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Review article

A review of hydroclimate variability and changes in the Blue Nile Basin, Ethiopia

Obsinet Abebe Wedajo [a,d,*], Fekadu Fufa [c], Tenalem Ayenew [a,b], Dessie Nedaw [a,b]

[a] *Africa Center of Excellence for Water Management, College of Natural and Computational Sciences, Addis Ababa University, Addis Ababa, PO Box 1176, Ethiopia*
[b] *School of Earth Science, College of Natural and Computational Sciences, Addis Ababa University, Addis Ababa, Ethiopia*
[c] *School of Civil and Environmental Engineering, Jimma Institute of Technology, Jimma University, Oromia, Ethiopia*
[d] *School of Civil and Environmental Engineering, Hachalu Hundesa Institute of Technology, Ambo University, Oromia, Ethiopia*

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ABSTRACT

Understanding the factors that influence hydroclimate variability is crucial for developing sustainable water management strategies in dynamic environments. The Blue Nile Basin, a significant freshwater resource in Africa, is facing challenges related to hydroclimate changes that impact sustainable development. Since the 1970s, the hydroclimate patterns of the region have undergone notable changes, prompting the need for a review of the literature on hydroclimate variability of the basin. Therefore, this study aims to offer a brief overview of the latest literature on hydroclimate variability and changes in the Blue Nile Basin. Based on the review of hydroclimate studies in the basin, it is evident that there have been significant advancements in our understanding of this complex system. However, the review also highlights that there are still areas of research that require further development to provide more comprehensive knowledge of the basin's hydroclimate. The projected intensification of hydroclimate change throughout the 21st century underscores the urgency for continued research efforts. The observed warming trend in the temperature of the basin and the discrepancies amongst research outputs on precipitation changes are important areas that require further investigation. Additionally, the inconsistency in reported changes in the watershed's hydrology and streamflow across the basin emphasizes the need for continued research to understand the factors behind these changes. Overall, this review provides valuable insights into the current state of hydroclimate studies in the basin and highlights the key areas for future research efforts to enhance our understanding of this vital system.

1. Introduction

Hydroclimate variability and change are usually described through the fluctuation of climatic and hydrological variables and by quantifying their associations. The determinants of climate variations and change are changes in the sun's energy, volcanic eruptions, fluxes of atmospheric concentrations of greenhouse gases (GHGs) such as CO2, and land cover change [1]. The factors can be altered due to natural climatic and terrestrial processes and prompted by human activities. There was empirical evidence that the drastic change in the natural environment and terrestrial climate since the past century is due to human-induced changes [2]. In recent years,

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* Corresponding author. Africa Center of Excellence for Water Management, College of Natural and Computational Sciences, Addis Ababa University, Addis Ababa, PO Box 1176, Ethiopia.

E-mail addresses: obsinet.abebe@aau.edu.et, obsineet@gmail.com (O.A. Wedajo).

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the increase in atmospheric concentrations of GHGs was more rapid and reached a new maximum record in 2020 [3]. Consequently, the past seven years (2015–2021) were the seven warmest years on record [3].

The change in the climate pattern directly influences the global water cycle, and changes in the water cycle impact the climate system due to the high interaction between climate and hydrological variables. The recent significant changes in the global climate are having an impact on the basin's hydrological systems and freshwater supply [1,2]. The degree of variations and the affected community are diverse at different spatial and temporal scales. Thus, understanding and quantifying the interaction between climate and hydrological variables is crucial at different scales to plan for adaptive water management in the changing world.

The Nile River Basin (NRB) is one of the most significant earth's freshwater supply sources with networks of transboundary freshwater networks, wetlands, and diverse ecosystems. The basin has competitive water demands for livelihoods for more than 272 million people in 11 riparian countries of Eastern and North-Eastern Africa [4]. The majority of the basin's water originated from the seasonal rainfall on highlands in Northern and South Western Ethiopia that contributes significant flow to the Blue Nile basin (Abbay), Atbara (Tekeze-Setit), and Sobat (Baro-Akobo) and flows towards Sudanese and South Sudanese lowlands [5].

The community of the basin is highly vulnerable to hydroclimate change impacts due to high poverty levels, the expansive and fragile dry land zone, low water storage capacity, poor farming practices, and large rural populations [4]. It was reported by Ref. [3] that increased temperature has contributed to a 34 % reduction in productivity growth in Africa since 1961. In recent years, the basin experienced many problems related to hydroclimate variability and changes such as rainfall variability [6,7], increase in frequency and severity of drought [8,9], and streamflow variability that has caused a threat to agriculture, water security, and food security of the region [3,4,10].

The NRB is known for having sub-basins with distinct characteristics and hydroclimate conditions [4]. The spatial and temporal patterns of the hydroclimate of the basin vary in different sub-basins at different scales owing to the interaction of the large-scale atmospheric circulation [7,11] with the complex topography of the basin [12] and the past environmental changes [13–15]. There was substantial development in the studies of the hydroclimate of NRB in the recent past. Many attempts have been made to understand the variability and changes in the hydroclimate of the basin by analyzing the correlation between climatic and hydrological variables. From the sub-basins in Ethiopia, the number of studies is increasing in the Blue Nile Basin (BNB) than in Tekeze-Setit and Baro-Akobo due to the growing international attention over the basin as a consequence of the conflict between Ethiopia and downstream countries Sudan and Egypt on the completion of the grand Ethiopian renaissance dam hydropower project. Thus, the current review study mainly focused on BNB in Ethiopia.

