 0 (Minimize)	Baseflow

Z_s and Z_o : Simulated and Observed Values;

$\overline{Z_s}$ and $\overline{Z_o}$: Mean Simulated and Observed Values

N_p: Number of observation points

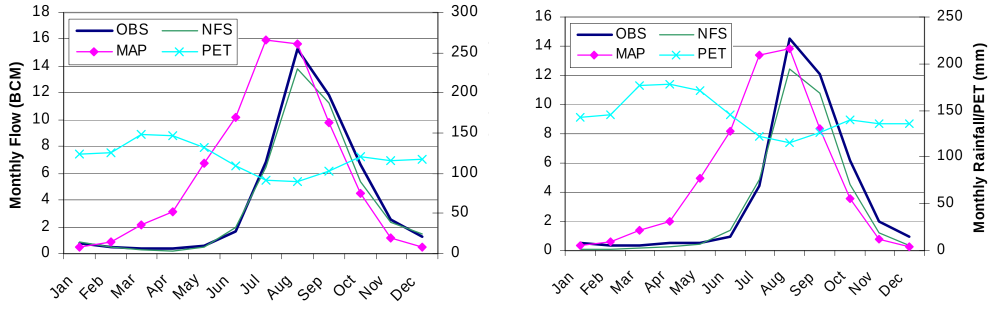
4. COMPARISON OF SIMULATED AND OBSERVED FLOWS

Owing to the length of the simulation and that rainfall for more than half the evaluation period is a monthly series, only monthly and annual time series of flows and mean monthly distributions are compared to those observed. For some stations, the observed record is not complete for the whole period, thus the comparison for those stations will be limited to their observed period. Rainfall and evaporation are presented as spatial averages over the catchment in consideration. To avoid the effects of initial conditions, the simulation is started in 1920 and the results are only reported for 1940-1999. Except for Lake Victoria, a much shorter period (2-3 years) is enough to eliminate the effects of the initial conditions. For Lake Victoria ,the reported response time is about 20 years (Sene, 2000) and a few iterations were made so that the initial level at the end of 1939 matches the observed level so that the initial condition for lake simulation reflects reality.

4.1. The Blue Nile

Diem represents the upper catchment of the Blue Nile while Khartoum is the outlet of the whole Blue Nile basin to the main Nile. Therefore the flow series are compared at both stations to assess the different components of the hydrological model. Up to Diem, the Blue Nile is modeled by the distributed water balance component with no special features considered (Tana Lake effect is small and was not modeled). Between Diem and Khartoum, the NFS simulates the Roseires and Sennar reservoirs and the irrigation diversions within those reaches. The inflows to both reservoirs are calculated from their respective sub-catchments (distributed water balance) in addition to incoming flows from the upstream reaches. Therefore, the simulated flow at Khartoum provides an examination of the NFS reservoir model in addition to the distributed water balance and routing model. Sennar dam started operation in 1925, thus it is included for the whole simulation period. On the other hand, Roseires Dam operated in 1966 only. Thus, the simulation was performed till the end of 1965 with no dam at Roseires and then it was included for the rest of the period.

Figure 2 shows that the simulated mean monthly hydrographs at both stations are close to the observed except for a slightly underestimated peak (by 10% at Diem and 15% at Khartoum). The mean peak time and the rise and recession of the hydrograph are all well captured. Natural flow at Khartoum should be more than that at Diem but because of reservoirs losses and irrigation diversions, the observed flow at Khartoum is about 5.5 Billion Cubic Meters (BCM) less than that at Diem. Due to the extra underestimation at Khartoum, this difference increases to about 8.3 BCM for the simulation.



a) Diem *b) Khartoum*

Figure 2 Mean monthly flow, rainfall and PET distributions at Diem and Khartoum (1940-1999)

Figure 3 shows a large underestimation of the total annual flows at Diem in the 1940s and early 1950s (as high as 71%) that are probably resulting from the underestimation of rainfall during this period. Similar observations apply for the annual series at Khartoum (not shown) with even larger underestimation. Another source of error for Khartoum is the use of constant irrigation abstractions due to the lack of data on the evolution of irrigation schemes in Sudan. This also explains the poor performance in the early period when irrigation abstractions were much smaller. Annual precipitation for the 1970-1976 is nearly constant resulting in a poor simulation of flows for those years. Inspecting the input rainfall for that period, it was found that there were no gauge data over the Blue Nile and Atbara catchments in the database that was used to calculate the daily grids. In this case the gridding algorithm uses the climatological mean rather than the monthly series which resulted in nearly constant annual flows. In general, the simulation for other periods (e.g. 1955-1970, 1985-1999) agreed with the observed values. Given the highly non-linear relationship between rainfall and runoff, small percentage changes in rainfall are magnified in the resulting flows. The correlation between the simulated annual series and the input Mean Areal Precipitation (MAP) is much higher than that for the observed series. This indicated that a large proportion of the simulation errors are due to errors in the rainfall estimation.

