INVESTIGATING THE CLIMATE SENSITIVITY OF DIFFERENT NILE SUB-BASINS

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ABSTRACT

The Nile Basin spans different hydro-climatic zones ranging from tropical wet climate to semi-arid and arid climate. Climate change impacts on the Nile flows will thus vary depending on the location of the studied sub-basin. In this study, the sensitivity to climatic changes of three different sub-catchments, namely, the Upper Kagera in Lake Victoria Basin, Gilgel Abbay in the Blue Nile Basin, and the Atbara, is studied in terms of flow response to uniform changes in rainfall and potential evapotranspiration using the HBV hydrological model. Results show that runoff is more sensitive to precipitation changes than to potential evapotranspiration changes and that the sensitivity increases with the aridity of the catchment.

Keywords: Nile Basin, HBV Model, Climate Sensitivity

1. INTRODUCTION

During the past few decades, it has become apparent that human activities such as fossil fuel burning and land-use change (e.g. deforestation) have considerably increased the atmospheric concentrations of greenhouse gases (GHGs). As a result, changes in climate have started and are expected to continue for centuries/millennia after GHGs concentrations stabilize (if at all possible). It is expected that climate change will cause a chain of impacts at the global, regional, and local levels affecting all economic sectors in one way or another.

Climate fluctuations have dramatically changed both the structure and the regime of the River Nile, and it is only within "recent" times that the Nile has taken on its current hydrologic characteristics and its connectivity between Equatorial Africa and the Mediterranean Sea (Said [18]). A number of studies have looked at the implications of these fluctuations for water resources in Egypt, particularly since the prolonged period of low flows during the 1970s and 1980s (e.g. Abu-Zeid & Biswas, Conway & Hulme [8]). The historical fluctuations in Nile River discharge have also been reviewed by

Shahin [20], Evans [9], Sutcliffe & Lazenby [22] and Sutcliffe & Parks [23]. Other studies have attempted to evaluate the sensitivity of the Nile discharge to changes in temperature and precipitation and the impacts of future climate change on runoff in the Nile Basin. Probably, the first of these studies was that of Kite and Waititu [14] who looked at the Nzoia River, a tributary of Lake Victoria and found that a 10% increase in precipitation brought about 40% increase in runoff and that the relationship is non-linear. Compared to precipitation, runoff was found less sensitive to changes in potential evapotranspiration (PET) but still, a change of 6% in PET brought more than 10% change in runoff.

Conway & Hulme [7] applied a range of hypothetical changes in PET and precipitation to drive sub-basin models of the Blue Nile and Lake Victoria to examine their sensitivity. PET was changed by ±4% (corresponding to ± 1°C temperature change) and precipitation was changed in 5% steps from -25% to +25%. Changes in precipitation produced larger changes in runoff than changes in PET. The runoff response was greater than the precipitation anomaly: a 10% increase in precipitation caused a 34% increase in runoff in the Blue Nile while a 4% decrease in PET causes an 8% increase in runoff. In contrast, for Lake Victoria a 10% increase in precipitation causes a 31% increase in runoff and a 4% increase in PET caused an 11% decrease in runoff.

Sayed [19] also studied the sensitivity the of different Nile sub-basins to uniform changes in rainfall using a distributed hydrological model (The Nile Forecast System, NFS – Nile Forecast Center [17]). For Lake Victoria basin, he found that a 10% increase in rainfall would result in 5.7% increase in Lake outflows indicating a relatively low sensitivity, which contradicts with previous studies. On the other hand, a 10% increase in rainfall over the upper Blue Nile and Atbara sub-basins would cause increases of 34% and 32% respectively, indicating that these sub-basins are much more sensitive to climatic changes than Lake Victoria sub-basin. Reductions of 10% in rainfall would result in reductions of outflows of 24%, 24% and 4.3% for the Atabra, Blue Nile and Lake Victoria sub-basins respectively. The balance of these changes at Dongola gives changes of 30% (-25%) in mean annual flow for a 10% increase (reduction) of rainfall over the whole Nile basin because of the dominance of the Ethiopian plateau flows (through Atbara and Blue Nile).

Little work has, however, been done in evaluating the sensitivity of climate change at different spatial and temporal scale within the river basin system. Such studies are needed to highlight the variation of impacts of climate change at different scale. Most of the studies in climate change impact study focus on the global water availability in the basin. The lack of such local scale investigation is attributed mainly to the fact that research efforts are invested on regional, global or national scale impact assessment. In addition, local scale studies require data at several locations within a small study area which may not be easy to obtain.

The authors argue that understanding of the variability of impacts of climate change and sensitivity at different scales will help better identify adaptation mechanisms to be implemented economically and according to priority areas. In this regard, this study makes selection of three catchment studies which are located in different hydro-meteorological zones of the Nile and has varying spatial scale (i.e. size). The sensitivity of the selected sub-basins to climatic changes is evaluated through the application of uniform changes of precipitation and potential evapotranspiration and calculating river flows calculated accordingly using a lumped catchment model. This study presents an attempt to relate the climate sensitivity to catchment characteristics.