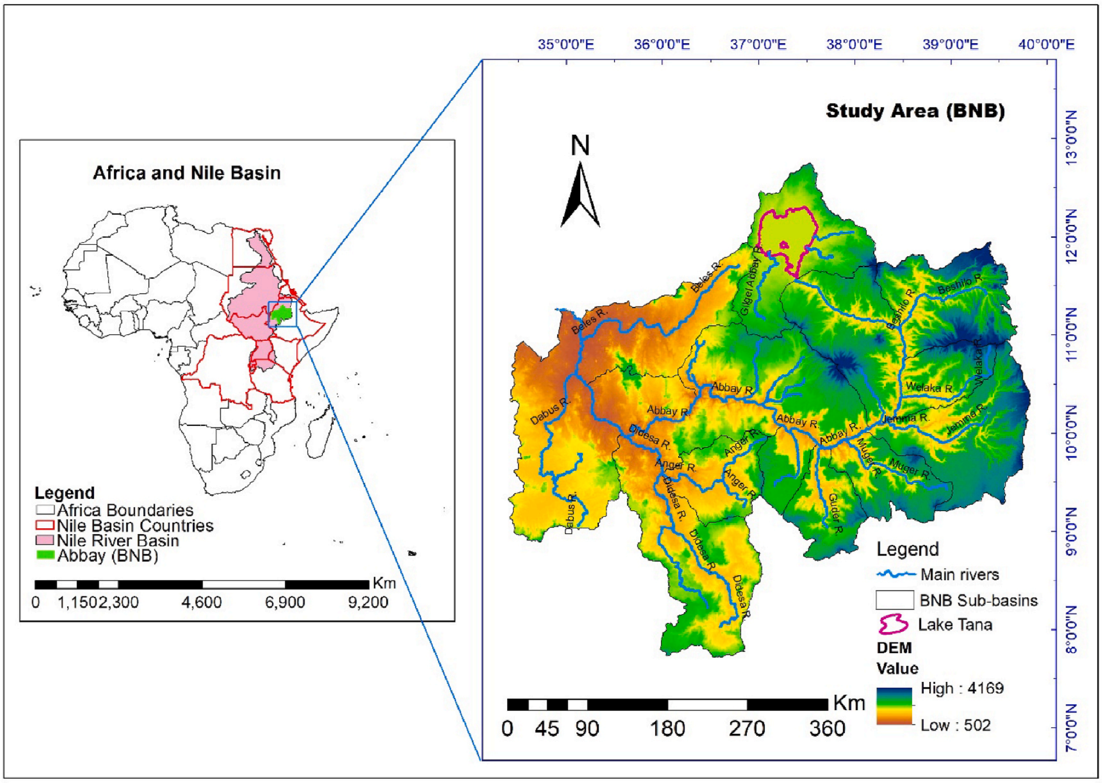

Fig. 1. The location map of the study area. African countries and Nile River Basin Countries (left), and the topography mapped from SRTM DEM with sub-basins of the Blue Nile Basin, the main streams, and Lake Tana are shown (right).

Fig. 1 shows the location map of the Blue Nile in the Nile Basin of Africa.

Most of the past hydroclimate studies in the BNB were conducted from the long-term perspective since the data record began, despite the long-term data scarcity. However, there have been significant advances in hydroclimate research owing to the development in climate and hydrological modeling and the data availability improvement with remote sensing techniques in recent years. Rapid changes in hydroclimate conditions have been happening in the global and regional climate systems in the past decade [1,3]. The ongoing fast change needs quick updates and immediate responses for a better adaptation plan. Thus, the integrated knowledge of the progress and the indication of the remaining research area from the recently advancing literature is crucial.

The previous review study by Ref. [16] has provided knowledge about hydrological extremes in the BNB under historical and future climate conditions. The study by Ref. [10] has reviewed the climate-induced water security risks to agriculture of the BNB. The previous review studies focused on understanding the impacts of climate change on specific hydrologic events and a particular sector. Nonetheless, the current study provides an integrated overview of historical and future changes in the hydroclimate and highlights the advancements in knowledge from the most recent literature. The focus of the current study is to offer a concise update on hydroclimate variability and changes in the BNB from recently advancing literature. The information from this review study is vital for policymakers, researchers, and other stakeholders working towards sustainable development of the region.

2. Methods

2.1. Study area

The study area of this review paper is BNB, which drains the North West and Western regions of Ethiopia. The geographical location of the basin is displayed in Fig. 1. The BNB is the largest tributary of the main Nile and covers about 17 % of Ethiopia's land area with an approximate size of 176,000 Km^2 [17]. The study by Ref. [14] estimates the long-term (1971–2010) mean annual streamflow volume at the El Diem outlet to be 50.7 billion m^3. The basin is known for its complex topography ranging between 502 m and 4169 m (Fig. 1). The basin area with the higher elevation has a humid climate, while the region with lower elevation has a semi-arid climate [18,19]. The northward and southward movement of the Intertropical Convergence Zone (ITCZ) controls the considerable seasonal variation of rainfall in the BNB [19,17]. The mean annual rainfall of the basin ranges from 800 to 2200 mm from northeast to southwest [17], indicating the existence of diverse climatic zones within the basin. The majority of the basin area receives a high amount of rainfall in summer (June–September). The mean annual minimum and maximum temperature over the BNB has increased from 12.69 to 13.32, 26.43 to 26.91, and from 1981 to 2010 [20]. A recent water balance study of the basin reveals that evapotranspiration (ET) accounts for 58 % of the annual water budget [21]. The average basin scale ET from 1992 to 2014, estimated by Ref. [21], is 608 mm/year.

2.2. Methodology

The literature search, screening, collection, and review followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 2020 [22]. We searched for literature using different search engines such as Google Scholar, Science Direct, Web of Science, Wiley Online Library, Research Gate, and Google. We used a wide range of search terms related to the study's title, including hydroclimate, hydrology, climate, temperature, precipitation, evapotranspiration, streamflow, and Blue Nile. We screened articles based on our established criteria and selected basin. The literature included in the study spanned the period from 2011 to 2022.

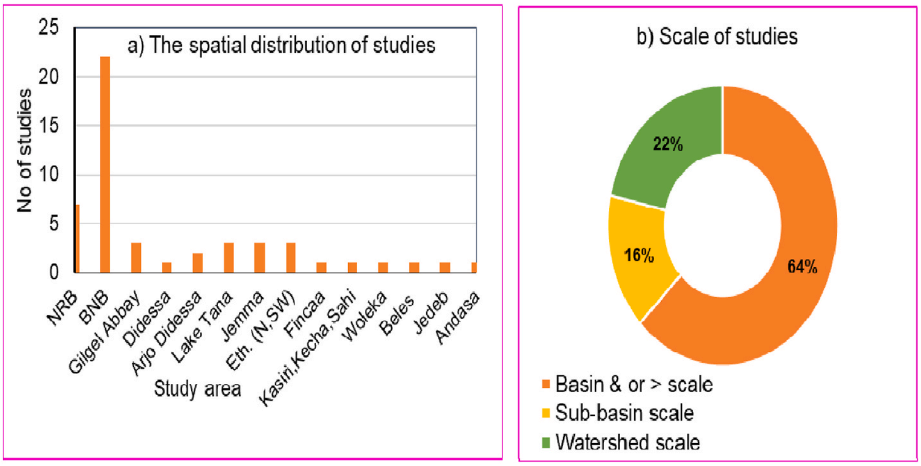

Fig. 2. Spatial distribution and scale of considered literature.