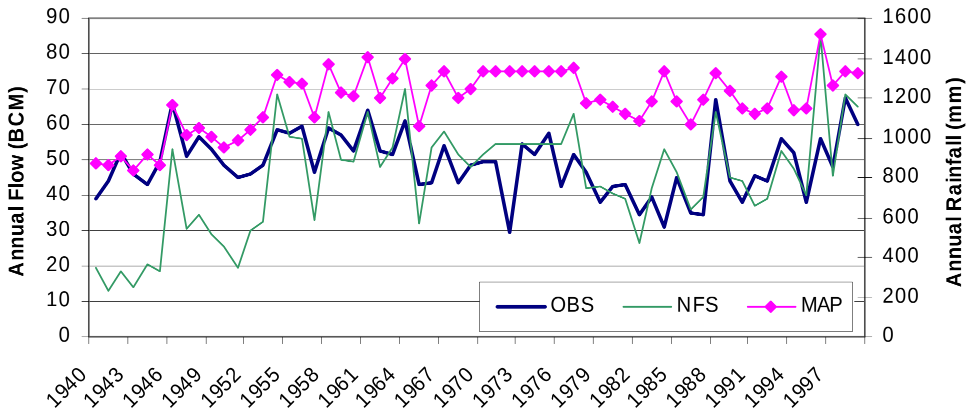


Figure 3 Annual observed and simulated discharges and rainfall series at Diem

In general, the monthly flow series of both stations agree with the observed values, outside the above discussed periods. Most errors occurred in the flood season (Jul-Oct) as mentioned by Sayed and Saad's (2002) results for the short period 1997-2002. On average, more than 80% of the flow is generated during the flood period, thus these errors are directly visible in the annual series. The base flow seems to be underestimated for Khartoum in most years. However, the NFS is capable of explaining about 79% and 71% of the observed flow variability for Diem and Khartoum respectively, with small long-term biases (-0.32 and -0.57 BCM for Diem and Khartoum respectively). Thus, the NFS performance is generally satisfactory for the Blue Nile in spite of the uncertainties in rainfall estimates and irrigation abstractions in addition to the fact that Lake Tana and small swamps, within some tributaries, were not modeled.

4.2. The Atbara

The river Atbara is studied at its outlet to the Nile at Atbara town. The Khashm El-Girba dam is not modeled by the NFS but the irrigation diversions are taken into account. The effect of the dam is thought to be small due to its small capacity. The mean hydrograph at Atbara is well reproduced as shown in Figure 4.

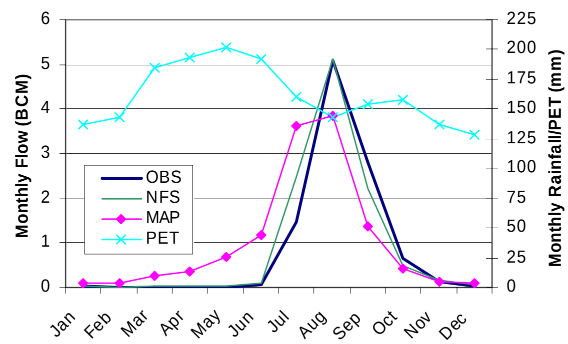


Figure 4 Mean monthly flow, MAP and PET distributions at Atbara mouth (1940-1999)

However, the rising and falling limbs, of the simulated hydrograph, have slightly different slopes from the observed. The better prediction of the mean peak results from underestimation in the early years (1940-1953), similar to the Blue Nile, counterweighted by overestimation in the latter years (1980-1995) (Figure 5). The nearly constant simulated flows in the period 1970-1976 resulted from the constant rainfall during this period due to the lack of gauge data within this region as in the case of the Blue Nile. This is because both catchments have no buffer zones (lakes, wetlands) that made the changes in rainfall directly visible in the runoff regime. As the Atbara runs nearly dry outside the flood season, errors in the annual flow are mainly due to errors in simulating the peak flow. The association between the simulated annual series and the MAP series is quite high (75%) compared to that of the observed flow (32%) indicating that rainfall estimates are the main source of error. However, the simulation explains about 67% of the observed variance in the monthly series with a very small long-term bias.

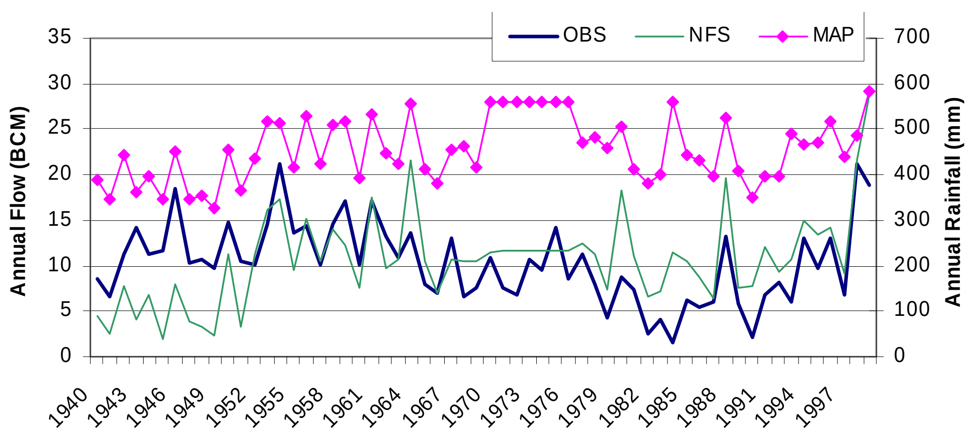


Figure 5 Annual observed and simulated discharge and MAP series at Atbara mouth

4.3. Lake Victoria

The catchment of Lake Victoria is simulated by the NFS in two stages: first the inflow from the catchment to the lake is modeled using the pixel scale water balance model. Then the lake model is solved to calculate the lake outflow and level at Jinja considering the rainfall and evaporation rates over the lake. The Owen Falls dam downstream of Jinja is not simulated as it was designed to imitate the so-called Agreed Curve of the lake outflow. Several previous studies, e.g. Kite (1981), showed that it satisfies the design requirements. Lake Victoria basin is characterized by larger rainfall over the lake portion (1604 mm) compared to the surrounding land (1055 mm) while evaporation is slightly higher over the lake (1485 mm) compared to the land (1471 mm). The NFS enhances the lake rainfall further by 4.3% when the lake model is applied.

