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FLOOD FORECASTING IN BLUE NILE BASIN USING A PROCESS-BASED HYDROLOGICAL MODEL

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Abstract

Predictions of variations in global and regional hydrological cycles and their response to changes in climate and the environment are key problems for future human life. Therefore, basin-scale hydrological forecasts, along with predictions regarding future climate change, are needed in areas with high flood potential. This study forecasts hydrological process scenarios in Blue Nile basin using a distributed hydrological model (DHM) and predicted scenarios of precipitation from two general circulation models, CCSM3 model and Miroc3.2-hires. Firstly, river discharge was simulated by the DHM using the observed rainfall from 1976 to 1979 and then, simulating future precipitations from 2011 to 2040, discharge scenarios were predicted.

Keywords: Blue Nile Basin, Distributed Hydrological Model, flood forecast, CCSM3, Miroc3.2

Introduction

The Intergovernmental Panel on Climate Change (IPCC) had been created by the United Nations Environment Program and the World Meteorological Organization to oversee and report the current understanding of climate change and its potential impacts (IPCC, 2007). The IPCC has released four assessment reports on the understanding of climate change as well as numerous other special reports and technical reports. The IPCC researchers use sophisticated general circulation models (GCMs) to simulate atmospheric, land and sea interactions as a result of probable emissions scenarios. The emission scenarios used in these models are very detailed and consider multiple factors of climate change. The Earth`s climate has changed many times during the planet`s history, with events ranging from ice ages to long period of warmth. Climate changes have visible impacts on the natural systems. However their impact will be significant with the hydrological cycle. Climate change is expected to aggravate current stress on water resources availability from population growth, urbanization and land-use change (IPCC, 2007).

Scientists agreed that changes in the earth`s climate will hit developing countries like Ethiopia first and hardest because their economics are strongly dependent on crude forms of natural resources and their economic structure is less flexible to adjust to such drastic changes (NMSA, 2001). In recent years, a large part of the scientific community has made efforts analyzing the impact of projected climate change on water resources and proposing adaptation strategies (e.g. Loaiciga et al., 1996; Hattermann et al., 2008; Wilby et al., 2008; Allamano et al., 2009; Goulden et al., 2009). The usual framework of this type of study can be seen in Elshamy et al, 2009. This approach has become very popular as it potentially allows the quantification of changes in floods, flow duration curves, and whatever part of the hydrological cycle (Bloschl et al, 2010). Different studies have been conducted to assess the impact of climate change on hydrology in different parts of the world (Abdo et al., 2009). Many of these studies indicated water resource variability associated with climate change. It is noted that a few studies quantified the combined effects of future climate and land use changes on hydrology (Van Roosmalen et al., 2009) which is a key study area for the future. Recently, a number of studies analyzed the effects of climate change on the hydrology of the Nile River Basin (NRB), the world`s longest river. In fact, the NRB could be vulnerable to water stress under climate change because of the limited water availability and the increasing demand for water from different sectors (Bates et al., 2008). In addition, there is a serious concern about the fact that sea level rise could adversely impact on people living in Nile Delta and other coastal areas. Nevertheless, Conway (2005) found that there is no clear indication of how Nile River flow would be affected by climate change, because of the uncertainty in projected rainfall patterns in various parts of the basin and the influence of complex water management (and water governance structures). More recently, Githui et al. (2008) used a technique of adjustment (the so-called delta change method) of historical time series to project GCM impacts on flood risks in the Nzoia River, one of the major river systems draining into Lake Victoria. In addition, Elshamy et al. (2009) analyzed climate effects on the main Nile at Dongola and the Blue Nile at Diem, using a spatio-temporal statistical downscaling technique for various GCMs and showed varying trends depending on the GCM used. Furthermore, Soliman et al. (2009) investigated climate change effects on the Blue Nile catchment using the regional climate model RegCM3 to downscale the results of the ECHAM5 general circulation model (Max Planck Institute, Hamburg, Germany). These studies demonstrate a large diversity in the use of IPCC scenario, climate models and downscaling techniques (time series adjustments, statistical and physically-based methods). These different techniques may lead to opposing trends and contradicting recommendations for policy makers.