The number of studies in each basin and the scales of the studies organized from the included literature for this review are shown in Fig. 2 a and b. Fig. 2a shows the number of studies in each basin and Fig. 2b shows the scale of the reviewed studies.

A comprehensive search of electronic databases yielded 240 review materials in total. Many of these materials are duplicates retrieved from multiple databases. At the first screening stage, removing the duplicates based on title screening and the exclusion based on the required period was made. The next screening was abstract screening based on having at least one or more hydroclimate variables, such as temperature, precipitation, streamflow/runoff, and ET. By full document screening, articles focused on a specific model's performance rather than providing information on the required variables excluded. The review excluded hydroclimate studies that focused on geochemical records and hydroclimate change that occurred during paleo-climatic change.

After conducting systematic screening processes, we have ultimately selected fifty review materials for the review. Data relevant to the review subtopics were then extracted and analyzed in Microsoft Excel. The selected studies were geographically diverse, covering a range of spatial scales. Specifically, 64 % of the reviewed materials were conducted on a large scale, while the remaining studies were conducted at sub-basin and watershed scales (Fig. 2). The GIS data used while defining the location of the study area and mapping the variation in streamflow trends from the reviewed literature was obtained from the Ethiopian Basin Authority and processed in Arc GIS 10.4.

3. Results and discussion

3.1. Trends of change in historical temperature

A plethora of studies have scrutinized the trends and variations of historical temperature changes in the NRB as a whole and specifically in the BNB at diverse spatial and temporal scales, utilizing varied statistical techniques and data from an array of sources [7,20,23–25]. Although certain discrepancies existed among the studies on the extent of the trends of change, the outcomes of studies at the NRB scale and different scales within BNB suggest that the basin's climate is consistently warming. The majority of the studies concurred that the warming of the globe has resulted in temperature increases and temperature-related extremes that are already evident in the basin [7,23,25]. Temperature showed considerable local variations in its spatiotemporal trends across the basin. For example, from 1960 to 2010 [24], discovered increasing temperature trends with varied rates across seasons and stations. Using the latest data from 1981 to 2010 [20], found that the temperature rose in 33 % of the area, and in about 12 % of the basin's western regions, it declined. Table 1 provides a summary of the findings on the trends of change in historical temperature, as well as historical precipitation.

3.2. Trends of change in historical precipitation

The most important and frequently studied climatic variable of BNB is precipitation in rainfall form. Understanding the patterns of rainfall variability and change is crucial in BNB because the livelihood of the majority of the basin people is highly dependent on rain-fed agriculture. Diurnal rainfall variability over upper BNB was studied by Ref. [12] from four satellite data. They have concluded that

Table 1

A comprehensive synthesis of research findings on the trends and variability of historical temperature and precipitation in the BNB.

Data Period	Basin	Main findings	Reference
1973–2005	Gilgel Abbay	A significant negative trend in spring & a positive trend in summer P based on monthly data.	[26]
1960–2010	BNB	*T* varied by a rate of +0.3 to +0.6 °C/decade & with no significant change in annual & seasonal P in 13 stations.	[24]
1971–2011	Ethiopia	Significant decline in (spring, summer, and annual) P with (2.6, 2.2, and 5.4) mm/year in SE but northern highlands did not display similar tendencies.	[27]
1981–2010,	UBNB	A significant change in ($T_{ma,x}$, $T_{\min)}$ by (+0.1, +0.15) °C/decade over 33 % of the area & declined in (12 %) in W & NE; Annual P insignificantly increased over 88 % of the basin area.	[20]
1954–2004	UBNB	Insignificant decrease in annual P in >80 % of the area; a significant decrease in summer P at 2/16 stations after the 1970s.	[17]
1901–2014	Woleka	Significant decline in annual, & summer P by −15.03 & −13.22 mm/decade respectively; a significant increasing trend of mean T by +0.046.	[28]
1948–2010	BNB	significant increase in T_{max} by +0.09 to +0.48 & T_{min} by +0.17 to +0.50 °C/decade; significant decline in annual P by −76.64 mm/decade	[29]
1980–2015	Lake Tana	A significant change in T and P by +1.08 °C/decade and +1.81 to −9.74mm/year.	[30]
1981–2014	Jemma	A significant increasing trend of annual and summer P in more than 78 % of the stations and a decreasing trend of spring P; the increasing trend of T.	[31]
1953–2014	BNB	P significantly varied by +12.85 to −17.78 mm/year	[32]
1981–2015	Didessa	A significant increase in T and P by +0.45 °C/decade and +3.3 to +4.65 mm/year	[33]
1900–2017	NRB	A significant change in T by +0.19 °C/decade and P by −16.2 mm/decade	[7]
1950–2018	BNB	Annual, Bega, Belg, & Kiremt P significantly declined by 36.38, 3.8, 7.8, and 24.7 mm/decade respectively.	[6]
1980–2020	Jemma	Spring P declined significantly by −1.08 to 2.25 mm; Summer P increased in 73 % of stations by +2.35–14.18 mm; Annual P increased by 5.76–19.80 mm.	[34]
1980–2019	BNB	A Positive trend in annual, dry, and small rainy seasons P in more than 54 % of the stations and a decline in the main rainy season in 64 % of the stations.	[35]

*P stands for precipitation; *T stands for mean temperature *T_{max} and T_{min} stand for maximum and minimum temperature; *BNB stands for Blue Nile Basin; *NRB for Nile River Basin; *N stands for North, *NC for north central,*E for east, *EC for East central,*SW for southwest.

there is an increase in rainfall with increasing elevation from north to south and from east to west, whereas areas on the windward side of high mountains receive higher rainfall than areas on the leeward side [12].