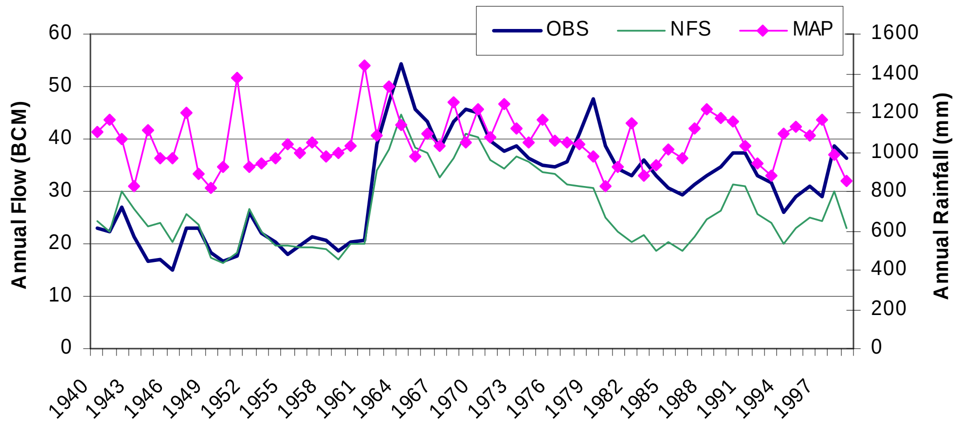


Figure 6 Annual observed and simulated discharge and MAP series at Jinja

The simulated annual flows (Figure 6) are generally in agreement with the observed till the year 1961 apart from some overestimation in the period 1942-1946. The abrupt jump in lake levels and outflows in the early 1960s is matched by a similar jump in the simulated flows but with a smaller magnitude. The simulated flows for the rest of the period are consistently underestimated with small underestimation during the period 1969-1977 (7% on average) and larger underestimation during the 1980s (up to 44% in 1984). It should be mentioned that the 1969-1977 period coincides with the WMO Hydrometeorological Survey project during which extensive rainfall and flow measurements were collected. Thus the rainfall estimate during this period is of better quality than other periods. In addition, calibration of NFS parameters for the Lake catchment was conducted using the 1970-1973 data. This explains the good match during this period. Due to the general under estimation since 1961, the simulated mean monthly hydrograph is underestimated by 14% on average with respect to observed values (Figure 7).

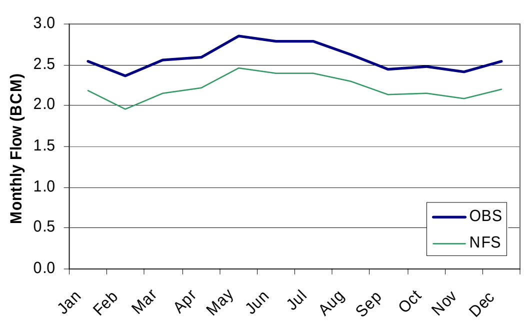


Figure 7 Mean monthly observed and simulated hydrograph at Jinja (1940-1999)

On the other hand, its shape was preserved by the simulation. This indicated that errors are more evenly distributed over the year than the case of the Blue Nile and Atbara. It is common in previous Lake Victoria modeling studies that the simulations gave a good match in some periods and lower quality matches in others (e.g. Tate et al., 2004). Due to the large lake area and the consequently long response time, a small error in a single year can affect the simulated flows for several years. This means that the underestimation of the flows in the late 1960s may be a consequence of the underestimation of the abrupt increase in the lake levels in the early 1960s.

The correlation between the simulated annual flow series and the area weighted MAP (lake and land areas) is only 0.26 but this is also larger than the correlation for the observed series (0.15). Both correlations are rather low because of the lake attenuation effect. The lag 1 correlation gives a better indication and again it is higher for the simulated series (0.59) compared to that of the observed (0.44) indicating that the rainfall is a possible source of simulation errors.

The monthly flow series is better simulated than the annual one. For a given year, monthly errors accumulate when the flows are summed to calculate the annual flow resulting in larger annual errors. The monthly flow is within ±15% of the observed for about 52% of the simulated months. Due to the high under estimation in the 1980s and 1990s, the simulation explains only 48% of the observed monthly variance. The NFS performance for Lake Victoria is less satisfactory than its performance for the Blue Nile and Atbara but it is still acceptable in the light of rainfall and evaporation errors and the long response time of the lake.

4.4. The Equatorial Lakes below Victoria

The next reliable flow station down the Nile is Mongalla for which records are available only till 1982. Thus, the comparisons for Mongalla will be limited to the period 1940-1982. The NFS simulates Lakes Kyoga and Albert, explicitly, while the rest of the catchment (including smaller lakes) is simulated using the distributed water balance model. The initial water levels for the two lakes were not adjusted to match the observed levels because of the complexity of the system and the major influence of Victoria Lake. The short and unreliable records for flow gauges between Jinja and Mongalla made it difficult to evaluate the NFS performance for each lake separately. In order to avoid the effect of errors from simulating Victoria Lake, the following analysis focuses on the gains and losses between Jinja and Mongalla, i.e. the evaluation compares the simulated and observed differences in flows between the two gauges given the MAP and PET for this sub-catchment area.

On annual basis, the flow at Mongalla is generally greater than that at Jinja indicating flow gains (Figure 8) except for a small loss value (0.82 BCM) in 1940. The NFS simulates flow gains in all years and highly overestimates these gains for the entire record except for the period 1979-1981. The relatively high overestimation in the early years of the record compared to the 1970s may partially have originated from incorrect initial lake levels. The correlation between the annual flow gains and the MAP series for the Jinja-Mongalla sub-catchment is 0.80 for the simulation while it is only 0.04 for the observed, which indicates that most of the errors originate from the rainfall. The resultant mean hydrograph (Figure 9) shows this overestimation which scales the loss/gain hydrograph by more than 300% in some months. However, the shape of the hydrograph is still preserved.

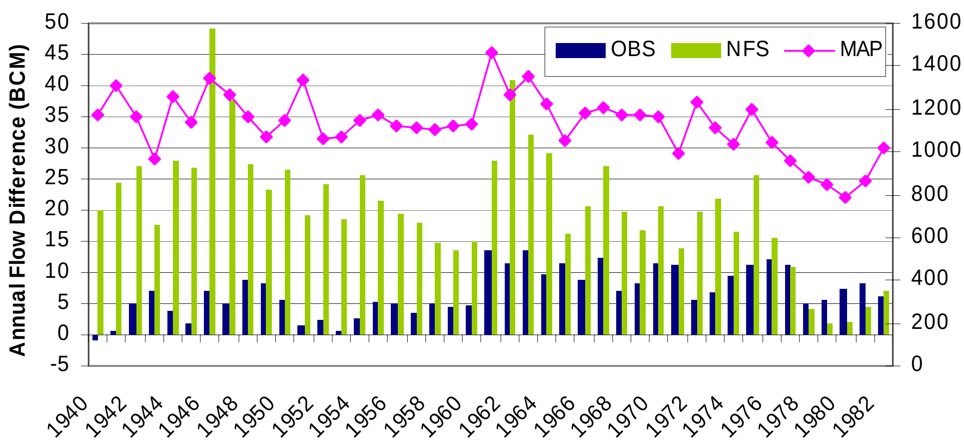


Figure 8 Annual observed and simulated flow loss/gain between Jinja and Mongalla and MAP series for the Equatorial Lakes Sub-basin