As Ethiopia is following agricultural based industrialization which is strongly tied with climate and a large part of the country is arid and semi-arid, climate change should be a concern. Studies done by many researchers indicated that the water resources are sensitive to climate change. However, most of the studies made so far are mainly at the catchment level. As a catchment encompasses different climatic zones, it might be difficult to identify the exact impact of the climate change so as to take adaptive measures. Therefore it is advisable to study the impact of climate change in sub-basin level. Hence, this study was targeted to address the effect of climate change on sub-basin and basin level in Blue Nile River. This study focused on Blue Nile basin which is among sub-basins of Nile River. Blue Nile Basin and Atbara basin are the largest basins feeding main Nile River, the biggest river in Africa. Blue Nile is the key socio-economic focal point in the area. It is used for hydropower generation, irrigation, recreation, fishing and navigation. However, due to climate variability and change, the water level in the basin fluctuates. On the other hand, water level drop is also observed in some periods of the year. Hence, this study will have a paramount importance in giving an insight on the vulnerability of Blue Nile to climate change. In this research, DHM using two general circulations model (GCM) outputs as forcing. First step is validating the DHM using the observed rain gauge precipitation. Next, predicting stream flow scenarios over the next 40 years using the GCM outputs is done. Finally, predicting observational records of hydrological data, such as precipitation and river discharge, and critically examine the trends to be suitable in water resource management in the future.

Study area

The Nile River encompasses ten countries. The Blue Nile basin, which is selected as the study area, is located in the high steep mountainous region of the upper Nile River (Fig. 1) on the Ethiopian plateau, which is concentrated at elevations of 2000-3000m, with several peaks up to 4000 m or more. The plateau country is not flat but very broken and hilly, with grassy uplands, swamp valleys and scattered trees. There are occasional rocky peaks, some of which are of volcanic origin. The curious course of the river may follow the original drainage pattern radiating from such volcanic centers. The basin is cut by deep ravines or canyons in which the Blue Nile and other rivers flow. The whole area is intersected by streams, most of which are highly seasonal in their flow. The catchment area of the Blue Nile basin lying upstream of the Khartoum hydrological station is 325000 Km^2. The average annual rainfall over the Blue Nile basin is about 1600 mm. It increases from about 1000mm near the Sudan border to about 1400-1800 mm over parts of the upper basin, in particular in the loop of the Blue Nile below Lake Tana, and above 1800 mm in the south within the Disessa basin (Conway 2000).

Past changes (Precipitation and Discharge data) on the BNB Precipitation

Rainfall in the Blue Nile Basin shows various modes of seasonality within the annual cycle and inter-annual variability depending on the location of the specific sub-catchment with respect to the Equator and moist advection wind regimes. The Blue Nile area (consisting of Ethiopian Highlands and Sudan) shows a uniform distribution, with the main wet season spanning the period June–September. According to Sutcliffe & Parks (1999), the annual rainfall amount varies from less than 50 mm/year (over the lower or main Nile) in northern Sudan and southern Egypt to more than 1200 mm/year over the Ethiopian part of the Nile. While there is generally no significant change detected in the annual rainfall in most of the Nile sub-basins, there appears to be decreasing in some key watersheds of the upper Nile in Ethiopia such as the southern Blue Nile (Wing et al., 2008). Referring to the longer term, e.g. the period 1905–1984, Sayed et al. (2004) provided evidence that the BNB has shown a slightly Increasing trend in rainfall over the observation period of 1905–1965, followed by a prolonged decline reaching its minimum in 1984. The rainfall is recovered significantly during the 1990s as the explanation of precipitation trend presented in IPCC Technical Paper

VI (Bates et al., 2008). However, the scientific literature does not provide clear indications on the trend in the occurrence of extreme rainfall events.

River Discharge

Observational studies over the Blue Nile confirm that the seasonal and inter-annual variability is more significant than any long-term trend (Awulachew et al., 2008). This is consistent with the variability of precipitation over the region. However, the variability of flow in the BNB appears to behave similarly in their temporal patterns of fluctuation (Awulachew et al., 2008).The variability in rainfall plays a significant role in the modelling of the Basin level. Based on the review of the publications on the climate variability of the BNB, Conway (2005) showed that climate variability of Ethiopian Highlands is primarily manifested by rainfall fluctuations.