Many studies have been conducted to identify the trends of change in long-term precipitation in BNB. Though there is considerable variation within the basin among different climatic zones, some of the previous studies in BNB didn't find a significant trend of change in historical precipitation. For instance, studies such as [19,20,24] didn't find a significant trend of change in historical precipitation. However, some studies have found significant trends in the historical precipitation of BNB at different spatiotemporal scales. The study referenced as [26] reports a noteworthy negative trend in precipitation during the winter and spring months, as well as a significant increasing trend during the summer season, within the Gilgel Abbay watershed for the period spanning 1973 to 2005. Within the same sub-basin of Lake Tana, a study reported a significant decrease in annual precipitation across the majority of the area, while one out of ten stations showed a positive trend during the period from 1980 to 2015 [30]. Besides, a decline in spring precipitation and an increase in annual and summer precipitation were reported by Refs. [34,31] in the Jemma watershed.

The findings of the reviewed studies on the historical precipitation trend were heterogeneous, either decreasing/increasing or no change across time and seasons, depending on the studied watershed and study period. Considerable spatial and temporal variation in precipitation was seen within the basin (Table 1).

3.3. The driving factors of precipitation change

Many studies have made considerable attempts to understand the cause of rainfall variability over Ethiopian highlands. In reference [18], the authors pointed out that the changes that occur in the Pacific Ocean drive the decadal oscillations in climate variations and related changes in BNB. The study by Ref. [11] indicates El Niño event tends to decrease June–September rainfall but increases February to May rainfall, while the Lanina event has the opposite effect on upper BNB rainfall. El Nino-southern oscillation is identified as the main cause of below-average summer (June–September) rainfall over the BNB [6,7,11]. The occurrence of prolonged droughts within the BNB was found to be associated with the El Niño Southern Oscillation, as evidenced by low values of rainfall anomalies [6]. Additionally, a study referenced as [9] reported a drying trend in southwestern Ethiopia that is linked to warming in the Atlantic Ocean and the sea surface temperature gradient across the Western Pacific Ocean.

Numerous studies have endeavored to elucidate the underlying causes of changes in hydroclimate variability within the BNB. For example, a study referenced as [29] has established that multi-decadal changes in hydroclimate variability are governed by large-scale regional atmospheric forcing, temperature increases induced by global warming, and temperature-related extremes. Furthermore, the amplified influence of the Indian Ocean Dipole and El Niño, which affect hydroclimate variation across various scales, has been attributed to global warming in the region after the 1970s [7]. While most research output supports the premise that rainfall variability within the basin is contingent on various large-scale atmospheric circulation anomalies, local-scale variations exist due to the orographic effect of the basin's topography and elevation [12]. Ultimately, the root cause of the observed changes lies in alterations to the aforementioned driving factors [6,7].

3.4. Time-series analysis to investigate trends in hydroclimate variables

In the investigation of changes in hydro-climatic variables, time series analysis has emerged as an important tool. Among the various methods of trend analysis for climatic and hydrological time series data, the non-parametric trend test is the most commonly used. This method is preferred because it does not make any assumptions about the distribution of variables and is rank-based, which minimizes the impact on the results of trend analysis [26]. Many studies have employed the Man Kendal (MK) trend test, along with various statistical indices, to identify statistically significant changes and quantify the significance of trends in hydro-climatic time series data [17,24,26].

The non-parametric MK statistical trend test has undergone several improvements in recent years. The initial version determined the significance of trend changes, and the Sen Slope was added to quantify trend magnitude. The latest version accounts for long-term persistence (LTP) in time series. The utilization of improved statistical tools may impact the results of trend analysis. In a recent study cited as [29], the authors expressed concerns about the trend significance of previous hydro-climatic studies in the NRB due to LTP influences. To distinguish between unidirectional trends and natural climate variability, they utilized four versions of MK, including the latest one that considers LTP. They found that the latest version significantly reduced the number of grid points exhibiting a significant change in climate and weather extremes.

3.5. Observed hydroclimate extremes

Numerous efforts have been undertaken to comprehend the patterns and fluctuations of hydroclimate extremes. Recent observations of hydroclimate extremes in the region reveal an uptick in low flow extremes [18], an increase in the occurrence and severity of drought [8,9], a rise in the concentration of precipitation during the primary rainy season [6], and instances of flooding [8]. The investigation conducted by authors referenced as [18] analyzed the long-term historical trends of hydro-climatic extremes in the BNB from 1964 to 2009 using the quantile anomaly analysis (QPM) methodology. The findings do not indicate a consistent increase or decrease in rainfall and flow extremes. However, low flow extremes have increased, and there are noteworthy decadal variations.

The authors cited as [9] analyzed Ethiopia's extreme rainfall events from 1979 to 2014. The result for the area located in the northwestern BNB area shows frequent and more severe drought centered in 1983/1984 and becoming moderate in recent years. In the southwestern BNB, drought in the spring season has become more frequent and intense since 1977 [9]. Similarly, the study by Ref. [8]

for the period 1950–2019 found that the flood event and drought severity and frequency increased in NRB after 1988. Similarly [31], have indicated that climate extremes increased in intensity and frequency from 1981 to 2014 in the upper parts of the basin. In contrast [29], reported very few localized rainfall extremes and increases in temperature during 1948–2010.

The observed hydrological extremes can be explained by climate plus other watershed variables such as land use, topography, soil type, and land/water management practices [8,15,18]. Besides [36], have demonstrated the dependence of the occurrences of droughts and floods in upper catchments of BNB on the timing of El Nino and La Nina events by comparing the river discharge data and the two event indexes during 1965–2012. They concluded that there is a chance of 67 % occurrence of an extreme flood when the El Nino event is followed by the La Nina event, and 83 % of the El Nino events starting in April–June resulted in drought.

3.6. *Observed hydrological variability and changes*

A thorough understanding of the underlying causes of historical hydrological variability is crucial for effective watershed management in a changing environment. The BNB is experiencing rapid population growth, deforestation for agriculture, and altered water availability due to climate and land use/land cover (LULC) changes [4,13–15,26,37]. Despite limited hydrological data availability, several studies have reported hydrological variability and changes in the BNB. For example, a study by Ref. [38] found that the hydrology of the BNB in the 1960s exhibited diverse responses to watershed variables categorized into three groups: land use, climate and topography, and geology and soil types, among different watersheds.