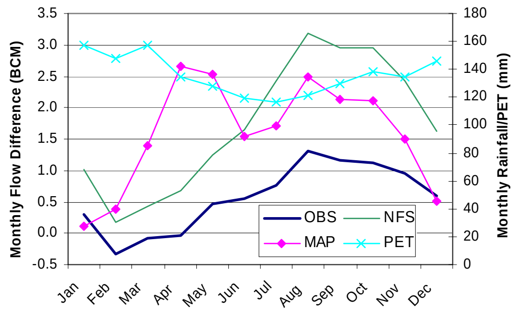


Figure 9 Mean monthly flow, MAP and PET distributions at Mongalla (1940-1982)

The simulated monthly discharges at Mongalla shows the same large and consistent overestimation till 1964 where the overestimation of the gains is counterbalanced by the under-estimation of Lake Victoria outflows so that the agreement of the flow records is better till 1978 when the underestimation of Jinja flows are large and the gains are better estimated so that the simulated flow at Mongalla is actually underestimated. Only in the short period 1970-1973, which was possibly used for calibration, the gains/losses and the actual discharge at Mongalla are well reproduced. The seasonal cycle is reproduced but the errors are large and therefore, considerable effort is required to check the water balance of each lake to develop better rainfall estimates and better flow simulation at Mongalla. Lakes Kyoga and Albert are generally poorly studied compared to Lake Victoria and the available level and flow records for the two lakes and their basins are rather shorter and less reliable (Sutcliffe and Parks, 1999).

4.5. The Sobat

The NFS divides the Sobat basin into several sub-catchments. First it applies the distributed water balance model to the sub-catchment of the upper Baro till Gambella and the adjacent areas above the Machar Marshes. The net rainfall over the swamp area and inflows from the Upper Baro form the inputs to the swamp model of Machar. The outflow from the swamp area is then combined with flows of the Pipor with allowance for losses in the lower reaches of both tributaries. The source for the parameters of the swamp model for Machar could not be traced from the documentation. The comparisons presented here are based on the flow of the whole Sobat basin at Hillet Doleib near its mouth for which the observed record is only available till 1982.

The simulation of annual total flow volumes (Figure 10) looks poor. There are large discrepancies between simulated and observed annual flows but more noticeable are the shifts in the annual peaks and troughs where the observed series lagged behind the simulated one or two years. The peaks and troughs in the simulated flow series seem to coincide with the peaks and troughs in MAP indicating a faster response to rainfall than observed (correlation with MAP is 0.88 of simulated and 0.31 for observed).

The mean seasonal hydrograph (Figure 11) shows good agreement in the low flow period (February – June) and the total mean volume is only slightly over estimated (7%). However, the simulated peak is higher and occured one month earlier than the observed one. The rising and falling limbs of the hydrograph have higher rates than those observed which caused the simulated peak to look sharper, i.e. the simulated hydrograph is more dynamic than observed. This may be due to the incorrect simulation of the swamp effect on the attenuation of the flow.

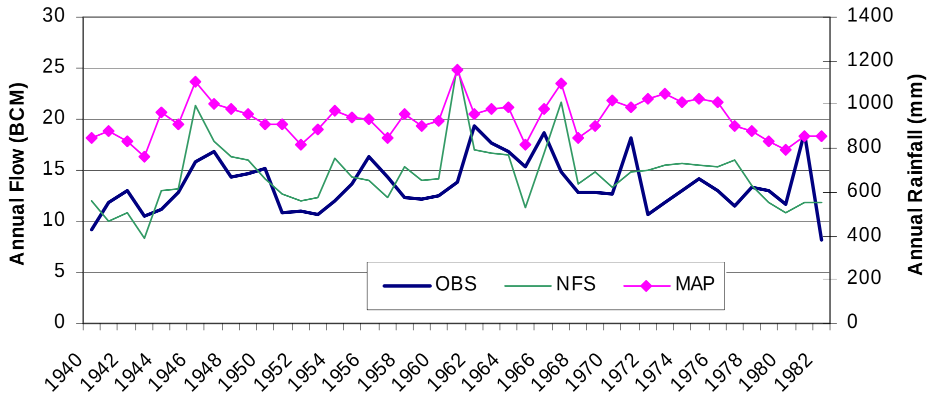


Figure 10 Annual observed and simulated flow and MAP series at Hillet Doleib

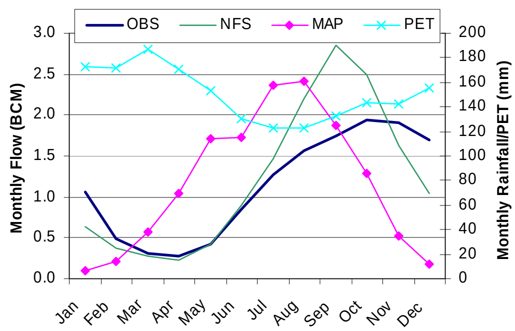


Figure 11 Mean monthly flow, MAP and PET distributions at Hillet Doleib (1940-1982)

Observing the monthly time series, the NFS consistently overestimated the peak flow and simulated it one to two months earlier while the low flow is generally well captured. The simulated peak flow occurred about 2 months after the peak MAP (lag 2 correlation with MAP is 0.88) while the observed peak occurs about 1 month later (lag 3 correlation with MAP is 0.86). This indicated that the errors partially originated, from the swamp model and the simulation could be improved by tuning the swamp model parameters. This does not eliminate errors in estimating rainfall as indicated by the annual series comparison. The current simulation explained only 8% of the observed monthly variance.