2. STUDY AREA

The Nile River (Figure 1) travels more than 6500 km from its most remote source, at the headwaters of the River Kagera, the main feeder of Lake Victoria, till it discharges to the Mediterranean Sea (Shahin [20]). The Nile is an international river that traverses, with its tributaries, a total of ten countries: Tanzania, Uganda, Rwanda, Burundi, D.R. Congo (formerly Zaire), Kenya, Ethiopia, Eritrea, Sudan, and Egypt. The Nile has played a major role in shaping the region since the ancient Egyptian civilization. The Nile flood provided the necessary conditions for settlement based on agriculture in the Nile Valley and Delta.

This study focuses on three sub-catchments of the Nile basin: The Atbara, one of the main sub-basins, the upper basin of the Kagera till Rusumo Falls, the most important tributary of Lake Victoria, and the Gilgel Abbay, the main feeder of Lake Tana. The following sections give brief descriptions of each sub-basin. Figure 1 shows the location of the three sub-catchments within the Nile Basin.

2.1 The Atbara

The River Atbara is the last tributary that joins the Nile. It originates in the Ethiopian Highlands to the north of Lake Tana and extends between 34° and 40°E and 11° 45’ and 18°N. There is little consensus upon the area of the Atbara basin. Hurst [13] reported an area of 100,000 km^2 which is taken forward by Shahin [20] and Sutcliffe & Parks [23], while Conway & Hulme [8] reported a larger area of about 137,000 km^2. The area delineated from the Hydro 1K dataset (USGS) is much larger at 235,000 km^2 due to the difficulty of delineating the northeastern part of the catchment which is generally flat. However, those additional areas contribute nothing to the flow. The upper basin has an average annual precipitation of 550 mm while the lower basin receives only about 200mm with a high potential evapotranspiration rate of about 2,300 mm.

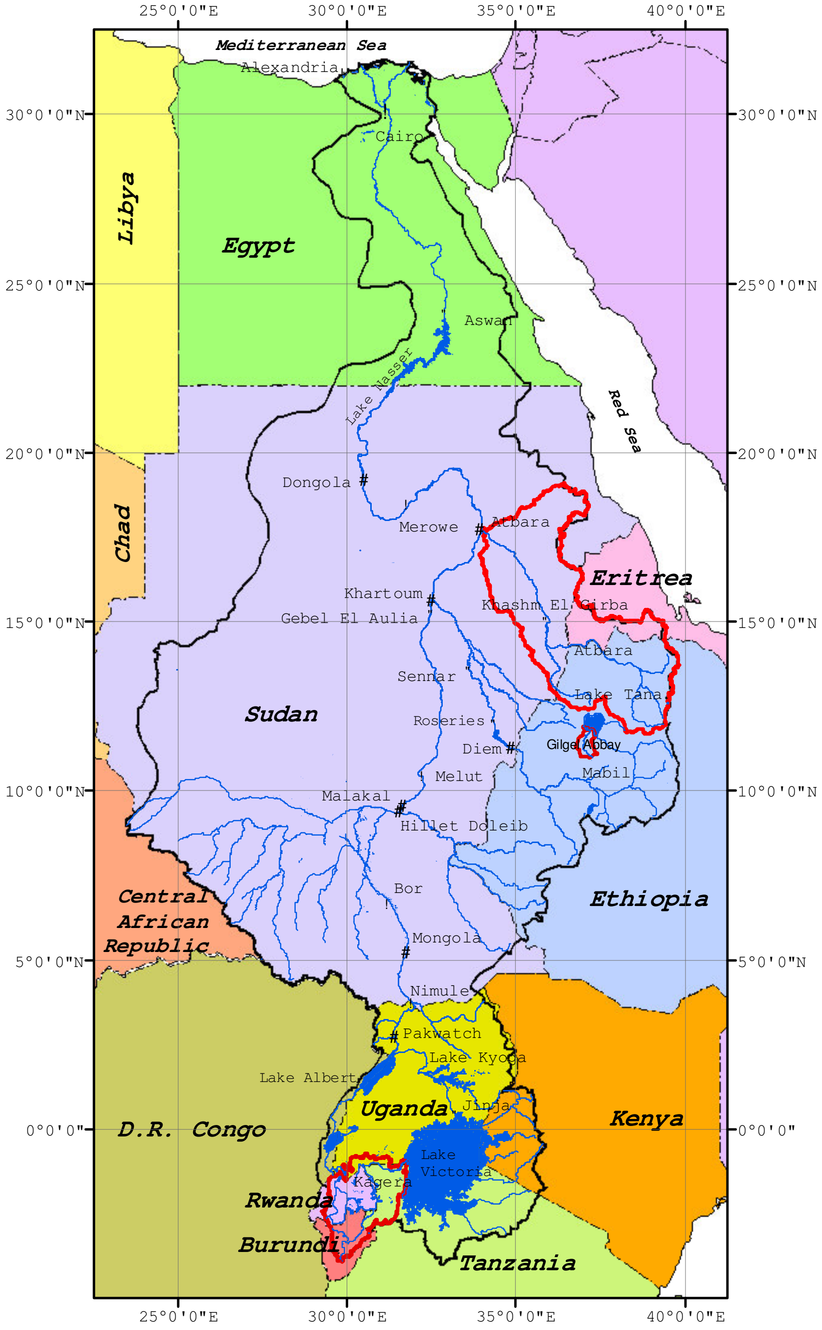


Figure 1 Nile Basin Map - Selected sub-catchments are highlighed in red color

The total annual contribution of the Atbara, as measured at its mouth near the junction with the Nile is 10.95 BCM (1940-1982 average). All of this flow comes from the upper basin as the lower reach is a source of loss due to the high evaporation rate and due to irrigation diversions and losses from the reservoir of Khashm El-Girba dam. This figure is not naturalized and thus is lower than that reported by Shahin [20] (11.88 BCM for the 1912-1973 period) but is very close to the longer term average (11.05 BCM) given by Sutcliffe & Parks [23] for the period 1903-1994. The Atbara is highly seasonally with almost a triangular hydrograph peaking in August while it runs dry from January till May. Figure 2 illustrates the Atbara catchment and shows the location of rainfall and evapotranspiration stations that are used in modeling the basin.