The observed change in climate and LULC change have significantly affected the hydrology and water resource availability of the BNB since the 1970s. In the northern BNB Gilgel Abbay watershed [26], indicated that there was a change in streamflow derived by rainfall variation and LULC changes during 1973–2005. However, the effect of dry season rainfall variation on streamflow was minor because it is small ($<$10 mm) in amount. Based on the river discharge record of six stations from the upper catchments and one station downstream at El Diem station for the period 1964–2009 [39], showed the correlation of long-term high QDF (flow duration frequency) with climate oscillations. However, low-flow QDF shifts are influenced by climate and land/water management practices.

A reduction in natural vegetation cover in the Kasiry, Kecha, and Sahi watersheds and clearance of forest and shrubland in the Andasa watershed during 1981–2016 was observed [13,15,37]. This led to increased surface runoff and lowered dry season streamflow, indicating a dominant role of LULC change in the hydrological responses of the watersheds. However, some studies showed the significance of climate change impacts over LULC change impacts at the basin and watershed scale [14,39,40]. The observed correlation between rainfall and streamflow magnitude was not straightforward, suggesting the combined effects of climate and LULC changes on watershed characteristics [13–15,37].

Depending on the reviewed literature, it was difficult to make a general conclusion on the significance of the impacts of either climate or LULC change in the BNB deriving historical hydrological change. However, it is conclusive that the effects of LULC are dominant at smaller scales and on base flows [13,15,26,37,39]. Climate variation controls the basin's long-term annual flows and seasonal streamflow variation [11,14,39]. Besides, some studies at the basin scale agreed that the recently emerging hydroclimate changes of the basin are due to the influence of the drastic global climate change of the recent few decades [6,7,23].

3.7. *Advancement of hydroclimate studies*

The hydrological variables can be measured by collecting detailed information from the experimental watershed by available hydrological measurement techniques. Due to limited measurement techniques, resources, and heterogeneities in watershed characteristics, measurement of hydrological components at watersheds and basin-scale is difficult and not feasible [41]. Hydrological models fill the hydrological data gap through simulations of catchment processes from input data such as land use, soil, topography, and climatic variables. In BNB, hydrological models ranging from simple water budgets to conceptual rainfall-runoff models, semi-distributed and distributed physically-based models, have been applied to simulate hydrological components of watersheds. For instance Ref. [21], has used a distributed water and energy model (WEP) to estimate the water budget of upper BNB. The study by Ref. [11] used distributed and lumped hydrological models to evaluate climate anomaly impacts on BNB. Numerous studies have applied a semi-distributed hydrological model in the hydrological studies of the basin [14,25,26,42–45].

The majority of recent hydroclimate studies in BNB focused on the impact assessments of different environmental changes ranging from global climate change to local catchment scale LULC changes. For instance Ref. [26], applied Hydrologisca Byrans Vattenbalansavdelning (HBV) light hydrological model to study the impacts of LULC and rainfall variability in Upper Gilgel Abbay catchment streamflow [25,42]; have applied the soil and water assessment tool (SWAT) hydrological model in the UBNB and Jemma watersheds respectively for the impact assessment of climate change on hydrology [43]; applied the hydrologic engineering center hydrologic modeling system (HEC-HMS) rainfall-runoff model in the climate change impact study of the upper Didessa catchment.

Hydrological modeling has emerged as a useful tool to investigate the historical hydrological changes in watersheds and to simulate potential future changes in response to projected climatic and LULC changes. Numerous studies have applied hydrological modeling techniques to watersheds of the BNB, including [11,14,19,26,42,44,45]. However, the reliability and accuracy of the model output are contingent upon the quality of input variables. The limited and often low-quality observations pose a challenge to the performance of hydrological models, which impedes our ability to understand the hydrological variability of the basin. To successfully model watershed hydrology, it is imperative to have sufficient records of high-quality weather and hydrological data that can facilitate the calibration and validation of the hydrological components of the model.

Most of the recent studies that advanced the understanding of hydroclimate variability of the BNB over the past decade have used climatic data from climate reanalysis/remote sensing products. To mention some of them [11], have used ERA-40 reanalysis data [42];

have used Climate Forecast System Reanalysis (CFSR) data [33]; have applied remote sensing products temperature from INACTS and rainfall from CHIRPS-V2 [7]; have used climatic variables from 20th Century Reanalysis V2 dataset [8]; have applied GRACE/GRACE-FO climatic variables compared for precipitation with TRMM 3B43 product.

The advancement with remote sensing techniques enabled the understanding of long-term trends of hydroclimate variability hindered by short-term data availability. For example, the availability of long-term gridded monthly precipitation data from the Global Precipitation and Climate Centre (GPCC V7) and temperature from the Climate research unit (CRU TS 3.23) enabled the evaluation of a long-term trend of temperature and precipitation of the Woleka sub-basin of BNB during 1905–2014 [28]. Though there was advancement in using climate reanalysis/remote sensing products, the reliability of the study depends on the quantification of the uncertainty related to the data because satellite-based estimation may inherit bias in the region of complex topography like BNB.

