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Variability of Hydrological Modeling of the Blue Nile

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***Abstract*—**The Blue Nile Basin is the most important tributary of the Nile River. Egypt and Sudan are almost dependent on water originated from the Blue Nile. This multi-dependency creates conflicts among the three countries Egypt, Sudan, and Ethiopia making the management of these conflicts as an international issue. Good assessment of the water resources of the Blue Nile is an important to help in managing such conflicts. Hydrological models are good tool for such assessment. This paper presents a critical review of the nature and variability of the climate and hydrology of the Blue Nile Basin as a first step of using hydrological modeling to assess the water resources of the Blue Nile. Many several attempts are done to develop basin-scale hydrological modeling on the Blue Nile. Lumped and semi distributed models used averages of meteorological inputs and watershed characteristics in hydrological simulation, to analyze runoff for flood control and water resource management. Distributed models include the temporal and spatial variability of catchment conditions and meteorological inputs to allow better representation of the hydrological process. The main challenge of all used models was to assess the water resources of the basin is the shortage of the data needed for models calibration and validation. It is recommended to use distributed model for their higher accuracy to cope with the great variability and complexity of the Blue Nile basin and to collect sufficient data to have more sophisticated and accurate hydrological modeling.

***Keywords*—**Blue Nile Basin, Climate Change, Hydrological Modeling, Watershed.

I. Introduction

THE Nile River extends from 4° South to 31° North, so it's considered the longest river in the world with total length about 6670 km and its drainage area according to FAO 2007 is about 3.1 million km^2 which is about 10% of Africa area. It flows through eleven countries before reaching the Mediterranean Sea. They are Ethiopia, Eritrea, Sudan, Uganda, Tanzania, Kenya, Rwanda, Burundi, Egypt, Democratic Republic of the Congo, and South Sudan. Egypt and the Sudan are the two major users of this river, while Blue Nile in Ethiopia is the primary source [1]. 59% of the annual flow of the Nile comes from Upper Blue Nile Basin, 14% from the Baro–Akobo–Sobat sub-system, 13% from the Tekeze/Atbara/Gash sub-system and the remaining 14% comes from the equatorial lakes [2]. Topography of the Blue Nile is divided into two features, the ragged topography, mountainous areas in the Ethiopian highlands and the flat topography in the lowlands in Sudan [3]. Despite the importance of the Blue Nile River Basin, there is a lack of properly monitored hydrologic data in this region. The Upper Blue Nile River Basin of Ethiopia is an example where data are limited, water resources are valuable, and competition for water among riparian countries is strong. There are few reliable meteorological or hydrologic stations throughout the entire basin due to inaccessibility, remoteness, and economic limitations [4]. So limited published data were present until the US Bureau of Reclamation published land and water resources data from 1958 to 1963 followed by the Abbay River Basin Integrated Development Master Plan Project conducted by the Ministry of Water Resources (MOWR), Ethiopia [5].

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II. Characterization of the Blue Nile Watershed

The Blue Nile (also called Abbay River in Ethiopia) is located between latitude 160 2' N and 70 40' N, and longitude 320 30' E and 390 49' E. It has an estimated area of 324,530 km^2 [6] as shown in Fig. 1 and supplies nearly 84% of the water to the Nile River during high flow season. The Blue Nile originates at the outlet of Lake Tana –contributes with about 10% of the total Blue Nile flow [7]– traveling southward in the Ethiopian highlands then northwest for about 900 kilometers from Lake Tana until it leaves Ethiopia and goes through the huge plains of Sudan where it begins a more northerly path, with a difference in elevations about 1300-1500 meters and some peaks over 3500 m. It is joined by many important tributaries, from the central and southwestern Ethiopian highlands, and then it reaches the lowlands and crosses into Sudan [8]. The Blue Nile with its tributaries covers more than 300,000 km^2 as its basin is sub divided into 18 major sub basins namely, Lower Blue Nile, Upper Blue Nile, Dinder, Rahad, Tana, Beshelo, Beles, Dabus, Diddessa, Jemma, Muger, Guder, Fincha, Anger, Wenbera, South Gojam, North Gojam and Welaka. Fig. 2 shows these 18 sub-basins [3]. Through the basin, the soil is generally vertisols or latosols. The drainage system is well defined, and the gradient of most tributaries is steep [9].