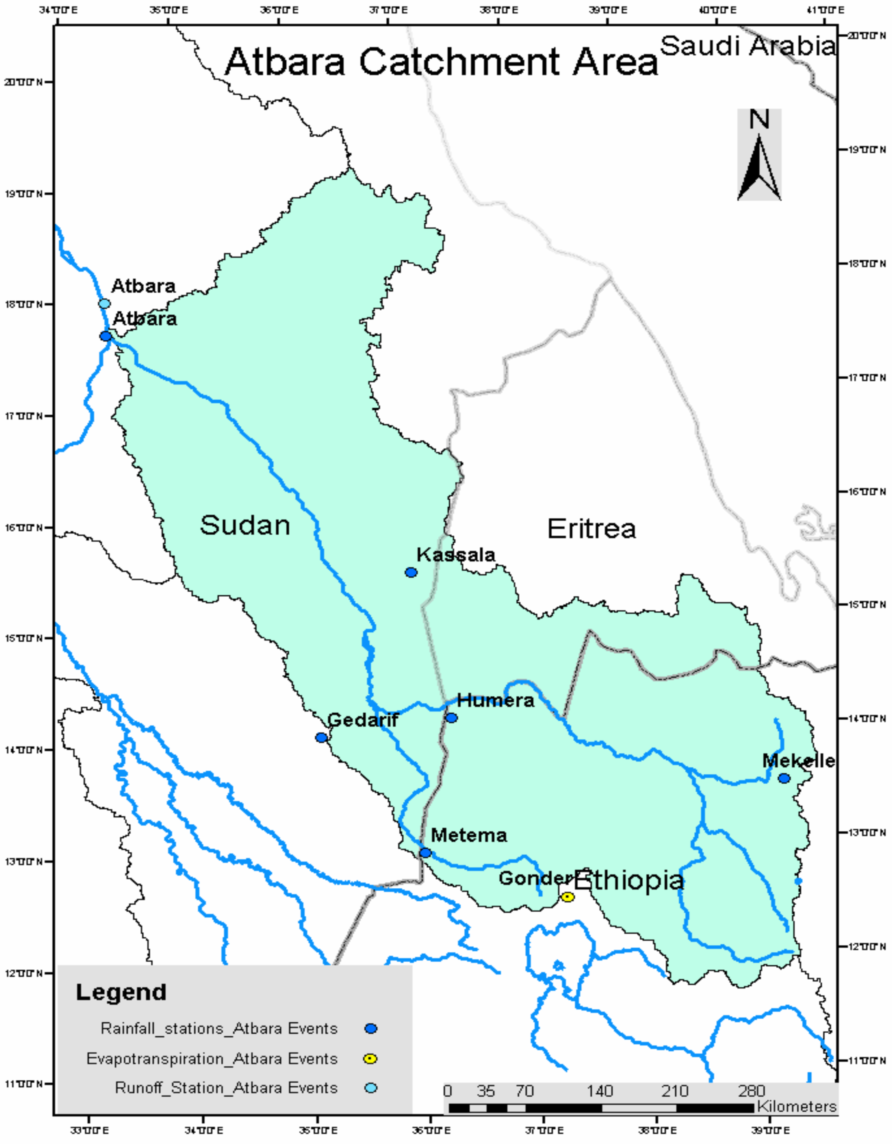


Figure 2 Atbara Catchment area

2.2 The Kagera

The Kagera basin is among the most important of the 23 sub-catchments of Lake Victoria and its headwaters are the most remote of the River Nile. Geographically, it lies in the south west of the Lake Victoria Basin between 0º45' and 4°S and 19º15' and 32ºE. There is a near consensus amongst the different literature on the basin area of about 60,000 km^2. Using SRTM data, the basin has been delineated as having a total area of 58,349 km^2 (roughly 23% of the Lake Victoria basin). About 6% of this area is occupied by small lakes and swamps (Georgia Water Resources Institute et al. [11]).

The basin has a general elevation of 1200-1,600 m, but rises above 2,500 m in the west, with peaks reaching 4,500 m. The upper tributaries are generally steep but include flat reaches where swamps have formed (Sutcliffe & Parks [23]). The slope diminishes for the middle reach between Kigali and Rusumo Falls allowing the formation of a larger papyrus swamp. Below the falls, the Kagera flows north in a zone of lakes and swamps before it turns east where it enters the lake downstream of the main gauging station at Kayaka Ferry. Rusumo Falls represents the outlet of the upper basin just below the confluence of the two tributaries: Ruvuvu (or Ruvubu) and Nyaborongo. The area of the upper basin is little over 31,000 km^2 (Figure 3).