4.6. The Sudd and Bahr El-Ghazal

The NFS models Bahr El-Ghazal using the distributed water balance model. However, the small contribution of the basin and the lack of a reliable record at its outlet near Lake No hinder the proper evaluation of the NFS performance over this vast area. Moreover, spills from Bahr El-Ghazal to the Sudd make it more difficult to separate the outflow from the two sub-catchments. The Sudd receives flows from the equatorial lakes complex as simulated at Mongalla, and the runoff of Bahr El-Jabal and Bahr El-Ghazal sub-catchments simulated by the distributed water balance model. Combined with the net rainfall over the Sudd swamps, these are input to the swamp model whose parameters were taken from Sutcliffe and Parks (1987). The Sudd outflows, which include a small contribution from Bahr El-Ghazal basin, are combined with the outflows from the Sobat to form the White Nile flows at Malakal. This is the most reliable flow gauge in the area. In order to evaluate the NFS performance over the Sudd region, the following results compare the simulated and observed flow gains/losses over the Mongalla-Malakal reach after subtracting the Sobat and Mongalla flows from those at Malakal. Because the observed flow records at both Mongalla and Hillet Doleib stopped in1982, the comparisons of the Sudd losses are limited to the period 1940-1982.

The combined contribution of Bahr El-Jabal and Bahr El-Ghazal is negative for both the observed and simulated flow series (Figure 12). In the first half of the period (1940-1961), the NFS highly over estimates these losses by as much as 5 times (e.g. 1944 and 1945) probably due to the overestimated inflow rates into the swamp from the Equatorial Lakes (see the simulation results at Mongalla above) during the same period. Although the Mongalla series has been deducted, over estimating the inflows to the swamp model led to overestimation of the flooded areas and consequently resulted in higher losses than observed. The observed losses increased in the early 1960s in response to the increased inflows from the upper catchment following the dramatic 2.5m rise in Lake Victoria level. In this period, the simulated losses are still overestimated but to a lower degree (20% on average for the period 1962-1975 compared to 170% on average for the period 1940-1961). In the period (1976-1982) the NFS underestimated the losses in response to the underestimation of the inflow at Mongalla. One reason for these errors is that the permanent swap area used in the NFS is 30,290 km^2, which is higher than the reported estimates in the literature, especially before 1961. Unfortunately, the NFS does not provide the output of the simulated swamp area. The correlation between simulated annual losses and rainfall over Bahr El-Jabal is higher than that for the observed (0.48 compared to 0.05, losses increase with rainfall due to the expansion of swamps). However, the relatively low correlation with MAP indicated that the rainfall errors over the area are less important than the inflows from upstream or direct evaporation losses from the overestimated swamp area. The correlation between the Sudd losses and Mongalla flows is about 0.87 for the observed and 0.85 for the simulated series.

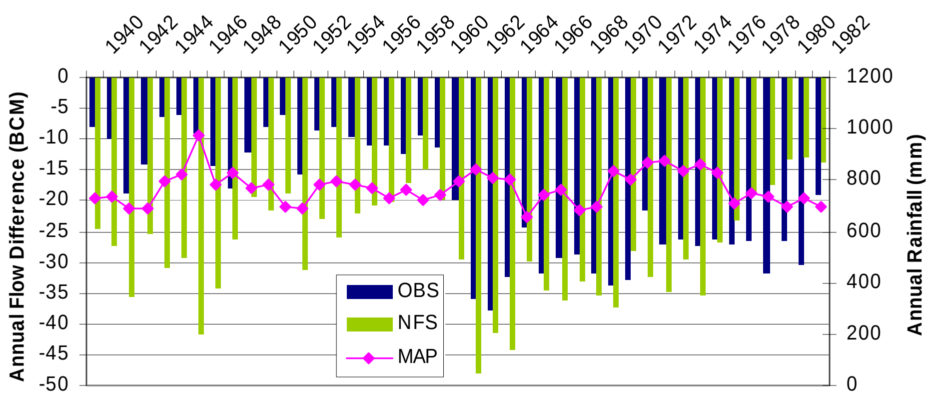


Figure 12 Annual observed and simulated flow losses and MAP series over the Sudd

On the monthly level, the mean monthly hydrograph of the losses is consistently overestimated. The overall hydrograph shape, including the peak loss time (August), which coincides with the peak rainfall rate, is well reproduced. The losses at the peak are overestimated more than those in the dry season (November – March) despite the fact that higher evaporation rate occurs during this season. This may be explained by the additional evaporation from seasonally inundated areas during the wet season which dry during the winter. A recent study by Mohamed et al. (2004) calculated the total actual evaporation from the Sudd in the year 2000 as 1,636mm (indicated as AET 2000 on Figure 13) while the climatological potential evaporation value used in the NFS is about 1,944mm (spatially averaged). This may have contributed to the overestimation of the losses. The actual evaporation is close to the NFS PET during the rainy season which means the high overestimation of losses is more related to inflows to the swamps. The actual evaporation is lower than the potential during the dry season indicating that the smaller overestimation of losses during this period may rise from using the potential rate of evaporation. However, most of the dry season losses arise from the permanent swamps for which evaporation would remain at the potential rate. This indicated that the seasonal variation of the swamp area might not be correctly simulated. Given the lack of data on the seasonal and inter-annual variations of the swamp area, the validation of the swamp model is difficult. The monthly series (not shown) over the Sudd confirmed that the long-term pattern occurred most of the time.