Lake Tana is a natural lake which is considered the largest lake in Ethiopia and the third largest in the Nile Basin. It has an elevation of 1830 m above sea level [10] and covers around 3000 km^2 [11] with a drainage area of approximately 15,000 km^2 and contributes about 10% of the total Blue Nile flow [10]. The major rivers feeding Lake Tana are the Gilgel Abay, the Rib, the Gumara, and the Megech [12]. The rainy season on Lake Tana is between June and September [13]. The lake outflows peak is at September, two months after maximum rainfall at July due to its large storage capacity and the restriction at its outlet [9]. Lake has an annual average precipitation of nearly 1,000 mm and evaporation rates of 1,150 mm per year [10]. At the outlet from Lake Tana, the monthly flow volume for September is an average of 1.3 billion m^3, while in April the average monthly flow volume is only about 60,000 km^3.

The Upper Blue Nile basin is the largest river basin in terms of volume of discharge and second largest in terms of area in Ethiopia and is the largest tributary of the Main Nile [14]. It covers an area around 175 000 km^2 out of 1100000 km^2 of Ethiopia's area [15]. Most of the highlands of the upper Blue Nile basin are at elevations between 1,500 and 3,000 m and have daily mean temperatures that fluctuate between 15–18°C, with rainfall totals similar to Lake Tana [10].

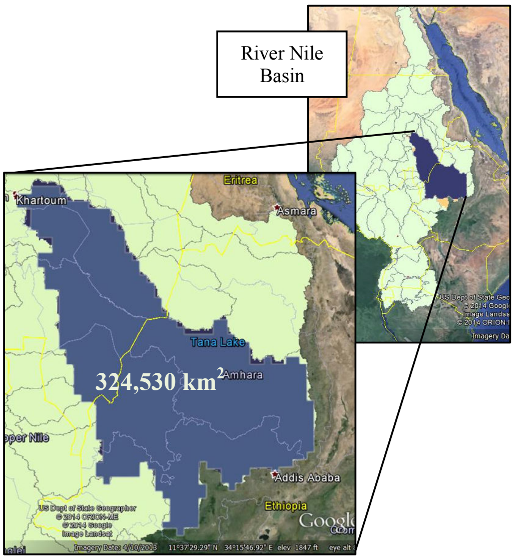

Fig. 1 The left figure is the watershed of River Nile basin done by ARCGIS and the right one is the watershed of the Blue Nile basin which is excluded also from ARCGIS

III. Some of the Common Applied models on Blue Nile Watershed

It's considerably important to have a better understanding of the hydrological characteristics of different watersheds in the headwaters of the Nile River because of its trans-boundary nature [16], the international interest in the utilization of its water resources, the need to improve, enhance development, and management activities of these resources, and the potential for negative impacts of climate change in the future [17].

Collick and Easton (2009) developed a realistic, simple model that is useful as a tool for planning watershed management in Ethiopian highlands. They used daily and weekly hydrological data, including rainfall, evaporation, and discharge from 1982 to 1993. Their study showed that semi-distributed water balance models that require different amounts of rain after the start of the wet season before becoming hydrological, have a good potential to predict discharge in gauged and un-gauged basins [17].

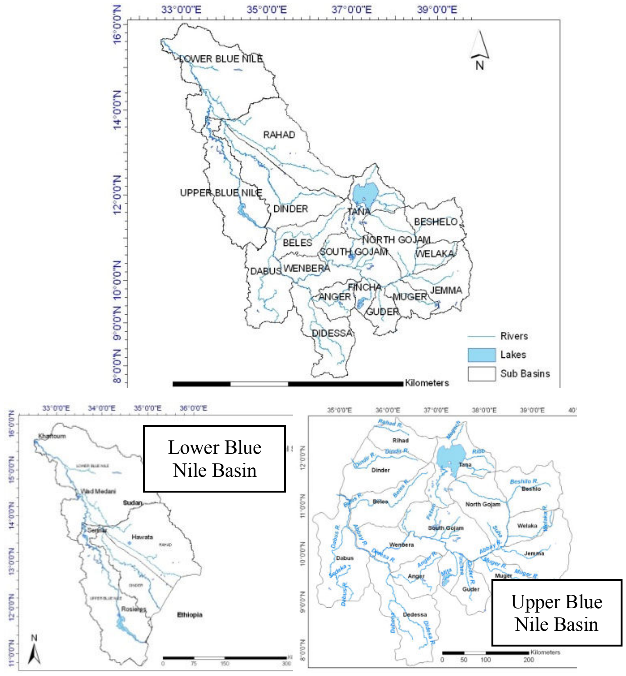

Fig. 2 (a) Blue Nile basin and its 18 sub basins, (b) Lake Tana and Upper Blue Basin, (c) Lower Blue Basin and Dinder-Rahad Basin [3]