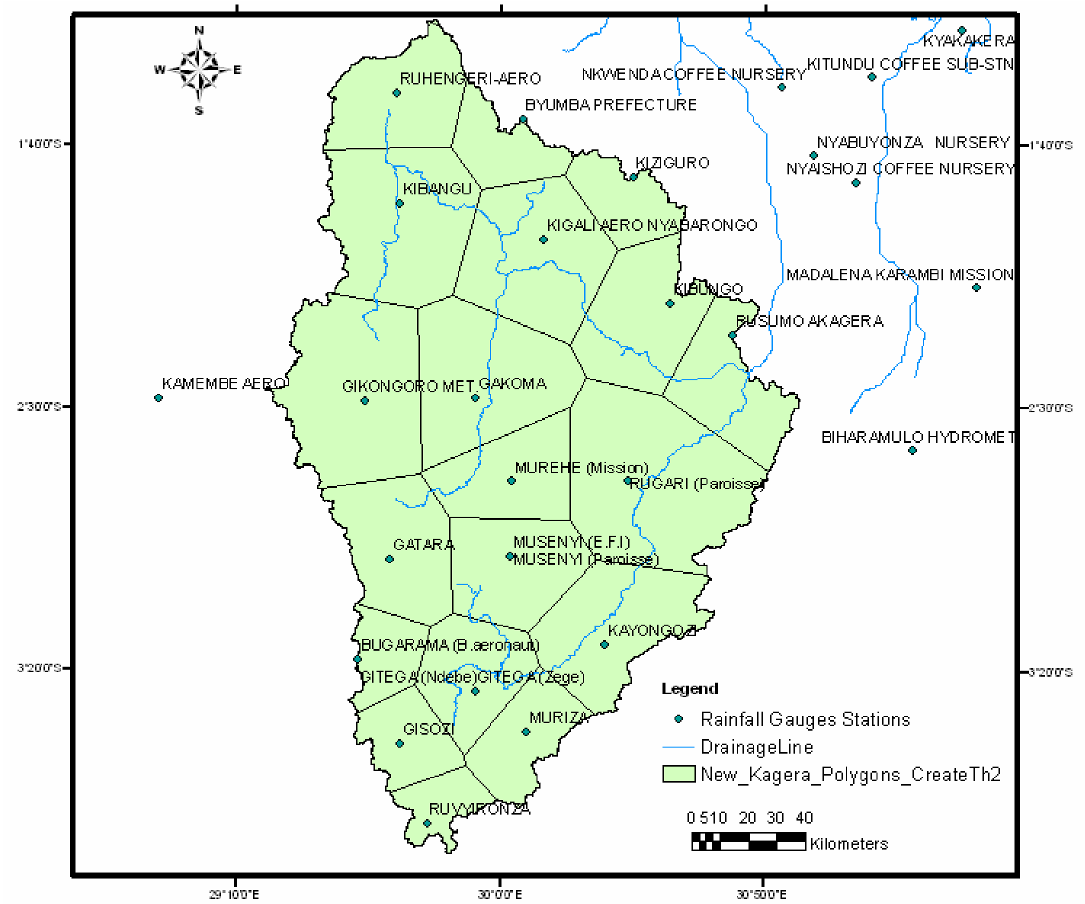


Figure 3 Theissen Polygons covering the Upper Kagera Catchment Area

The rainfall is less than 1,000mm over most of the eastern half of the basin but rises to over 1,800 mm in the west, where most of the runoff is generated. Rainfall over the Kagera basin has a bimodal distribution with a higher peak in April in response to the longer south-westerly monsoon and a smaller peak in November. Basin runoff (as measured by the discharge at Kayaka Ferry/Nyakanyasi responds with a delayed higher peak in July and lower peak in December-January. The long (3-month) delay between rainfall and runoff is caused by the attenuation through lakes and swamps in the basin which also reduce the seasonal and inter-annual variability of the runoff hydrograph at Kayala Ferry. The average flow of the Kagera at Kayaka Ferry is about 9 BCM (1940-1977 average) and about 7.5 BCM at Rusumo Falls (1955-1991).

2.3 The Gilgel Abbay

The Gilgel Abbay is the largest contributor to Lake Tana. The Gilgel Abbay, literally means in Amharic "The little Abbay", has its source in the mountainous Sekela area to the south of the lake and flows northward receiving other tributaries on its way to Lake Tana. The catchments is situated between 11° and 12°N and 36° 45' and 37° 30'E and has an area of 4,100 km^2 (Shaka [21]). Elevation ranges between 1700 and 3500m and the basin is characterized by its steep slopes. The climate of the catchment is marked by a wet season from May to September with distinct mono-modal rainfall distribution. The monthly rainfall varies from 193mm in May to 456mm in August and the total annual rainfall ranges between 2400mm in the headwaters of the river to 1200mm near its outlet. The stream flow attains its peak discharge in August while the lowest discharge is in March. The land use system is predominantly agriculture occupying more than 80% of the catchment. The rest of the area of the catchment covers the combined practice of agro-pastoral. The flow measuring station is located near Merawi nearly bisecting the river length to Lake Tana. The area upstream this gauging station is about 1664 km^2 and the average annual flow of about 1.74 BCM (1980-2000 average).