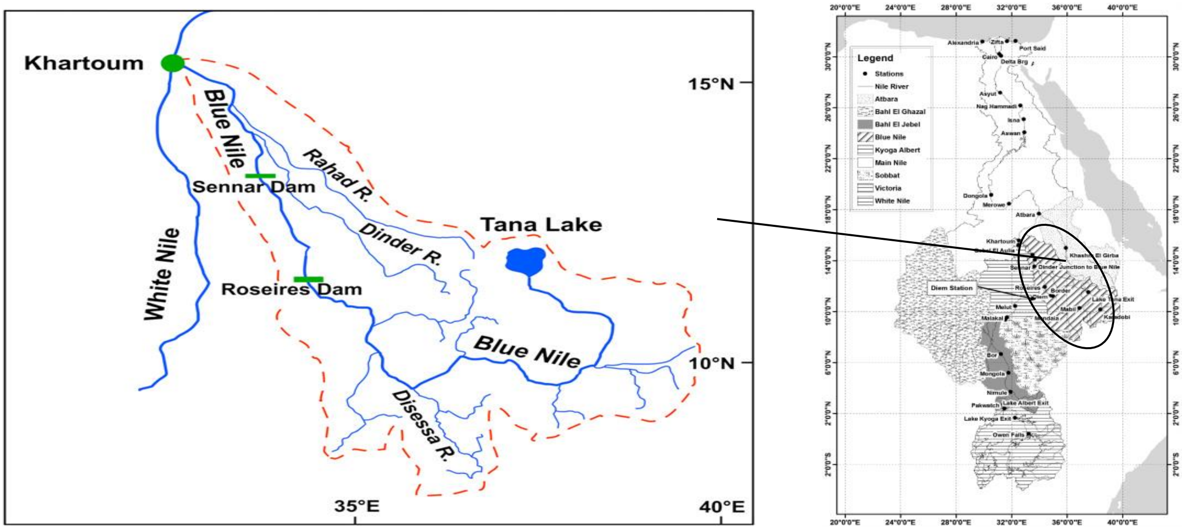

Figure 1. Study Area

Data Availability

The basin topography was simulated by a digital elevation model having 1 Km resolution. The original elevation data were obtained from HYDRO1K. Land cover information was collected from a 1996 USGS global land use map (Global Land Cover Characteristics Data Base Version 2.0). This map classifies land use into 31 types; the dominant land use types in the study area were Savanna (58%) and agricultural land (18%). Information on the soil water properties was collected from FAO soil Databases based on the food and Agricultural Organization (FAO)/UNESCO soil map of the world. The spatial reference for both land cover and soil types is 1 km. For discharge calibration, observed discharge data from Ministry of Water Resources and Irrigation (Nile Water Sector-Nile Control Department) were collected in the study period from 2001 to 2002. Meteorological data were obtained from the Nile Basin Capacity Database. According to the data quality, the daily rainfall data of 4 years (1976 to 1979) at 35 gauges were selected for the calibration of Hydrological model. Future rainfall scenario was taken from future GCM experiments: MIROC3.2_hires and CCSM3. As climate scenario Special Report on Emission Scenarios (SRES) A1B indicating in the high economic growth rate was chosen. The distribution of the available rainfall data is shown in Fig.2. All of the collected meteorological data were adjusted to 1km resolution for the computation units. The Thiessen polygon method was used to obtain weighted average rainfall by determination of the distance between each pair of rain gauge points.

Methodology

A distributed Hydrological model, GBHM was calibrated and validated. The downscaled climate outputs were used as an input to GBHM model and used to assess the impact of climate change on the Blue Nile Basin. The climate projection analysis was done for each year in the coming 40 years. The period 2001-2002 was taken as baseline period against which comparison was made.

Hydrological model set up

To simulate the current and long-term discharge dynamics for the river basin, the DHM geomorphology-based hydrological model (GBHM) is used. This model's features were physically based on hydrological processes. That is, the water budget at each computational unit was simulated by a hill-slope module, and the lateral inflow was routed downstream by a kinematic wave module. The discharge at each gauge point was obtained. A 4-km grid is chosen as computational units. Each computational unit is viewed as a rectangular inclined plane with a defined length and unit width. The inclination angle was given by the surface slope, and the bedrock was assumed to be parallel to the surface. The hill-slope element introduced by Yang et al (2002) is used. The hill-slope module is applied in computational units having this feature. The module is divided into four parts: storage of precipitation in the soil; precipitation storage in the canopy; water exchange between the saturated layer, unsaturated layer, and the surface; and evapotranspiration from the canopy and the soil. Richard's equation is used to calculate the water exchange between the saturated and unsaturated layers (Van Dam et al., 2000). Darcy's law is used to calculate the water flow in the saturated zone (Manning, 1997).