Gebrehiwot and Ilstedt (2011) conducted a study to identify the best watershed variables explaining the variation in the hydrological regime, with a special focus on low flows. They used Principal Component Analysis (PCA) and Partial Least Square (PLS) to analyze the relationship between five hydrologic variables which are total flow, high flow, low flow, runoff coefficient and low flow index. They studied the effect of those variables on land use, climate and topography. They concluded that for sustaining water availability in dry periods, conservation of woodland, savannah grassland and wetland is important, whereas more grazing land and bush land could exacerbate water shortages during the dry season. Their study also highlighted how low flows can be generally lower in areas with volcanic soils, such as tuffs/basalts, which cover half of the Blue Nile Basin [18].

IV. Blue Nile Precipitation and Flow Analysis and Modeling

Ethiopia is mainly an agricultural society, and the success of seasonal crops has large implications. As the majority of agriculture depends on rain fed [19], the rainfall is the most important hydrologic parameter that plays an essential role in the country's welfare and food security assessment. During the rainy season, about 85% to 95% of annual crops are produced [20]. Rainfall in the Blue Nile varies considerably with the time of the year like the main rainy season which is called Kiremt, occurs from June to September, and the dry season which is called Bega from October to January or February and the mild season which is called Belg from February or March to May [21]. Historical hydro-meteorological data analysis of the basin showed a high variability in the rainfall pattern and river flows [22] across a range of spatial and temporal scale [23]. Rainfall over the Blue Nile is typically monsoonal with most rain occurring between July and September [24]. In monsoonal climates, a given rainfall volume at the onset of the monsoon produces a drastically different run-off volume than the same rainfall volume at the end of the monsoon [25]. In the Blue Nile basin, rainfall ranges between 2200 mm and 126 mm per year. As the Ethiopian highlands have the highest rainfall ranging from 2200 mm to 1500 mm, while the Ethiopian lowlands have the range from 1500 mm to 1000 mm [3]. For all riparian countries, the runoff variability of upper basins is an important concern in water resources management. Runoff variability of large un-gauged international basins affects water availability to downstream countries making management of transboundary water difficult [5]. The Blue Nile had shown marked decreasing tendency of flows from 1960s to 1980s [26]. Mean annual Blue Nile flows are 45.9 km^3 (1961–1990) and have ranged from 79 km^3 (1909) to 20.6 km^3 (1913) and the lowest decade-mean flow was 37.9 km^3 (1978-1987) [24]. The Blue Nile has highly seasonal flood regimes with over than 80% of annual discharge occurring in four months from July to September. Steep slopes in these catchments produce rapid runoff response times; where in the dry season many of the Blue Nile tributaries are often dry [27]. To predict runoff and its fluctuations successfully is to have a reliable hydrologic model and an appropriate parameter regionalization approach.

Conway (2000) conducted a study to present the spatial and temporal characteristics of climate in the region of central Ethiopia that comprises the Upper Blue Nile. Using records from 11 gauges, he constructed a 99-year basin-wide area age time series of rainfall from 1900 to 1998. He found that the annual rainfall generally declines from over 2000 millimeters in the south-west to less than 1000 millimeters in the north-east. He found that basin-wide mean annual rainfall is 1421 mm from 1961 to 1990 and has ranged from 1148 mm to 1757 mm in 1913 and 1903 respectively. The driest decade in the whole record is centered on 1984 and since then rainfall has increased gradually[14].