3. METHODOLOGY

For this study, the HBV hydrological model is used in a lumped form. The HBV model was developed at Swedish Meteorological and Hydrological Institute (SMHI) during the early 1970s. In different model versions HBV has been applied in more than 40 countries all over the world. It has been applied to countries with such different climatic conditions as for example Sweden, Zimbabwe, India and Colombia. The model has been applied for scales ranging from lysimeter plots (Lindström & Rodhe [16]) to the entire Baltic Sea drainage basin (Bergström & Carlsson [4] and Graham [12]). The model is used for flood forecasting in the Nordic countries, and many other purposes, such as spillway design floods simulation, water resources evaluation, nutrient load estimates (Arheimer [2]), and climate change impact studies (Booij [6]).

Arheimer and Fogelberg [3] applied HBV to twelve catchments with different hydrological and climate conditions throughout Europe. They found that the model performance is of good accuracy in northern and middle Europe, while it was more difficult to capture the peakiness of the flow in the more southern countries. Liden and Harlin [15] applied the model successfully in four geographically varying countries in Africa, Latin America and Europe showing a good potential for model use in different parts of the world.

3.1 HBV MODEL DESCRIPTION

The HBV model (Bergström [5]) is a rainfall-runoff model, which includes conceptual numerical descriptions of hydrological processes at the catchment scale. It can be applied as a lumped model for the whole catchment or in a distributed way. The general water balance can be described as:

$$P - E - Q = \frac{d}{dt}\left[SP + SM + UZ + LZ + lakes\right] \tag{1}$$

where:

P = precipitation
E = evapotranspiration
Q = runoff
SP = snow pack
SM = soil moisture
UZ = upper groundwater zone
LZ = lower groundwater zone
$lakes$ = water volume stored in lakes, wetlands, etc.

The model consists of a precipitation routine representing rainfall and snow, a soil moisture routine determining actual evapotranspiration, overland flow and subsurface flow, a fast flow routine representing storm flow, a slow flow routine representing subsurface flow, a transformation routine for flow delay and attenuation and a routing routine for river flow. In this study, a spreadsheet version of the HBV model has been used (Killingtveit, personal communication) and modified to handle monthly and daily time series data spanning several years (the original model handled daily data for each year separately).

The HBV model requires temperature, precipitation, and potential evapotranspiration data for it to operate. Temperature data is needed mainly for snow accumulation and melt calculations and thus were ignored as these processes are absent in the selected basins. For precipitation and evapotranspiration, the number of stations and methods used depended on the catchment. Concurrent flow data is also needed for model calibration and validation before it can be applied to study the sensitivity of the selected basins.

3.2 REQUIRED DATA

For the Atbara, monthly rainfall records from 6 stations (see Figure 2) in and around the basin were collected for the period 1979-1988. The arithmetic mean of these stations was used to represent catchment mean rainfall. Evapotranspiration for Gondar just outside the basin for the same period was used as there were no stations with available data inside the basin. Flow data at the basin outlet near Atbara city was used for calibration and validation. The time period was split into two for that purpose and the period 1979-1983 was used for calibration while the period 1984-1988 was used for validation.

For the Kagera, there was much more data which enabled more detailed derivation of areal rainfall. Data from 113 stations within the upper Kagera basin (up to Rusumo Falls) were collected from different sources (mainly from the Rwanda Meteorological Services and the database of the Nile Decision Support Tool (DST – Georgia Water Resources Institute, Georgia Institute of Technology [11]). The data covered the period 1907-2005 but with a varying number of stations over time and numerous gaps. A total of 20 stations were used and the mean areal rainfall over the catchment was calculated using the Theisen polygons method (see Figure 3). The time period was also limited to 1960-1998 to have a homogenous record. However, unlike the Atbara, daily data was available for the Kagera. Evaporation for Kigali was used for the Upper Kagera and was extracted from the DST for the period 1971-2005.

Different datasets are available for discharge measurements from three sources. Those include daily discharge for 1971-1973 from the NFS database and for 1955-1979 from the Rwandese database. Stage measurements were available from the DST database for the period 1956-1996. A rating curve was constructed using concurrent discharge and stage measurements and was used to generate a time series for discharge over the period 1956-1996. The quality of the data varies with many frequent gaps in the 1960s. The discharge series from 1971 to 1990 seems to be of better quality having fewer gaps. The HBV application was however limited to the period 1979-1989 because this was the best period with concurrent rainfall, evaporation, and flow data. The period 1979-1985 was used for calibration while the period 1986-1989 was used for validation.

Three rainfall stations in the surrounding area of Gilgel Abbay were identified with records starting between 1980 and 1986 and ending in 2000. The arithmetic mean of rainfall at the three stations was used to represent the catchment mean areal rainfall. Monthly evaporation data available at Bahir Dar station from 1988 to 2000 was also available. These were disaggregated into daily series by dividing into equal daily values for each month. The discharge of Gilgel Abbay near Merawi has been used for the study. The available record is long starting from January 1973 up to January 2004. Therefore, data sets with concurrent record period of rainfall, evaporation and discharge with relatively few gaps cover the period 1988 till 2000 and have been used in this study. The period 1988-1995 was used for calibration while the period 1996-2000 was used for validation.