Remotely sensed data-based hydrological data such as gridded global ET and soil moisture are a golden opportunity to retrieve from in situ hydrological data scarcity. Despite the data scarcity, a few studies have utilized remotely sensed data-based hydrological data such as ET and soil moisture from international remote sensing data archives. For instance Ref. [46], has used a remotely sensed ET data set, the Global and Evaporation Amsterdam Model (GLEAM), to study the changes in ET and its components over the NRB. Moreover, satellite image analysis was employed to detect historical LULC changes and helps in the studies of hydrological responses of

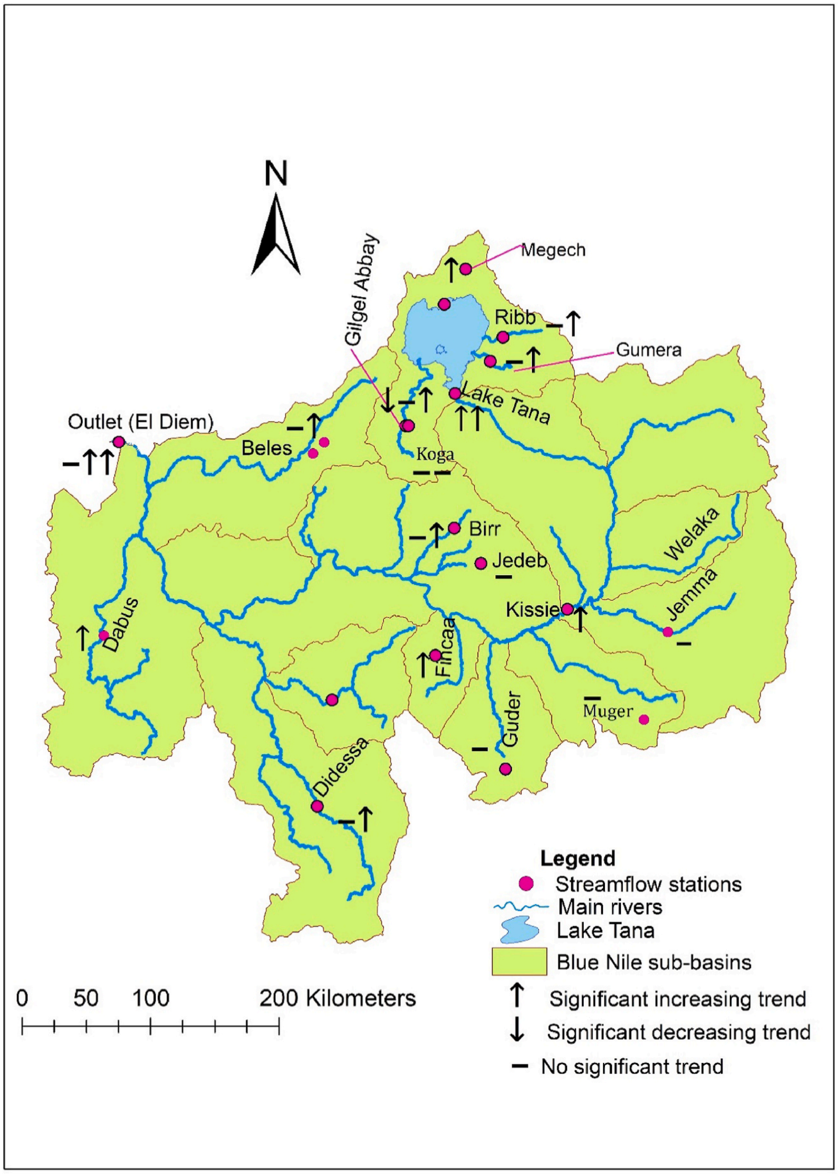

Fig. 3. The trends of historical streamflow volume mapped from the reviewed studies. The result for total annual flow was considered. The no of arrows and dash indicated the number of studies for a specific watershed/stream.

The trends of change in the historical streamflow at different locations within the basin mapped from the reviewed studies are displayed in Fig. 3.

watersheds to the changes [13,14,26]. To better describe the trends of change in BNB's watershed hydrology, Fig. 3 shows the conclusions of the evaluated research on trends of historical streamflow mapped by this study.

3.8. *Future temperature and precipitation projection*

To make projections of future climate variables, Global Climate Models (GCMs) employ scenarios of anticipated alterations in greenhouse gases and other radiative substances to estimate physical modifications in the atmosphere and oceans. The World Climate Research Program's (WCRP) Coupled Model Inter-comparison Project (CMIP) phases 3 and 5 have been widely used to project future temperature and precipitation across the twenty-first century. However, the challenge of utilizing GCMs for studies at the basin scale arises from their poor performance in projecting climatic variables within the context of the science of the global climate system. This is especially common in regions with complex topography due to the influence of multiple local factors on regional hydro-climatic diversity. BNB is among such regions where the confidence in the projected precipitation is low in the high land area of the basin, as demonstrated by previous studies [44,47].

Several tools with dynamical or statistical downscaling methodologies were developed and used to project future climate change from multiple GCMs at various scales. In BNB, many studies have used statistically or dynamically downscaled GCM data to predict temperature and precipitation in the twenty-first century. Authors referenced as [44,48] have applied statistical downscaling techniques from single GCMs. Different regional climate models under the coordinated regional climate downscaling experiment (CORDEX) initiative have played a substantial role in the dynamical downscaling of the GCMs output. Studies such as [19,33,45,49] have used dynamically downscaled multiple GCMs outputs embedded in different RCMs and the ensemble means of several GCMs outputs.

Despite some variations in the output of GCMs, the prevailing consensus in the literature is that temperature in the BNB will rise in response to various Representative Concentration Pathways (RCPs) and Special Reports on Emissions Scenarios (SRES) scenarios.

Table 2
Summary of research findings on projected hydroclimate variation and change in the BNB.