To simulate transpiration, the Normalized Difference Vegetation Index (NDVI) from Advanced Very High Resolution Radiometer (AVHRR) is used to obtain the canopy cover ratio in each computational unit. The land use type and soil type from the USGS and FAO data determined each parameter of each hill-slope equation, and each parameter is calibrated for each type of soil and land use. The simulated discharge flowing from each computational unit is accumulated into interval flows, which were identified according to the Pfafstetter Basin Numbering System. The accumulated discharge is routed from the upper to the lower basin according to the Pfafstetter numbering scheme by using the kinematic wave module. Thus, the discharge at each control point was obtained.

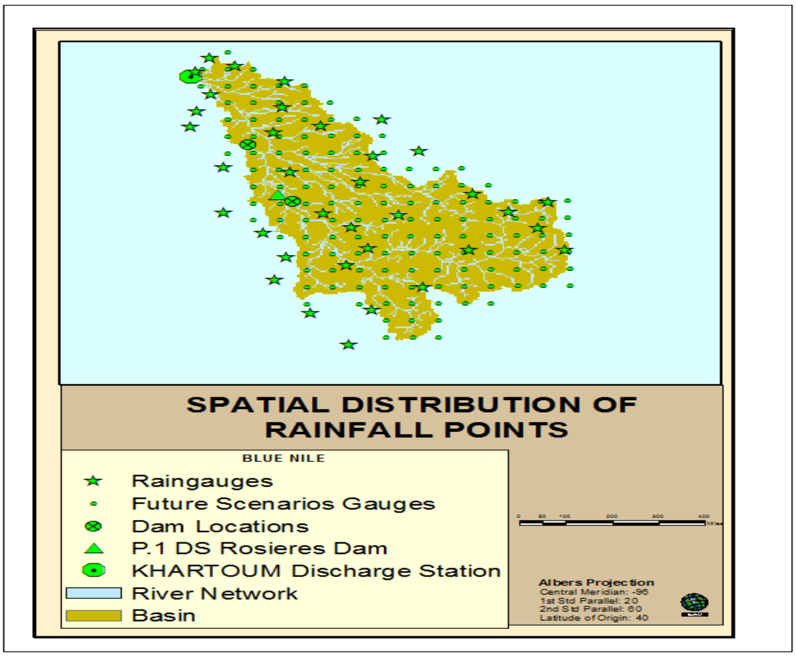

Figure 2. Spatial distribution of rainfall and discharge points

Model Calibration

Calibration of the parameters mentioned in the previous section is done by comparing the discharge simulated using rain gauge data and the observed discharge at the outlet of the basin in Khartoum station from 1976 to 1979. The simulation time step was 1h. Because only daily precipitation observations were available, they were transformed to hourly data on the basis of the average time distribution in one day. To include the effect of the Rosieres dam in the simulation, the released flow was assumed to be the same as the observed discharge at P.1 located downstream Raisers dam (Fig.2). On the other hand, the effect of Sennar Dam is neglected due to the small size of the dam.

Evaluation of GCM Outputs

Daily future precipitation determined by the GCMs was compared against the average of the available daily rainfall ground data from 1971 to 1982. The timing of base flow and peak flow was studied in this comparison.

We should be aware that each future climate by GCM simulations does not necessarily show similar characteristics of climate condition of observed climate in short time scale, since scenario simulation by GCMs reflect their own internal climate systems, resulting from different time series of dry and flood season and other seasonal to annual climate oscillations. The monthly average precipitation from rain gauge and two modified GCM outputs is shown from 2001 to 2010 in Fig.3. This figure shows that GCM outputs could capture the main events such as low density and high density of rainfall along the year in Blue Nile Basin. Then, GCM outputs have an accepted quality that can be considered for future prediction.

Scenarios of Future River discharge

We obtained simulated discharge from 2011 to 2040 with GCM outputs. Since simulated discharge using GCM outputs cannot be forecasted within short training period, our analysis is based on the highest and average peak discharge within six five years groups.