Seleshi and Zanke (2008) analyzed changes in annual, June–September and March–May rainfall totals and also rainy days over Ethiopia based on 11 stations located in five major climatic zones over the common period 1965–2002. They classified the seasons in Ethiopia into three seasons, the first is the main rainy season from June to September (Kiremt), the second is the dry season from October to December/January (Bega), and the third is the small rainy season from February/March to May (Belg). They were using a non-parametric Mann–Kendall test to detect any trend over their study period and they calculated the slopes of the trends by least-squares linear fitting. They deduced finally that there is no trend in the annual, Kiremt and Belg rainfall totals over central, northern and northwestern Ethiopia in the period 1965–2002, while the annual and Kiremt total rainfall in eastern and southern Ethiopia show a significant decline since 1982. They found also that Kiremt rainy days in eastern Ethiopia show a significant decline since 1982 compared with the period 1965–1981 [25].

Abtew and Melesse (2009) analyzed monthly and annual Upper Blue Nile Basin rainfall data in order to learn the rainfall statistics and its temporal and spatial distribution using frequency analysis and spatial characterization of the rainfall. Monthly basin average rainfall data were computed from a network of 32 gauges with varying lengths of records from 1960 to 2002. They found that the temporal basin rainfall variation is relatively small whereas the spatial variation is high. They concluded that the upper Blue Nile Basin is relatively wet with a mean annual rainfall of 1423 mm. Also they deduced that the 100-year-drought basin annual rainfall is 1132 mm and the 100-year-wet basin annual rainfall is 1745 mm. They classified the rainy seasons regarding the months of the year. From June to September is the wet season with 74% of the annual rainfall, from November to April is the dry season and May and October are transition months [28].

Tesemma and Mohamed (2010) investigated trends of precipitation and discharge over a 40-year period from 1964 to 2003 in the Blue Nile Basin using both statistical analysis and a semi-distributed rainfall/runoff model to improve the understanding of future conditions. They used average monthly basin precipitation and monthly discharge data. They concluded that the precipitation did not change over the entire basin and the annual discharge increased for the upper Blue Nile only [29].

Abdo, Fiseha and Rientjes (2009) used General Circulation Model (GCM) and water balance modeling -Statistical Down-Scaling Model and HBV semi-distributed rainfall/runoff model- to assess hydrological impacts by climate changes at Gilgel Abay catchment that drains in Lake Tana. They used a GCM model first to provide global climate change scenarios for future, and then they applied downscaling techniques for downscaling GCM outputs to be suitable for hydrological modeling. Finally they used hydrological models to simulate the effects of climate change on hydrological regimes. They concluded that the catchment is sensitive to climate change especially to changes in rainfall [30].

Kim and Kaluarachchi studied the impacts of climate change on both hydrology and water resources operations in the upper Blue Nile River Basin using hydrologic sensitivity, flow statistics, and several related indices, and they were analyzed using the outcomes of six different general circulation models (GCMs) for the 2050s. They weighted the outcomes of these six GCMs to provide average future changes. They also assessed the changes in outflows from the two proposed dams, Karadobi and Border to downstream countries.

V. Overview of Hydrological Models in Common Use in the Blue Nile

Hydrological models became increasingly important tools for the management of the water resources [13]. They help to study the available water resources in the past and the present and to provide a way to choose the best management decisions [31].The purpose of hydrological modeling at large river basin scale is predominantly to support decision making for water resources management, and their sufficiency [31]. So many hydrological models are applied to study the processes governing the generation of run-off at various scales in the basin, from the small watershed to the basin level and to quantify the water resources at these scales, with regard to climatic conditions and rainfall characteristics.

Peggy and Johnson (1994) developed a monthly water balance model to present the existing stream-flow data for the Blue Nile River and its tributaries within the Blue Nile River basin in Ethiopia. Then they used these data to provide a better understanding about the temporal and spatial variation of the river's hydrology in Ethiopia. They conducted comparisons between the predicted and observed monthly hydrographs for selected sub-watersheds within the Blue Nile basin. The model provided them results that are useful for forecasting flows into the Roseries Reservoir at the Sudan border and subsequently into the Aswan Reservoir in Egypt. They used their water balance model to determine the effect of global climatic changes on the volume of water that enters the Nile River basin from Ethiopia [6].

Kebedea and Travi (2006) conducted a simulation of Lake Tana level variation from 1960 to 1992 by modeling at a monthly time step to estimate the water budget of Lake Tana and its sensitivity to rainfall variations. They found that the lake level remained regular despite the 20% rainfall variations in the Blue Nile basin in the last 50 years. Also they concluded that unlike the terminal lakes in the Ethiopian rift valley or the other large lakes of tropical Africa, Lake Tana level is less sensitive to rainfall variation and changes in catchment characteristics [13].