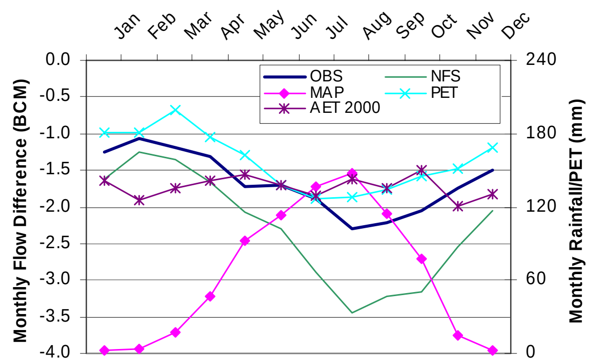


Figure 13 Mean monthly losses, MAP and PET distributions over the Sudd (1940-1982) and AET for 2000

Despite the highly overestimated losses over the Sudd, for the early part of the record (1940-1961), the highly overestimated flows at Mongalla counter weights the losses giving rise to a less pronounced overestimation of monthly and annual flows at Malakal (Figure 14). The errors over the Sobat are relatively smaller during this period and are generally on the positive (i.e. overestimation) side. The dry season flows are also higher than observed during this period. The increase in the observed flows in the early 1960s is picked up by the simulation but it occurs earlier (simulated in 1961 but observed in 1964). The rest of the simulated record at Malakal is closer to the observed but still with varying degrees of overestimation and underestimation coupled with one or two month error in estimating the peak time, originating from errors in the Sobat contribution as indicated by the mean monthly hydrograph if Figure 15 were compared to Figure 11.

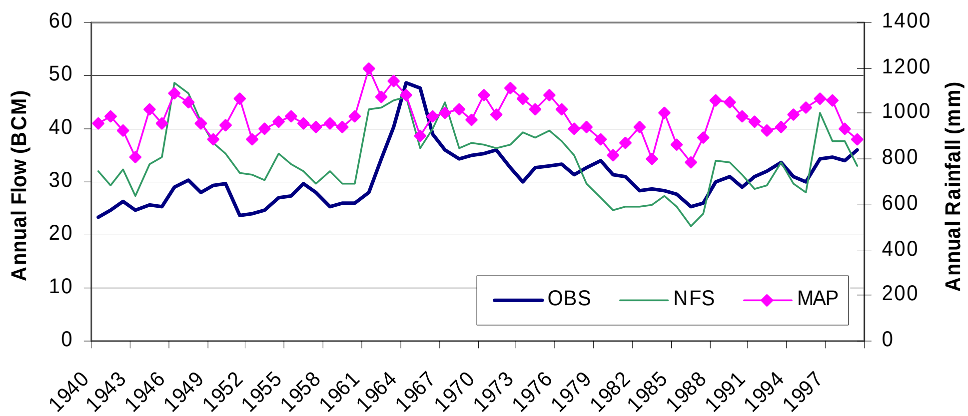


Figure 14 Annual observed and simulated flow and MAP series for the White Nile at Malakal

Apart from the rare high overestimations, the simulation of the period 1968-1999 can be considered satisfactory. The overall performance at Malakal is generally better than that of the sub-component flows at Mongalla, Hillet Doleib, or the Sudd losses because some errors compensate each others. As usual, the annual simulated flow at Malakal correlates with the annual MAP over the whole White Nile basin better than the observed (69% compared to 26%) indicating the errors of rainfall mentioned earlier in the various contributing sub-catchments.

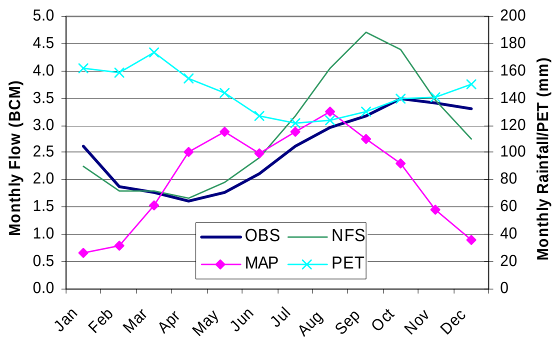


Figure 15 Mean monthly flow, MAP & PET distributions for the White Nile up to Malakal (1940-1999)

4.7. The Main Nile Upstream Khartoum

Between Malakal and Khartoum, the Nile receives no tributaries. The NFS simulates this reach using the Muskingum-Cunge routing scheme allowing for evaporation losses and irrigation diversions. The calculated discharge forms the inflow to the Gabal Al-Awlia dam whose operation is simulated using the reservoir sub-model. The dam release presents the flow at Mogren which is then combined with that of the Blue Nile at Khartoum to form the discharge of the main Nile. Thus, examining this reach tests the reach routing and reservoir components of the NFS hydrological model. In order to avoid the effects of errors from the inflow at Malakal, the gain/loss over this reach is studied by differencing the observed and simulated flow series at both locations. Because the gains and losses are small compared to the total flows, small inaccuracies in the total flows are exaggerated in the resulting series which should be kept in mind when the observed and simulated series are compared.

On annual basis (Figure 16), this reach is a source of water loss that the NFS consistently over estimates, especially in the earlier period up to 1980. The simulation of the 1981-1999 period is generally better, with smaller deviations (on average +43% or about 2.33 BCM). One error source during the earlier period is possibly the use of irrigation diversion estimates that belong to the recent past (i.e. 1980s and 1990s). Similar to the Blue Nile, irrigation schemes were probably smaller during the early period while the diversions are fixed annually, not reflecting the development of those schemes over time. However, the total annual diversions from this reach are only 2.4 BCM and this does not explain the high overestimation of losses. The inter-annual variability of evaporation rates is unlikely to explain the errors. The parameters of the routing scheme may be in error or the reservoir operating rules may have changed but it is also unlikely that these will account for such large deviations. There might be a contribution from rainfall over the sub-catchment of this reach which is not modeled by the NFS. The reason for such a poor simulation is thus needed to be further studied.