Results and Discussion

Calibration of DHM model

The simulated discharge calculated using rain gauge data at Khartoum station is shown in Fig.4. The hydrological data (daily data) from 1976 to 1979 are used for calibrating the model parameters in order to well detect the observed discharge in these years. The discharge calculated using rain gauge data was close to the observed discharge at Khartoum station. The Deviation of runoff volumes (Dv) and Nash-Sutcliffe coefficient (Nr) of the discharge simulated using rain gauge data versus the observed discharge was equal to 13.6%, 0.92 respectively. Where the Nr can range from $-\infty$ to 1; improved model performance is indicated as the Nr approaches 1, while a value of zero indicates that simulated values are no better than the mean of observed values. On the other hand, the Dv can take on values between -100% and 100%, with negative values indicating under-prediction and positive values indicating over-prediction. The value obtained is an indicator of the degree of error in the predictions. Generally, the lower this error is, the better the performance is, thus values close to zero indicate a good model performance.

Future Hydrological Scenarios

Simulated discharge from 2001 to 2002 at Khartoum station with two precipitation patterns from GCMs are shown in Fig.5. This graph is shown to evaluate the annual seasonality. The simulated tend of discharge was underestimated than observation using CCSM3-NCAR scenario and overestimated than observation using MIROC Hires3.2 scenario. Focusing on seasonality, the months with the highest peak discharge simulated are between July and September. Future hydrographs from 2011 to 2040 were simulated at Khartoum as shown in Fig. 6. In the part of this figure, hyetograph from MIROC output can be seen. A consistent response of the hydrological model in dotted line using MIROC data can be noticed. Particularly, it is evident for years 2016, 2021, and 2036. Then, we calculated the annual mean and highest discharge in seven year groups (2011-2015, 2016-2020, 2021-2025, 2026-2030, 2031-2035, and 2036-2040) at the Khartoum station as shown in Fig.7 and Fig.8. From Fig.7, the mean annual discharge at each group does not show a high variation. On the other hand, Fig.8 shows the annual highest discharge seems to increase for future groups, especially from 2026 to 2030 using CCSM3-NCAR output and from 2036 to 2040 using MIROC HIRES3.3 output. Actually, simulations with MIROC output predict higher flood peaks. On the other hand, calculated discharges with CCSM3 NCAR output predict lower flood peaks.