In order to estimate the hydrological balance of Lake Tana, Chebud and Melessea (2009) used a lumped mass balance approach which included water influx, subsurface inflow, precipitation, outflow from the lake constituting river discharge and evapotranspiration which were analyzed on monthly and annual bases. Their study has shown that the monthly and annually calculated lake level replicates the observed values with root mean square error value of 0.17 and 0.15 m, respectively [32].

Kim and Kaluarachchi (2010) conducted a study to assess how limitations of continuity and duration in data affect hydrologic model calibration. They wanted to evaluate whether discontinuous hydrographs are capable of calibrating a water balance mode or not. They calibrated previously developed water balance model for the upper Blue Nile River basin using continuous and discontinuous (randomly sampled) data of different lengths. Then they compared the performance of both methods in terms of parameter uncertainty and model efficiency. Their model computes monthly runoff using monthly precipitation and potential evapotranspiration over the basin. The overall framework performed in their study is not only specified to the study area only, as it can be easily extended to future studies related to hydrologic prediction of sparely gauged basins. Their findings is essential to develop a monitoring strategy for remote basins of the upper Blue Nile Basin where continuous observations are limited [21].

Rientjes and Haile (2011) evaluated the changes in land cover and rainfall in the Upper Gilgel Abbay catchment in the Upper Blue Nile basin and how these changes affected stream flow in terms of annual flow, high flows and low flows. They used classification analysis of three remote sensing images that were acquired in the dry season month of February for the years 1973, 1986, 2001, to assess the land cover change and they used statistical analysis to assess rainfall and stream flow data during the period 1973–2005. The land cover classification analysis they applied, indicated that a relatively large decrease of forested area and a large increase of agricultural land occurred from 1973 to 2001. This decrease was due to expansion of agricultural land. Regarding the rainfall and stream flow, they analyzed the rainfall at monthly base by use of the Mann-Kendall test statistic and their results indicated a decreasing trend for most months of the year except at the wet season months of June, July and August rainfall has increased. For the annual flow, they analyzed low and high flow at daily base by a low flow and a high flow index that is based on a 95% and 5% exceedance probability. They concluded that over the period 1973–2005 stream flow has changed in the Gilgel Abbay catchment by changes in land cover and changes in rainfall as the low flow index decreased while the high flow index increased [33].

Dile and Srinivasan (2014) assessed the applicability of the National Centers for Environmental Prediction's Climate Forecast System Reanalysis (CFSR) climate data in modeling the hydrology of the Upper Blue Nile (Lake Tana basin). They tested the applicability of this global weather data for hydrological modeling in data-scarce regions using a physically based model called SWAT2012. The Soil and Water Assessment Tool (SWAT) model is a basin-scale model where run-off is based on land use and soil type not on topography [34]. It requires spatial, temporal and management data to model the hydrology of a watershed. They compared observed weather data from climatic stations in and around the Lake Tana basin (conventional weather) with the CFSR weather data. Their study concluded that that the CFSR weather simulated the hydrology of the Lake Tana basin with a lower performance rate than conventional weather. However, in data-scarce regions such as remote parts of the Upper Blue Nile basin, CFSR weather could be a valuable option for hydrological predictions where conventional gauges are not available [12].

VI. Conclusion

The Blue Nile is the largest tributary of the Nile so sharing its water has been a sensitive issue of negotiation and political tension for many decades between the riparian countries Egypt, Sudan and Ethiopia. It's important to study its relevant hydrological cycle to avoid water scarcity and to have a good water resources management. So it's essential to investigate the availability of the rainfall data at the Blue Nile at relevant time scales. The available rainfall data in Ethiopia for the Blue Nile starts from daily and above. But unfortunately recording automatic gauges are found only in limited meteorological stations with some missing data in case of long recording series. Also estimating future availability of water and developing new managing strategies are considered as important challenges. The key to successfully predict runoff and its fluctuation regarding to the rainfall data relies on using a reliable hydrologic model. Most hydrologic modeling studies in the upper Blue Nile Basin have focused on estimating the runoff at the basin outlet without precipitation analysis. Despite reliable precipitation analysis provides valuable information to manage extreme scenarios like droughts, floods. So it's recommended to focus more on rainfall trends and scenarios and work on development of suitable hydrological models to act with the larger river basins and the lack of rain data.