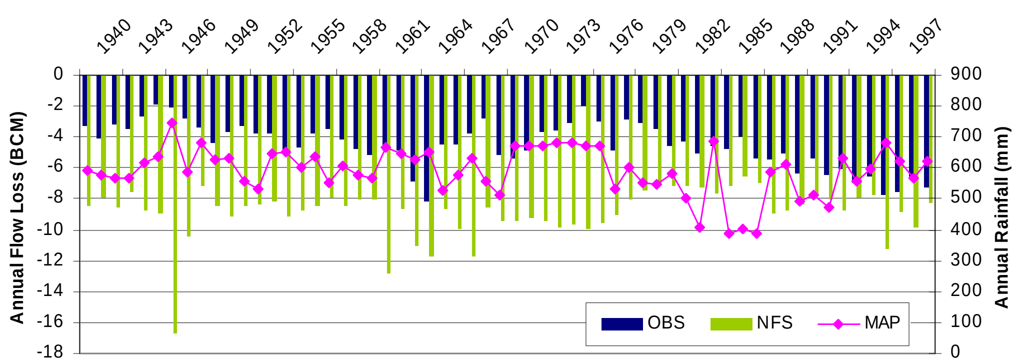


Figure 16 Annual observed & simulated flow losses & MAP series for the Malakal – Mogren reach

The mean monthly hydrograph of gains and losses (Figure 17) shows some observed gains during the dry season, peaking in April, that the NFS generally under estimates while it equally over estimates the losses that occured mainly in the wet season with a peak in August corresponding to the MAP peak.

The main reason for this monthly distribution of gains/losses is that the water travel time through the Malakal – Mogren reach delays the winter flow peak at Malakal till April at Mogren. The high flows arriving at Khartoum from the Blue Nile during the autumn held back the slower White Nile flows though backwater effects. The operation of the Gabal Al-Awlia Dam may have caused further delays. The simulated mean hydrograph at Mogren does not agree in shape with the observed except for the hydrograph lowest point in July. The annual flow series at Mogren is similar to that of Malakal as the amount of losses/gains is relatively small compared to the total flow. The correlation of the simulated series with the MAP over the whole White Nile is 0.68 which, as expected, is much higher than that for the observed (0.25). The simulation explains 47% of the observed variance of the monthly flow difference between Mogren and Malakal while it fails to explain the variability of the monthly flow series at Mogren due to combined effects of errors at Malakal and within this reach.

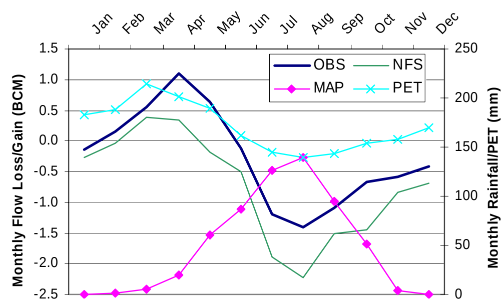


Figure 17 Mean monthly flow loss/gain, MAP & PET distributions for the Malakal- Mogren reach (1940-1999)

4.8. The Main Nile Downstream of Khartoum

Below the confluence of the White and Blue Niles at Khartoum, the Nile flows in a semi-arid zone till Dongola receiving additional flows from last tributary, Atbara, at Atbara town. The NFS uses the reach routing sub-model to simulate this reach divided into two segments: from Khartoum to Atbara and from Atbara to Dongola. Both segments are subject to evaporation losses but there are neither irrigation diversions nor any contribution from the very low rainfall over this reach. Below Dongola, the Nile delivers its waters to Lake Nasser and thus the last important station currently on the Nile is Dongola.

The annual and monthly series of gains/losses over the Khartoum – Dongola reach are calculated by subtracting the flows of the White Nile at Mogren, the Blue Nile at Khartoum, and the Atbara at Atbara mouth from the flow series at Dongola. The accuracy of both observed and simulated loss series is not very high as it represents the difference of two large quantities and will be affected by discharge estimation errors at any of the given sites. For most years, this reach is a source of either moderate losses (up to about 10 BCM or small gains (in the order of magnitude of 3 BCM). The only exception to this is the 80s where considerable gains of up to 8 BCM were observed. The NFS simulates losses for this reach all the time (except for a very minor gain in 1966) with lower variability than observed. The observed gains probably relate to some change in the rating curves of one of the used stations. The monthly series is better simulated compared to the annual series as the small errors on the monthly scale tend to add up causing larger deviations at the annual scale.

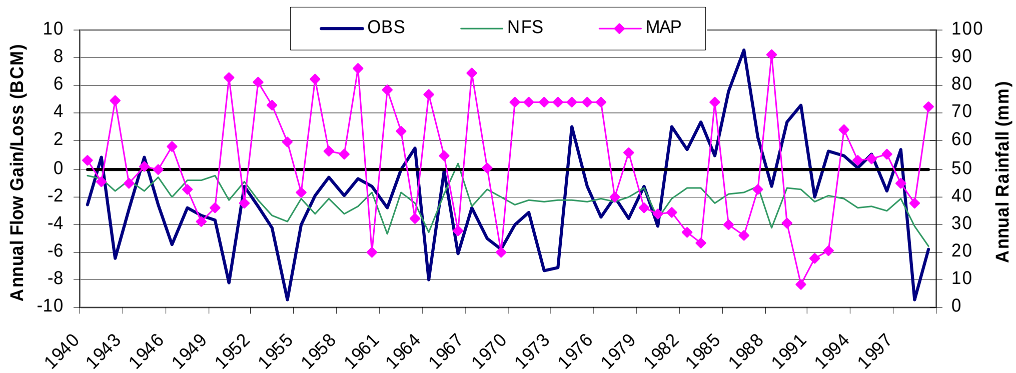
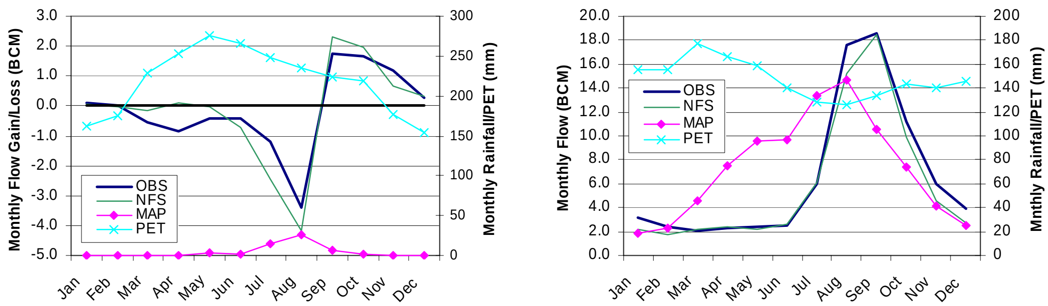