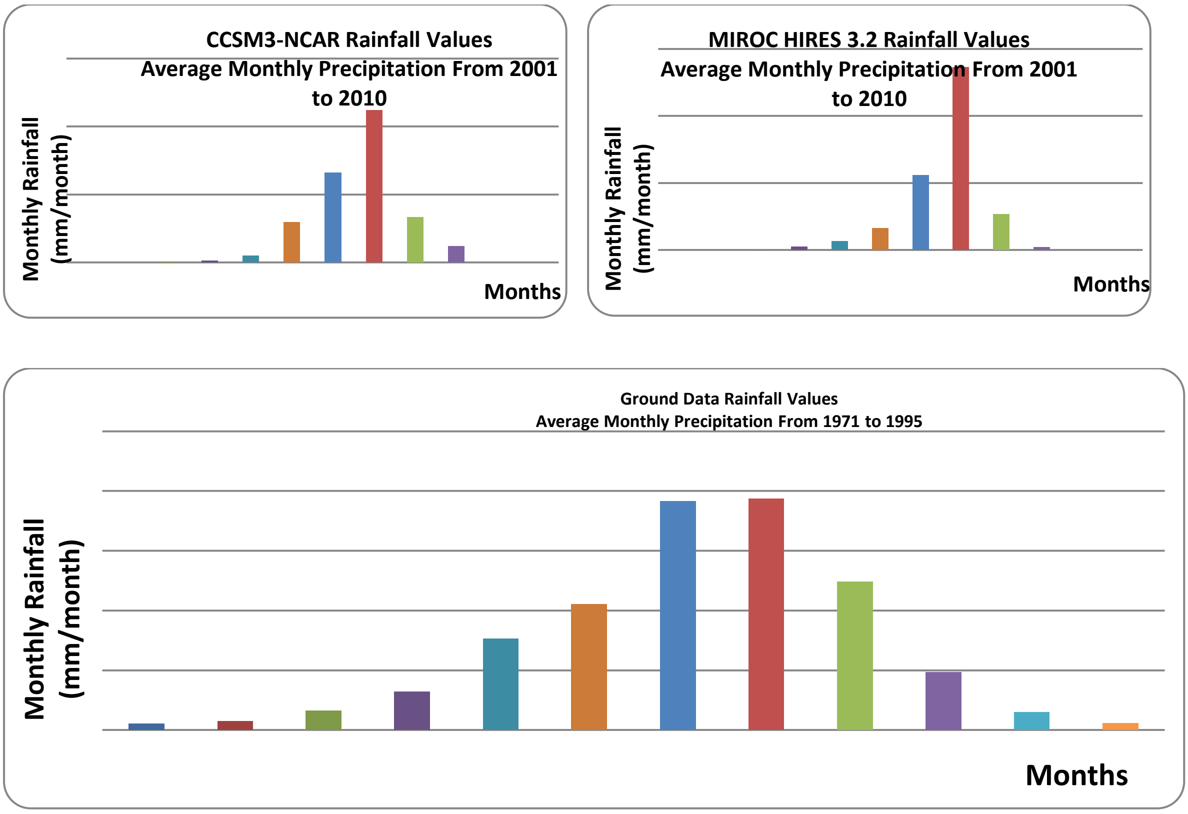

Fig. 3. Average Precipitation of entire target basin using GCM models comparing with average precipitation using ground data