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References

[1] Y. Arsano and I. Tamrat, "Ethiopia and the Eastern Nile Basin," *Aquat. Sci.*, vol. 67, no. 1, pp. 15–27, Mar. 2005.
[2] T. Beyene, D. P. Lettenmaier, and P. Kabat, "Hydrologic impacts of climate change on the Nile River Basin: implications of the 2007 IPCC scenarios," *Clim. Change*, vol. 100, no. 3–4, pp. 433–461, Oct. 2009.
[3] A. D. Yilma and S. B. Awulachew, "Characterization and Atlas of the Blue Nile Basin and its Sub basins," *Water Manag.*, 2009.
[4] U. Kim and J. J. Kaluarachchi, "Climate change impacts on water resources in the upper Blue Nile River Basin, Ethiopia," *J. Am. Water Resour. Assoc.*, vol. 45, no. 6, pp. 1361–1378, 2009.
[5] U. Kim and J. J. Kaluarachchi, "Application of parameter estimation and regionalization methodologies to ungauged basins of the Upper Blue Nile River Basin, Ethiopia," *J. Hydrol.*, vol. 362, no. 1–2, pp. 39–56, Nov. 2008.
[6] P. A. Johnson and P. D. Curtis, "Water Balance of Blue Nile River Basin in Ethiopia," *Journal of Irrigation and Drainage Engineering*, vol. 120, no. 3. pp. 573–590, 1994.
[7] D. N. Yates and K. M. Strzepek, "Modeling the Nile Basin under Climatic Change," *J. Hydrol. Eng.*, vol. 3, no. 2, pp. 98–108, Apr. 1998.
[8] P. J. Block, K. Strzepek, and B. Rajagopalan, "Integrated Management of the Blue Nile Basin in Ethiopia," 2007.
[9] D. Conway, "A water balance model of the Upper Blue Nile in Ethiopia," *Hydrol. Sci. J.*, vol. 42, no. 2, pp. 265–286, Dec. 2009.
[10] P. Block and K. Strzepek, "Economic analysis of large-scale upstream river basin development on the Blue Nile in Ethiopia considering transient conditions, climate variability, and climate," *J. Water Resour. Plan. …*, no. April, pp. 156–166, 2010.
[11] A. Wale, T. H. M. Rientjes, A. S. M. Gieske, and H. A. Getachew, "Ungauged catchment contributions to Lake Tana's water," vol. 3693, no. April, pp. 3682–3693, 2009.
[12] Y. T. Dile and R. Srinivasan, "Evaluation of CFSR climate data for hydrologic prediction in data-scarce watersheds: an application in the Blue Nile River Basin," *JAWRA J. Am. Water Resour. Assoc.*, vol. 77845, pp. 1–16, 2014.
[13] S. Kebede, Y. Travi, T. Alemayehu, and V. Marc, "Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile basin, Ethiopia," *J. Hydrol.*, vol. 316, no. 1–4, pp. 233–247, Jan. 2006.
[14] D. Studies, E. Anglia, and N. Nr, "The Climate and Hydrology of the Upper Blue Nile River," *Geogr. J.*, vol. 166, no. 1, pp. 49–62, 2000.
[15] A. Mishra and T. Hata, "A grid-based runoff generation and flow routing model for the Upper Blue Nile basin," *Hydrol. Sci. J.*, vol. 51, no. 2, pp. 191–206, Apr. 2006.
[16] J. G. Arnold, R. Srinivasan, R. S. Muttiah, and J. R. Williams, "Large area hydrologic modeling and assessment part 1: model development," *JAWRA J. Am. Water Resour. Assoc.*, vol. 34, pp. 73–89, 1998.
[17] A. S. Collick, Z. M. Easton, T. Ashagrie, B. Biruk, S. Tilahun, E. Adgo, S. B. Awulachew, G. Zeleke, and T. S. Steenhuis, "A simple semi-distributed water balance model for the Ethiopian highlands," *Hydrol. Process.*, vol. 23, no. 26, pp. 3718–3727, 2009.
[18] S. G. Gebrehiwot, U. Ilstedt, A. I. Gärdenas, and K. Bishop, "Hydrological characterization of watersheds in the Blue Nile Basin, Ethiopia," *Hydrol. Earth Syst. Sci.*, vol. 15, pp. 11–20, 2011.