Data period	Basin	Scenario	The main findings	Refer.
1952–2004 2050–2100	BNB	SRES	Annual P will significantly change by +6 % to +130 in SW to +70 mm towards North	[48]
1990–2001 2010–2040 2070–2100	Gilgel Abbay	SRES A2a, B2a	The monthly variations in T, P, and Q will be +2.5 to +5 °C, −30 to > +30 %, and −46 to +135 %, respectively. Q will rise by +35 % & +135 % in spring &summer.	[40]
1991–2000 2031–2040 2091–2100	Arjo Didesa	SRES A1b	(T, P & Q) will significantly change by (+0.4 to +1.86 °C, +33.22 % & +157 %) and (+1.96 to +4.91^{0}c, +8.4 % & +136 %) in 2030s and 2090s respectively	[50]
1988–2005 2035–2100	Tana	RCPs 4.5,8.5	From 2030s to 2070s, annual P and Q will vary by +35.4 to +74.7 % and −12.2 to +127.4 %, respectively.	[49]
1993–2012 2021–2040 2081–2100	Gilgel Abbay	RCPs 4.5,8.5	T will vary by +1.6 to +4 °C, decline in P, ET & Q by (−4 to −25, −23 & −24) % in the dry season, & rise by (+5 to +23, +6 to +19 & +18)% in the wet season	[45]
1986–2000 2041–2070	BNB	RCP 4.5	T & P varied by +0.98 to +1.39 & −2.8 to +2.7 %; annual ET & Q will vary by + 3–7 % & - 1 to 3 %	[51]
1979–2013 2046–2064 2081–2099	BNB	SRES A1b	T is likely to vary by +2 °C (10.3 %) to +3.7 °C (18.7 %); P & Q will change by (+7 % to + 48 %) & (+21 % to +97 %) with a strong seasonal shift.	[42]
1961–1990 2020–2100	Beles	SRES A2, B2	T_{max} & T_{min} will increase by 3.6 & 2.4 °C, PET will rise by 7.8 %, & Q will significantly fluctuate in the dry/wet season.	[52]
1970–1999 2030–2099	BNB	RCPs 4.5,8.5	P varied by +5 to +15.6 %; no change in ET up to 2150s; increase in annual ET & Q after 2050s.	[47]
2006–2015 2050s	Didesa	RCP 4.5, 8.5	The annual rate of change for T will be +0.02 to +0.06, with annual and spring P decreasing and summer P increasing.	[33]
1986–2015 2021–2080	Fincaa	RCPs/ LULC	A significant change in P and Q by −7.87 to −11.32 % and −1.79 to −9.09 %, respectively.	[53]
1983–2013 2021–2100	Jemma	RCPs	P will decline by (−19 % to −23 %); Q decline by −65 % near-term; increase in ET, GW, and water yield	[25]
1971–2000 2041–2070	Arjo Didesa	RCPs 4.5,8.5	Decline in annual P by -(0.36 to 21)%; increase in ET by +(3–7)%; annual Q will vary by –(1 to 3)%	[43]
1981–2010 2011–2100	Lake Tana	RCPs 4.5,8.5	T_{max} & T_{min} will increase by +2.14 &+3.2 °C; P, ET & Q by +25 %, +55.5 % & +26.4 % respectively.	[44]
1981–2010 2010–2099	BNB	RCPs 4.5,8.5	Annual P will vary by −10.8 % to −19 %; Q will change by −0.4 to 14 %; +27 % increase in PET	[54]
1981–2010 2031–2100	BNB	SSPs	T will warm by 1.1–3.8 °C; an insignificant increase in P within a rate of 5.9–17.7 mm under four SSPs.	[55]
1986–2015 2041–2100	SW Ethiopia	RCPs	T increased by +1.2 °C; Slight increase in P	[56]

In the data period column, the years written in bold are the base period of the studies, *T stands for temperature, *P stands for precipitation, *Q represents river discharge (streamflow), *ET represents evapotranspiration, *BNB stands for Blue Nile Basin, SW for southwest & CC for climate change.

However, discrepancies in the predicted trends of precipitation change have been observed (Table 2). For example, a study by Ref. [49] showed that precipitation would increase in the spring and summer seasons in the Lake Tana basin. Similarly [44], reported a 25 % increase in precipitation with unsatisfactory model performance in the same basin. In contrast [45], found that summer rainfall would increase while spring season rainfall would decrease in the Gilgel Abbay catchment in the Lake Tana basin. The projected changes in seasonal variation of precipitation in the BNB also vary. For example [42], reported significant seasonal change under the SRES A1B scenario using CMIP3, whereas [25] concluded that there would be no seasonal shift in rainfall using bias-corrected CMIP 5 RCPs scenarios in the Jemma watershed.

In the southwestern area of the BNB, a study by Ref. [33] has projected an increase in precipitation with seasonal shifts using an ensemble mean of 5 GCM outputs in the Didessa river basin [33]. A contrasting result was found in the watershed by Ref. [43]. By using bias-corrected 4 RCM output under scenarios RCP 4.5 and 8.5, they have predicted decreasing trends in precipitation. A similar trend was projected by Ref. [53] in the Fincaa watershed, one of the catchments in the southwest of the basin, by utilizing the ensemble mean of four RCM outputs. By using CMIP-6 SSPs scenarios from selected best-performing single climate model output [55], found the same trend with previous studies for temperature and a statistically insignificant increasing trend for precipitation of BNB. The selected best-performing model was the ERA 5 for temperature and BCC-CSM-2MR for precipitation projection. Table 2 summarizes the findings of the selected research on projected temperature and precipitation changes along with projected hydrological changes.

3.9. Role of multiple climate models group in reducing uncertainties

Different climate model groups have participated in climate prediction in different CMIP phases. CMIP 3 has participated in the IPCC's fourth assessment report (AR4). Further simulations were conducted by CMIP 5 for IPCC's fifth assessment reports (AR5). CMIP models have been advanced over the years to address the uncertainties associated with climate models. There were some advancements in CMIP 5 over CMIP 3. Thus, CMIP 5 can minimize climate prediction uncertainties inherited in CMIP 3. Some of the advancements in the CMIP 5 model include the use of radiative forcing scenarios RCPs, the inclusion of land cover change impacts, and essential biogeochemical processes [2]. Depending on CMIP 3 and CMIP 5 climate change predictions, there were general agreements among research output on the trends of change in the future temperature in the BNB. Numerous researchers have agreed that the climate of the basin is warming [19,29,33,40,49,50,52,53]. The magnitude of future temperature change predicted by RCP scenarios was not as large as that predicted by SRES scenarios [51].

In BNB, the main challenge of climate prediction with GCMS in CMIP 3 was the uncertainty of the direction of future change in precipitation [5,42]. To minimize climate model uncertainty, the IPCC (2014) recommends the use of large ensembles of different GCMs' climate change scenarios. However, using many climate change scenarios and statistical downscaling models is excessively time-consuming. Thus, studies have used either one or ensemble mean of a few GCMs with bias correction [44,48]. Though there were inconsistencies among different climate models, there were improvements with CMIP 5 in predicting future precipitation under greenhouse forcing in the BNB. To optimize the performance of the prediction, the majority of the recent studies have applied the ensemble mean of different numbers of GCM outputs nested in different RCMs [19,25,33,43,45,49,53]. Studies have evaluated the performance of different GCMs and provided information on the list of several best-performing GCM models in the basin to minimize the uncertainties associated with GCM selection. For instance Ref. [57], evaluated 105 GCMs for RCP 4.5 and 78 GCMs for RCP 8.5 based on the past climate of 1971–2000 and finally chose the five best-performing models for each scenario.