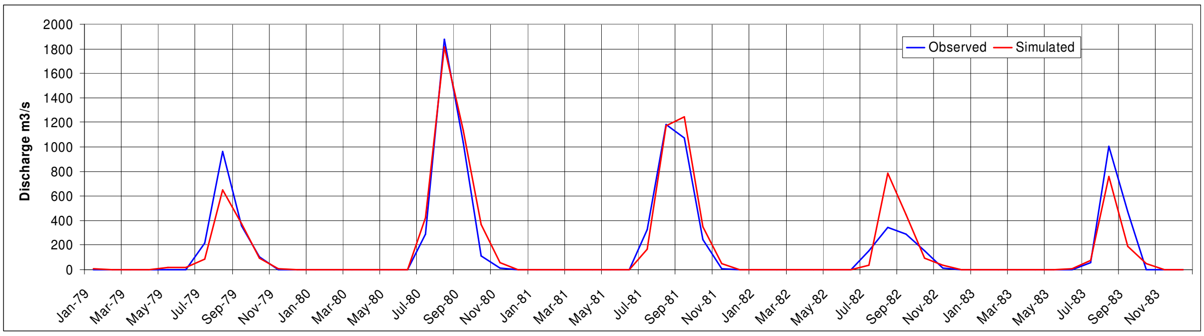
4. RESULTS AND ANALYSIS

4.1 Calibration and Validation

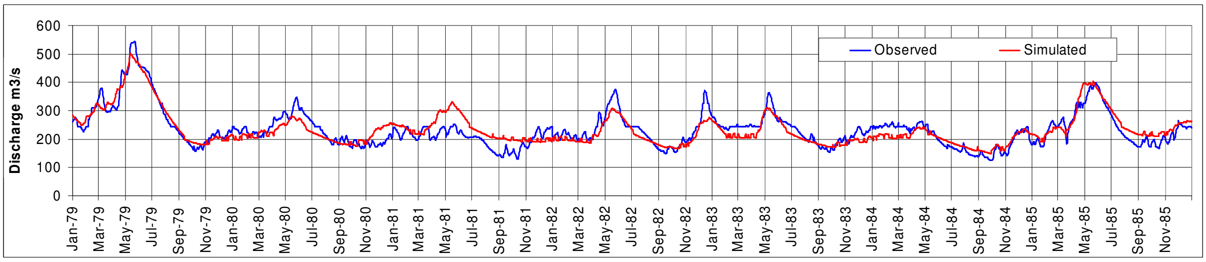
The HBV model has five parameters groups: the first includes rainfall/snow correction factors which is used to correct consistent underestimation or overestimation of rainfall/snow and relate them to elevation; the second group relates to snow and this is not important for the selected basins; the third describe soil properties and are thus important for our study; the fourth and fifth groups relate to the rates of runoff from the upper and lower layers and are important in getting the right partitioning of runoff into fast, slow, and groundwater components. For a detailed description of the parameters, the reader is referred to Bergström [5].

Before using the model to assess the sensitivity of flow to climatic variables, the model is first calibrated then validated. Available data for each catchment was spilt into two periods as given above and the model was calibrated for the first sub-period by optimizing its parameters to get the highest value of the Nash-Sutcliffe efficiency coefficient (Garrick et al. [10]). The calibration procedure was done in three steps: first, trial and error adjustments of the rainfall and potential evapotranspiration are performed till to minimize the volume bias over the calibration period (i.e. to have the mean simulated discharge as close as possible to the observed); second trial and error adjustments are made to obtain a close initial guess of the soil and runoff generation parameters; then finally the internal optimization routine within MS Excel was used to fine-tune those parameters. These steps may need to be reiterated if the mass balance is not satisfied after optimizing the parameters. Figure 4 shows the performance of the HBV for the calibration period.

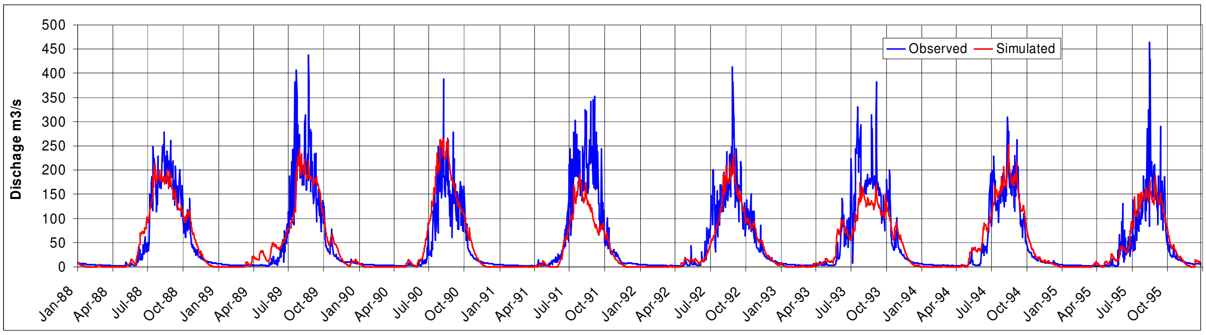
For the three basins, good performance is achieved. For the Atbara, the performance looks better than for the other two catchments but it should be noted that only monthly data was available and the model could not predict all peaks with the same accuracy (e.g. the peak of 1982 was overestimated). Aggregating daily data into monthly for the Kagera and Gilgel Abbay basins yielded better performance in terms of R^2 (not shown) as it smoothed the day-to-day variations of discharge especially for the Gilgel Abbay. The observed data for Gilgel Abbay at Merawi is too dynamic in comparison with that of the Kagera at Rusumo. This is due to their different sizes of their catchments and the different hydrological conditions. The Kagera has a larger catchment and the flow is regulated by lakes and wetlands and thus has a large baseflow component and relatively smooth peaks while the Gilgel Abbay has a small catchment and the flow are dominated by the fast runoff component with nearly zero baseflow. The Atbara is similar to Gilgel Abbay in that respect (zero baseflow) although it has a much larger catchment but daily data is not available to assess whether the flow would be as dynamic.