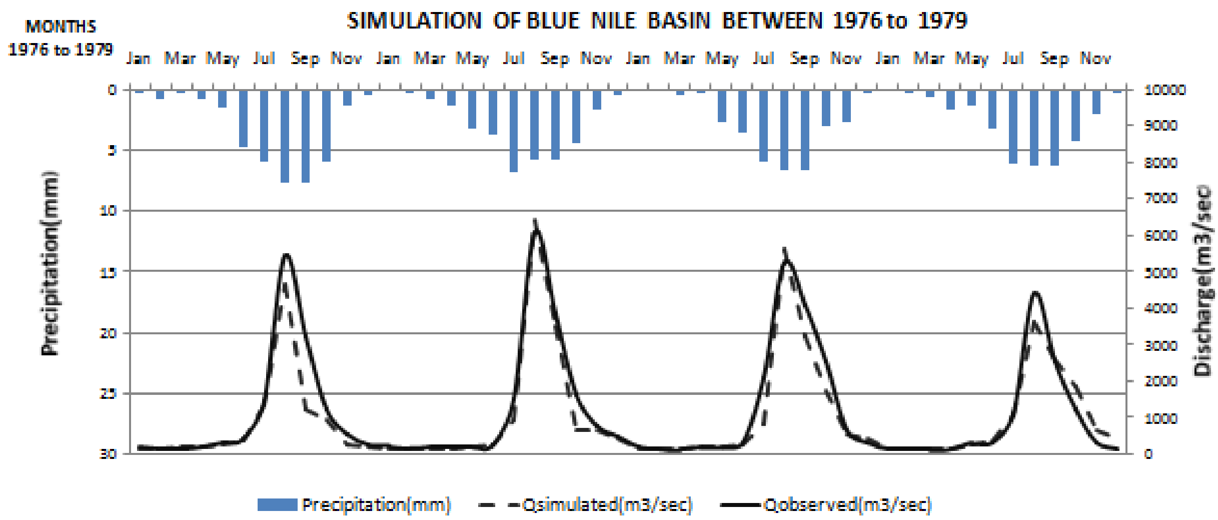

Fig. 4. Discharge simulation at Khartoum Station using Rain gauge data

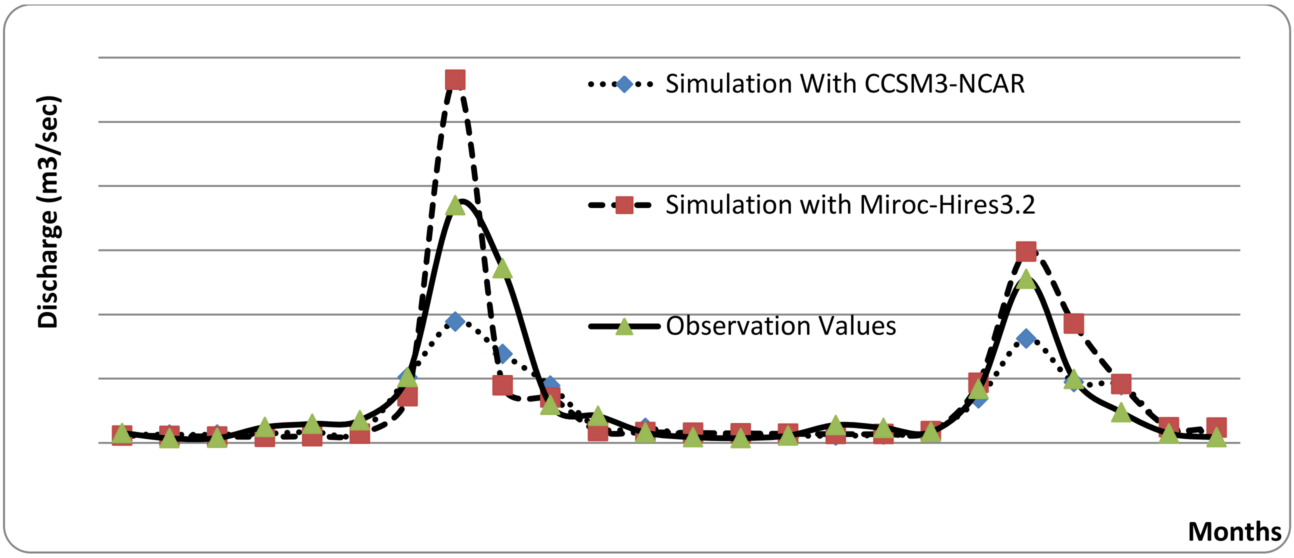

Fig. 5. Discharge simulation at Khartoum station with GCM outputs in 2001-2002

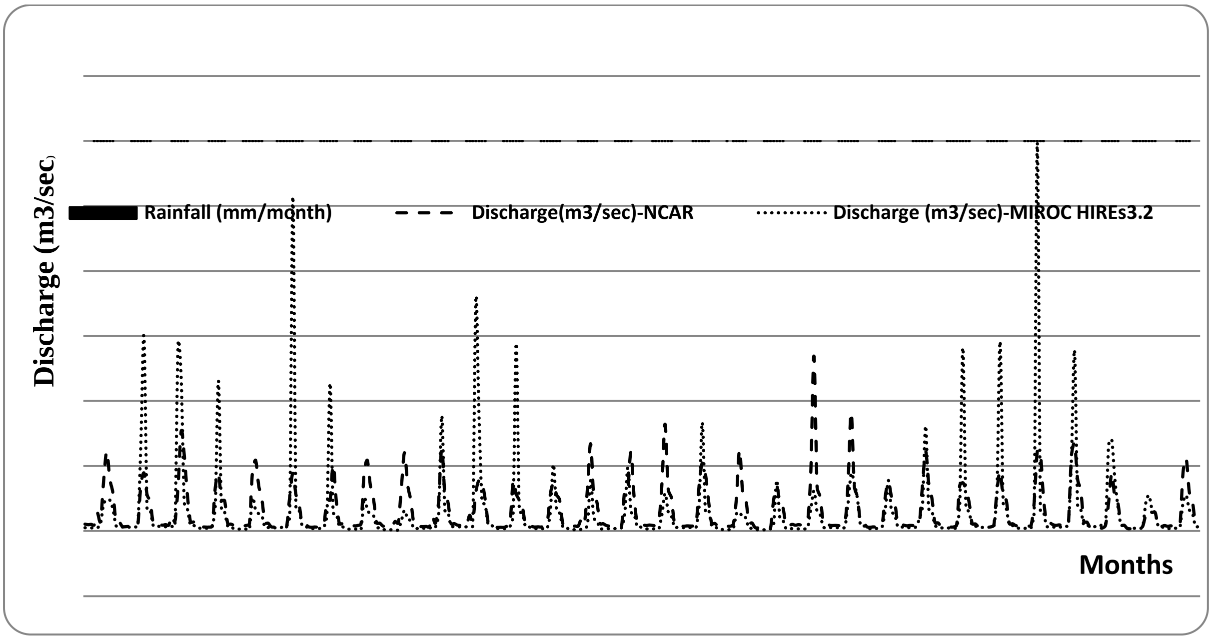

Fig. 6. Future hyetographs at Khartoum station using CCSM3-NCAR and MIROC Hires3.2