[19] Y. Seleshi and U. Zanke, "Recent changes in rainfall and rainy days in Ethiopia," *Int. J. Climatol.*, vol. 24, no. 8, pp. 973–983, Jun. 2004.
[20] P. Block and B. Rajagopalan, "Interannual variability and ensemble forecast of Upper Blue Nile Basin Kiremt season precipitation," *J. Hydrometeorol.*, vol. 8, no. 3, pp. 327–343, 2007.
[21] U. Kim and J. J. Kaluarachchi, "Hydrologic model calibration using discontinuous data: An example from the upper Blue Nile River Basin of Ethiopia," vol. 3717, no. September 2009, pp. 3705–3717, 2010.
[22] N. R. Basin, *Nile River Basin-Hydrology, Climate and Water Use*. .
[23] D. Conway, A. Persechino, S. Ardoin-Bardin, H. Hamandawana, C. Dieulin, and G. Mahé, "Rainfall and Water Resources Variability in Sub-Saharan Africa during the Twentieth Century," *J. Hydrometeorol.*, vol. 10, no. 1, pp. 41–59, Feb. 2009.
[24] D. Conway, "From headwater tributaries to international river: Observing and adapting to climate variability and change in the Nile basin," *Glob. Environ. Chang.*, vol. 15, no. 2, pp. 99–114, Jul. 2005.
[25] B. M. Liu, A. S. Collick, G. Zeleke, E. Adgo, Z. M. Easton, and T. S. Steenhuis, "Rainfall-discharge relationships for a monsoonal climate in the Ethiopian highlands," *Hydrol. Process.*, vol. 22, no. August 2007, pp. 1059–1067, 2008.
[26] G. Di Baldassarre, M. Elshamy, A. van Griensven, E. Soliman, M. Kigobe, P. Ndomba, J. Mutemi, F. Mutua, S. Moges, Y. Xuan, D. Solomatine, and S. Uhlenbrook, "Future hydrology and climate in the River Nile basin: a review," *Hydrol. Sci. J.*, vol. 56, no. 2, pp. 199–211, Mar. 2011.
[27] D. Conway and M. Hulme, "Recent fluctuations in precipitation and runoff over the Nile sub-basins and their impact on main Nile discharge," *Clim. Change*, vol. 25, no. 2, pp. 127–151, 1993.
[28] W. Abtew, A. M. Melesse, and T. Dessalegne, "Spatial, inter and intra-annual variability of the Upper Blue Nile Basin rainfall," *Hydrol. Process.*, vol. 23, no. 21, pp. 3075–3082, 2009.
[29] Z. K. Tesemma, Y. A. Mohamed, and T. S. Steenhuis, "Trends in rainfall and runoff in the Blue Nile Basin: 1964-2003," *Hydrol. Process.*, vol. 24, no. September, pp. 3747–3758, 2010.
[30] K. S. Abdo, B. M. Fiseha, T. H. M. Rientjes, A. S. M. Gieske, and A. T. Haile, "Assessment of climate change impacts on the hydrology of Gilgel Abay catchment in Lake Tana basin, Ethiopia," *Hydrol. Process.*, vol. 23, no. 26, pp. 3661–3669, 2009.
[31] R. Johnston and V. Smakhtin, "Hydrological Modeling of Large river Basins: How Much is Enough?," *Water Resour. Manag.*, vol. 28, no. 10, pp. 2695–2730, Jun. 2014.
[32] Y. A. Chebud and A. M. Melesse, "Modelling lake stage and water balance of Lake Tana , Ethiopia," vol. 3544, no. October, pp. 3534–3544, 2009.
[33] T. H. M. Rientjes, A. T. Haile, E. Kebede, C. M. M. Mannaerts, E. Habib, and T. S. Steenhuis, "Changes in land cover, rainfall and stream flow in Upper Gilgel Abbay catchment, Blue Nile basin - Ethiopia," *Hydrol. Earth Syst. Sci.*, vol. 15, no. 2008, pp. 1979–1989, 2011.
[34] S. B. Awulachew, D. Molden, and D. Peden, *The Nile River Basin: water, agriculture, governance and livelihoods*. Routledge, 2012.