a) Atbara@Atbara – Monthly Data for 1979-1983 – R^2=0.92



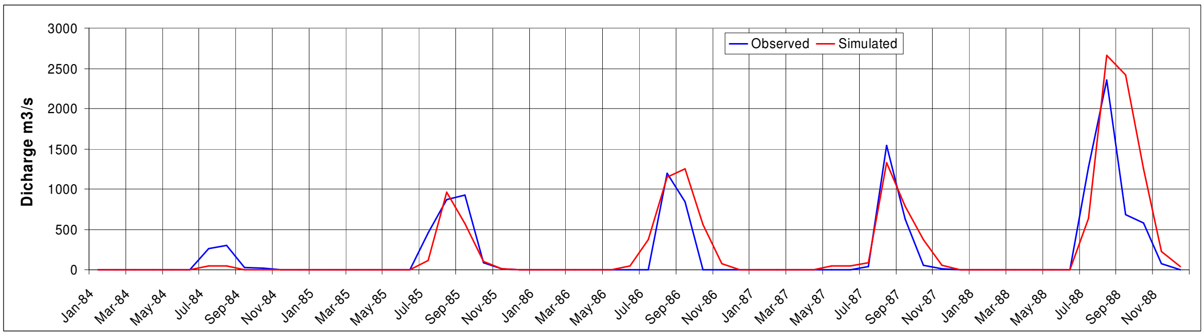
b) Upper Kagera@Rusumo – Daily Data for 1979-1985 – R^2=0.78



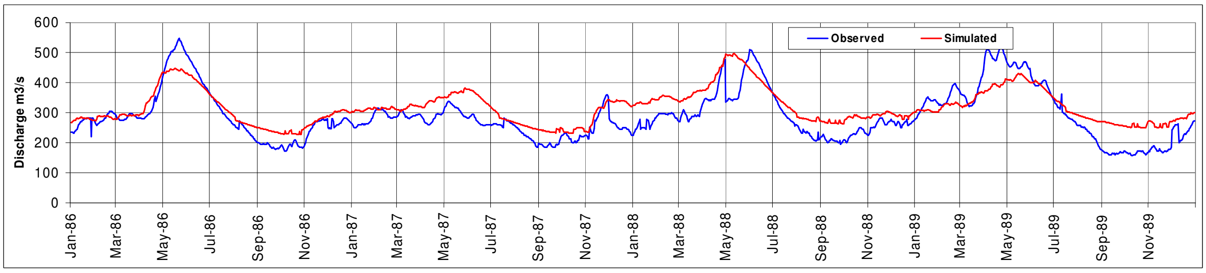
c) Gilgel Abbay@Merawi – Daily Data for 1988-1995 – R^2=0.79

Figure 4 Performance of the HBV during Calibration Period

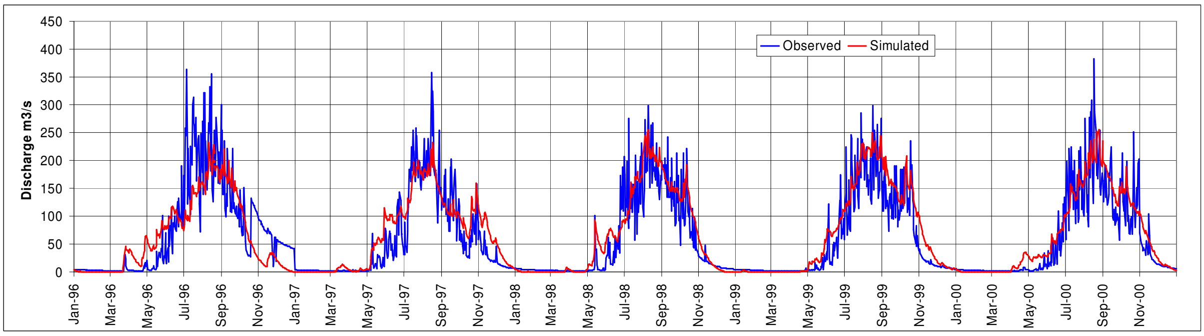
To have an independent test of the model, the calibrated parameters were used with data from subsequent periods as available for each catchment in a verification exercise. Figure 5 shows the results of this exercise. In terms of R^2, the performance during the verification period is worse for the Atbara and the Kagera but has slightly improved for the Gilgel Abbay. However, the overall mass balance is not satisfied for the Gilgel Abbay and Atbara (HBV underestimates the mean flow over the whole verification period for the Gilgel Abbay and overestimates it for the Atbara). The main reason for the deterioration of performance for the Atbara, may be the shorter calibration period compared to that used for the Gilgel Abbay. The monthly time step for the Atbara may be another reason of the deterioration of model performance. However, visual inspection of the Atbara discharge series for the verification period indicates that the simulation is not too poor as the model is capable of picking hydrograph peak times with slight over or underestimation of its value in most years. For the Kagera, the reason for performance deterioration may be the different hydrological conditions between the two periods as the first period was relatively drier. Errors in rainfall cannot be excluded either. Nevertheless, it is common that model performance varies between calibration and verification periods especially if the calibration period is relatively short (6 years for the Atbara, 7 for the Kagera, and 8 for the Gilgel Abbay) as the case here. Therefore, the results indicate that the HBV simulations of the three basins are sufficiently good to enable the use of the model in climate impact and sensitivity studies.