The most recent CMIP phase CMIP 6 model has a relatively high resolution expected to minimize the uncertainty in the previous phases of CMIPs. The model has updated experiments, concentration, land uses, and emissions scenarios of shared socio-economic pathways (SSPs). The attempts to evaluate past and future climate trends of BNB under CMIP 6 scenarios were made by authors referenced in Ref. [55]. The predicted trend was not different from that obtained by previous phases of CMIPs for temperature. The predicted precipitation didn't show a significant trend. However, the available literature was not enough for comparative evaluations. The projection of hydrological change at a different scale in BNB under SSPs needs future development.

3.10. Hydrological projections and climate change impacts

Future projections of hydrological change have been conducted by predicting climate change across the 21st century and inputting predicted climatic variables into the hydrological models. Historical hydroclimate data, GCMs outputs, and diverse hydrological models served as the main tools in projecting future changes. The obtained trends of change in streamflow are not different from the trends of predicted precipitation in several studies [42,45,49,50]. However, the magnitude of the projected change in precipitation and the projected streamflow was not straightforward due to the influence of the non-climatic watershed variable. Besides, the precipitation from GCM output was associated with a large prediction bias, especially over highlands [47]. Thus, the projected streamflow inherits uncertainty from climate models. With the climate model predicted precipitation, the certainty of future changes in streamflow highly depends on the choice of climate models [5].

By integrating the use of downscaling and various bias correction techniques on climate model projection with the hydrological model, studies have attempted to project future hydrological changes in the BNB at various scales. However, the trends of predicted streamflow varied considerably among studies and across watersheds, as evidenced by Table 2. Notably, the impact of climate change on BNB water resources was more pronounced when using SRES scenarios compared to RCPs, as highlighted by authors of the studies referenced [18,40,42,44]. Some studies have also sought to evaluate future hydrological changes by considering both climate and land use/land cover (LULC) changes. For example, the study cited as [44] investigated the combined impact of climate and LULC changes in the Lake Tana basin, while [53] examined such impacts in the Fincaa watershed. Interestingly, the results indicated that the impact of climate change was higher than that of combined climate and LULC impacts or LULC-only impacts.

4. Conclusions and Recommendations

4.1. Conclusions

The present review study has acknowledged the escalation in the number and sophistication of hydro-climate investigations, the endeavors to grasp past hydro-climate fluctuation, current advancements, and the forecasted alterations in the BNB over the past few decades. Time series analysis, encompassing historical archives or model results, has served as the basis for scrutinizing hydroclimate variation and change. The quality of historical data, the shortage of data availability, and the paucity of the hydro-meteorological network were recognized as principal impediments to understanding hydroclimate variability and alterations in the BNB from a long-term perspective. Conversely, notable progress has been made in utilizing hydrological modeling and reanalysis/remote sensing products to surmount the difficulties presented by historic hydroclimate data.

BNB is experiencing spatially and temporally varied warming, with most areas showing an increase in temperature at a rate ranging from +0.046 to +1.08 °C/decade. Historical precipitation trends are heterogeneous, with some areas showing a decrease or increase, while others show no change over time and seasons. Recent studies suggest that spring rainfall is fluctuating and impacting crop production and socio-economy. Streamflow variability indicates hydrological changes in BNB, with significant spatial variation among watersheds. Climate and LULC changes influence streamflow variation, with LULC effects predominant at small scales and on base flows. Long-term annual flows and seasonal variations are primarily controlled by climate variation. However, some watersheds did not fully address the hydrological impacts of climate and LULC change at the watershed scale.

Although the CMIP3 and CMIP5 models had low accuracy in predicting precipitation, a consensus was reached in the literature on the hydroclimate of BNB that temperature will continue to rise in the 21st century. The major challenge in climate prediction for BNB was uncertainty in the direction of future change in precipitation. However, the development of bias correction techniques, downscaling, and improvements in CMIP5 have led to improvements in the projection of precipitation under greenhouse forcing. Although some CMIP5 models still present inconsistent findings regarding the projected direction of change in BNB rainfall, researchers have resolved the issue by considering the ensemble mean of a few GCMs/RCMs outputs. Numerous studies demonstrate that most GCM/RCM outputs show the same direction of change as the ensemble mean of several GCM/RCM outputs in several studies despite some exceptional CMIP5 models producing contradictory results regarding the direction of future rainfall change [19,25,43,45,49,53,54].

This study noticed that spring season rainfall variation is a continuation of the recently progressing observed change in the basin. However, there is disagreement on the general direction of change in annual and summer precipitation (Table 2). The disputing results are due to GCMs' ability to capture the region's natural climate variability due to coarse resolution, the different scenarios, downscaling techniques, and different quality of historical data. Studies agreed on future ET trends, but there are discrepancies among studies on the projected streamflow change. The projected direction of change was related to the projected precipitation, and it was not straightforward in some studies. Identifying effective adaptation and mitigation strategies is crucial for sustainable water management in the basin.

4.2. Recommendations

To enhance knowledge of hydroclimate variability in the BNB, we recommend continuing hydroclimate studies using recent remote sensing data archives by quantifying related bias at the required scale. For the rivers passing through narrow banks and valleys with sparse streamflow gauging networks like BNB, we suggest using remotely sensed gridded evapotranspiration and soil moisture data to improve hydrological modeling output. Short-term field data collection can also help reduce uncertainty. To reduce uncertainties in future climate projections, we suggest improving GCM output by establishing good-quality historical data, using suitable downscaling and bias correction methods, and developing methodologies for downscaling CMIP 6 models at an appropriate resolution.

Data availability statement

Data included in article/supplementary material/referenced in article.

No additional information is available for this paper.

CRediT authorship contribution statement

Obsinet Abebe Wedajo: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Fekadu Fufa:** Writing – review & editing, Validation, Supervision, Conceptualization. **Tenalem Ayenew:** Visualization, Validation, Writing – review & editing. **Dessie Nedaw:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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