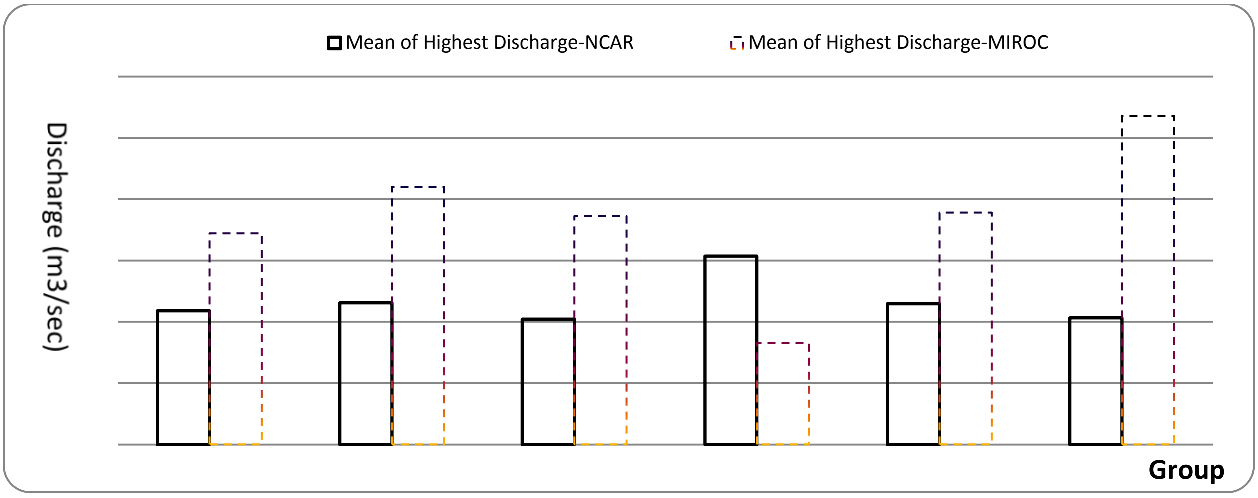

Fig.7. Average of highest discharge at each group

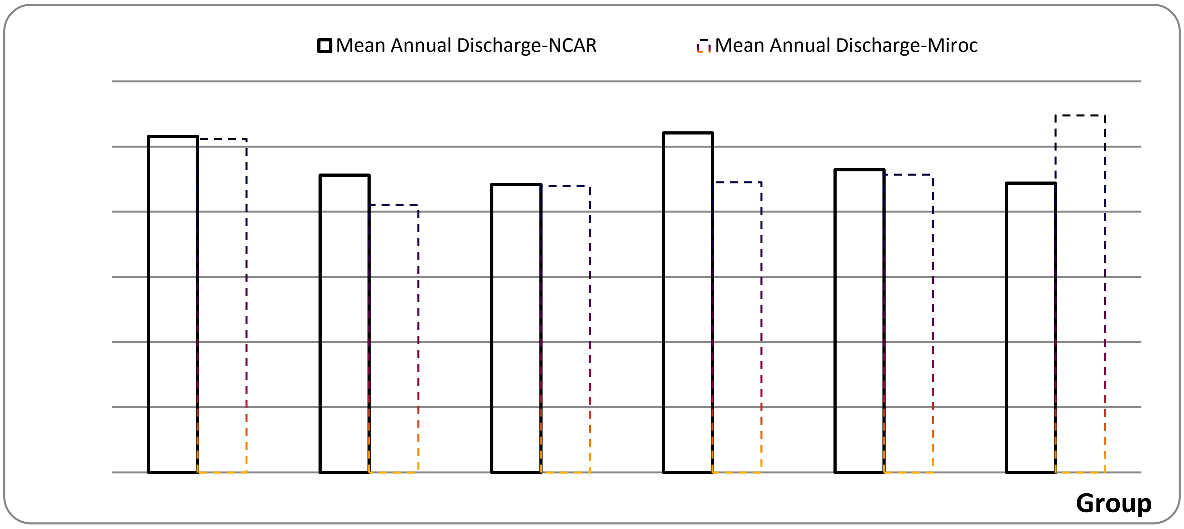

Fig. 8. Mean annual discharge at each group

Conclusion

In this paper, a distributed hydrological model and the data simulated by modified GCM are applied to Blue Nile Basin. The overall performance of the DHM model using observed precipitation showed acceptable agreement with observed river discharge. Future river discharge patterns are predicted forcing the DHM model using two modified GCMs. The results suggest that the mean highest peak discharge might increase within the future seven year groups. In addition, the higher flood peaks seems to be more concentrated in August in the simulated basin. In the future, more appropriate bias correction of the GCM output to the river basin is necessary in order to project future hydrology. Hence, long-term comparisons of in situ data and this models' output are essential. All of this information might be helpful for watershed management in Blue Nile Basin by controlling dams according to the knowledge of higher and lower Peaks and mean flow in the future groups.

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