a) Atbara@Atbara – Monthly Data for 1984-1988 – R2=0.58



b) Upper Kagera@Rusumo – Daily Data for 1986-1989 – R^2=0.60



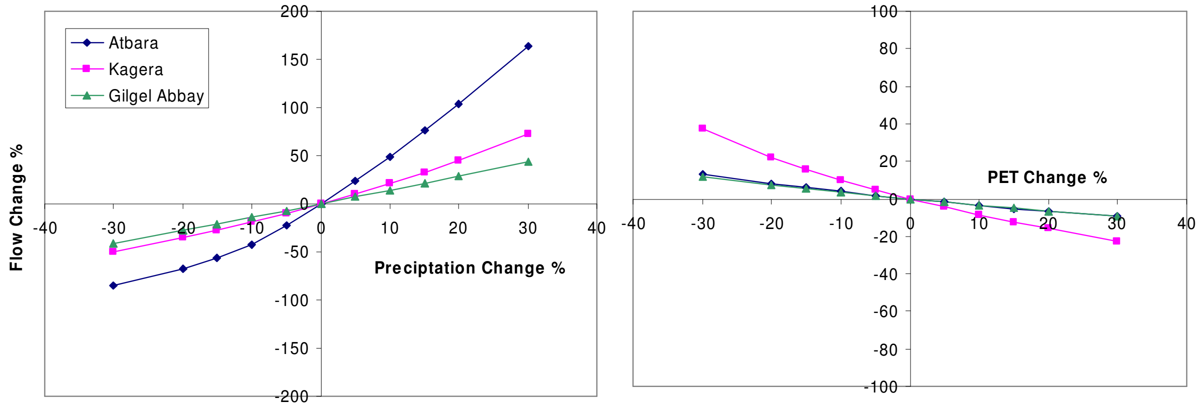
c) Gilgel Abbay@Merawi – Daily Data for 1996-2000 – R2=0.81

Figure 5 Performance of the HBV during Verification Period

4.2 Sensitivity Analyses

Using the respective calibrated parameters for each catchment, the sensitivity of discharge to changes in mean areal rainfall and evaporation has been assessed. This is done by modifying rainfall and evaporation separately (i.e. changing one variable while fixing the other) by ±5, 10, 15, 20, 25, and 30% and monitoring the change in average discharge. The calibration period for each catchment was used for this period as to have more confidence in the model performance.

Figure 6 shows the results of the sensitivity analyses for the three catchments. A few findings are revealed from those figures. First, in all three catchments, the flow is more sensitive to changes in rainfall than to changes in potential evapotranspiration (PET). Second, positive changes in rainfall are amplified in flow changes to a larger degree than negative changes; an increase in rainfall by10% yields flow increases of 49%, 29% and 14% for the Atbara, Kagera, and Gilgel Abbay respectively, while a 10% reduction in rainfall yields flow reductions of 42%, 19% and 14% for the three basins respectively. Third, the non-linearity of the relationship is higher for negative rainfall changes than for positive ones. Last but not least, while the three catchments have different degrees of sensitivity to rainfall changes, Atbara being the most sensitive, followed by the Kagera, and then the Gilgel Abbay. Regarding the sensitivity to PET changes are very similar for the Atbara and Gilgel Abbay while it is much higher for the Kagera. This may be due to the existence of lakes and swamps in the basin as well as its bimodal rainfall pattern. Compared to other studies (e.g. Sayed, 2004), the Atbara seems much more sensitive than reported; the reason may be the use of a low flow period in this analysis as the mean annual flow for the sensitivity period (1979-1983) is about 5.4 BCM which is less than half the long-term average for the river.



a) Precipitation *b) Potential Evapotranspiration*

Figure 6 Sensitivity of Different Catchments to Changes in Climatic Conditions

5. CONCLUSION

The HBV rainfall-runoff model is used to simulate the monthly flows of the Atbara and the daily flows of the Kagera and Gilgel Abbay. The Atbara and Gilgel Abbay catchments are dominated by fast surface runoff and quick response to rainfall while the Kagera has a large baseflow component due to the regulating effect of lakes and swamps in the sub-basin. After proper calibration for each catchment, the model was successful in capturing the main features of each catchment. Performance generally deteriorated in the verification period because of the short calibration period.

The HBV was then used to study the sensitivity of each catchment to changes in rainfall and potential evapotranspiration using hypothetical scenarios of uniform changes over each sub-basin. The results show that the sensitivity to rainfall is larger than that to PET because PET is only satisfied if the soil has enough moisture to supply the full evaporative demand which occurs during the wet season. The Kagera is more sensitive to PET than the other two basins and this may be due to that it has a bimodal rainfall and thus a longer wet period in addition to the existence of small lakes and swamps. The sensitivity of the Atbara to rainfall was the highest as it is the most seasonal of all three catchments. Although the Gilgel Abbay is more seasonal than the Kagera, its sensitivity to rainfall changes was lower probably because of its smaller size and as Kagera has a bimodal rainfall regime and thus its flows are affected by rainfall changes twice a year.

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