Figure 18 Annual observed & simulated flow losses and MAP for the Khartoum – Dongola reach

The mean monthly distribution of gains and losses over this reach (Figure 19a) generally matched with the NFS but it underestimates the August peak loss and there is a time shift of one month for February – June losses. The peak gains which is observed in October – November is slightly overestimated by the NFS. The errors in simulating the mean hydrograph for losses and gains over this reach are small compared to the actual flow so that the mean hydrograph at Dongola is well reproduced (Figure 19b). However, the NFS underestimated the mean flow for August during the winter months (November – February). This led to the underestimation of the mean annual flow volume by about 10%. This is a result of the large underestimation of flows in earlier periods i.e.1940-1955 originating from errors in simulating the Blue Nile and the Atbara as discussed above.



a) loss/gain for the Khartoum-Dongola *b) Dongola*

Figure 19 Mean monthly flow, MAP & PET distributions for Dongola (1940-1999)

The annual (Figure 20) and monthly flow series at Dongola are well reproduced for the period 1956-1999. The simulation explained about 76% of the observed monthly variability with a high correlation coefficient with the observed series (0.89). The larger deviations observed for the White Nile sub-basins are displayed in the underestimation of the base flow but because most of the flow originates from the Blue Nile and the Atbara, the annual volumes are only slightly affected except for the early period when the Blue Nile and Atbara simulations contained large underestimations.

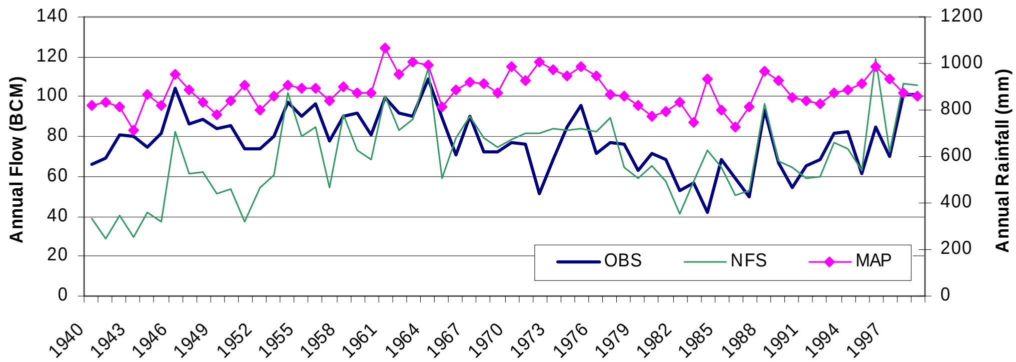


Figure 20 Annual observed & simulated flows and MAP for the Nile at Dongola

5. SUMMARY AND CONCLUSIONS

Table summarizes the results of the comparisons for the Nile at the designated key locations for the monthly series. These results are based on the 1940-1999 period except for Mongalla and Hillet Doleib where the values presented are based on the 1940-1982 period. The NFS performance is satisfactory for the Blue Nile which reflects the NFS historical development and design objectives. The main objective of the NFS was to forecast the inflows of the Nile basin to Lake Nasser which are calculated at Dongola rather than performing long term simulations. As most of the flow originates from the Blue Nile, the development and calibration of the NFS focused on the Blue Nile. As a result the performance for this catchment is better than other areas especially in recent years and the performance at Dongola is also satisfactory because its flow is dominated by that of the Blue Nile. The performance for the Atbara is reasonable because of its similarity with the Blue Nile.

Table 2 Statistics of simulated monthly flow series at key Nile gauges

Station	*MAE* (BCM)	*RMSE* (BCM)	*MLE*	*MSLE*	R^2	Mean Annual Volume (BCM)	
						OBS	SIM
Diem	1.19	2.29	-0.18	0.28	0.79	48.84	44.92
Khartoum	1.47	2.71	-0.79	2.42	0.71	43.38	36.60
Atbara	0.44	0.99	-0.12	1.64	0.67	10.32	10.74
Jinja	0.46	0.59	-0.14	0.06	0.48	31.00	26.63
Mongalla	1.29	1.71	0.28	0.24	-0.93	37.13	48.38
Hillet Doleib	0.47	0.68	0.04	0.31	0.08	13.55	14.54
Malakal	0.65	0.94	0.07	0.08	-0.22	30.76	34.05
Mogren	0.62	0.82	-0.04	0.18	-0.31	26.23	25.19
Dongola	1.78	3.02	-0.14	0.16	0.76	78.07	70.33

The NFS is generally operated in forecast mode with the output of the distributed hydrological model for the White Nile at Malakal often replaced by the output of a stochastic model of observed flows based on the long travel time between Malakal and Dongola. For these reasons, the White Nile sub-basins are less satisfactorily modelled than the Blue Nile and the Atbara especially below the more historically studied Lake Victoria for which the simulation is reasonable. Therefore, the NFS reliability is highest for the Blue Nile, followed by the Atbara, and then Lake Victoria sub-basins. However, additional data records can be used to improve the model in these other sub-basins via calibration. For example, satellite techniques are promising in estimating wetland areas which can improve the estimates of losses over the Sudd and Machar.

Most of the simulation errors are probably related to errors in rainfall estimates which can be, at least partially, rectified by using other rainfall estimates from global data bases or using other methods of converting gauge data into grid estimates. Other sources of errors include over estimation or under estimation of basin areas (e.g. Atbara), lack of historical data on irrigation abstractions and neglecting the inter-annual variability of PET. Errors in model calibration and formulation are not excluded either. The latter period of record (1990s is generally simulated better than the earlier period for most areas because errors in rainfall estimates are generally smaller as more data were collected since the establishment of the NFC. In addition, the used irrigation abstractions reflect the recent past rather than they of the 1940s and 1950s. Thus, the NFS has actually helped in collecting flow and rainfall data and is potentially capable of simulating the different sub-catchments of the Nile and can be used to assess climate change impacts over the Nile basin with more confidence in the Blue Nile and Atbrara areas than other subcatchments.

6. ACKNOWLEDGEMNET

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