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Understanding flood and drought extremes under a changing climate in the Blue Nile Basin: A review

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ABSTRACT

Extreme flood and drought events arise from temporal and spatial variations in the Earth's water cycle, significantly affecting water resources and the environment. This review aimed to evaluate the effects of climate variabilities on extreme flood and drought events within the Blue Nile Basin. A systematic literature review and content analysis were conducted to understand the hydrological dynamics of floods and droughts. A Scopus database was used to find relevant literature review articles related to flood and drought extreme events using search terms queries. The findings suggest that rising temperatures and fluctuating precipitation patterns are leading to more frequent and severe floods and droughts. Future projections also suggest increased drought severity in most basin areas, coupled with more frequent floods. Fluctuations between dry and wet conditions have intensified these extremes. While insufficient rainfall triggers droughts, excessive and concentrated rainfall contributes to floods. The wet projection shows more frequent floods, while the dry projection indicates severe droughts throughout most of the basin. This review provides a valuable starting point for further action towards a more climate-resilient and water-secure for sustainable environmental development and management over the basin.

1. Introduction

The Blue Nile River Basin (BNRB) is a vital water resource shared by Ethiopia and Sudan (Taye et al., 2015). The basin plays a crucial role in sustaining life and livelihoods in northwestern Ethiopia. The Blue Nile River is the largest contributor to the Nile River, providing approximately 60% of its annual flow (Senay et al., 2014). BNRB is a critical freshwater resource, significantly influencing global water resource patterns due to its substantial contribution to the Nile River's flow and its role in regional hydrology. Its contribution is significantly influencing hydrology, climate, water management, agriculture, energy production, and ecosystem health in the region (Ingrao et al., 2023;

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Tariku et al., 2021). The basin generates about 50 billion cubic meters of water annually at the Ethio-Sudan border (Abtew and Dessu, 2019), and It is the principal tributary of the Nile, providing 62% of the flow reaching Aswan, Egypt (Awulachew et al., 2011). The resource also sustains millions of people in Ethiopia, Egypt, and Sudan and supports agriculture and hydropower production. However, the basin is vulnerable to flood and drought extremes (hydrological extremes), including devastating floods and crippling droughts, which have been exacerbated by climate change (Taye et al., 2015). The basin experienced significant seasonal rainfall that caused damaging floods in the downstream area, as well as variations in rainfall that led to periods of drought that could hurt livelihoods and agricultural output (Tenagashaw and Andualem, 2022; Zaroug et al., 2014). Climate variability aggravates these extremes, potentially leading to more frequent and intense hydrological extremes (Lazin et al., 2023; Tedla et al., 2022a). The effect of climate change also threatens the livelihood of indigenous communities living in fragile ecosystems (Hazarika et al., 2024). Rangeland degradation is a major issue for Ethiopian pastoralists as a result of climate change and other related environmental issues (Daba and Mammo, 2024). The improved forecasting of floods and droughts is crucial for mitigating the impact of these extremes and ensuring the sustainable use of environments in the basin.

The BNB water resource is unevenly distributed and fluctuates significantly throughout the year, impacting agriculture, food security, and international relations. The basin's predictable water flow is essential for irrigating vast swathes of land, ensuring agricultural productivity and food security for millions (Yenehun et al., 2021). The basin experiences significant seasonal and annual fluctuations in water availability. While the basin boasts a high average flow due to Ethiopian highlands rainfall (Yenehun et al., 2021), significant variations occurred spatially and temporally (Abate et al., 2015). High and low flow occur during the rainy and dry seasons, respectively in the basin (McCartney et al., 2013). The distribution of water resources within the BNB is highly uneven; specifically, the upper parts of the basin have abundant water resources compared to the lower region. Lake Tana, the source of the BNB, plays a crucial role in regulating the water resource flow. However, evaporation from the lake has a significant, impact on downstream water availability (Yenehun et al., 2021). However, balancing the needs of these countries for agriculture, hydropower, and drinking water is a major challenge (Whittington et al., 2005). Climate change projections suggest potential alterations in rainfall patterns within the basin, potentially impacting the Blue Nile's long-term water availability (Abate et al., 2015).

Flood and drought extremes encompass natural events that significantly alter the water resources of a basin (Wang et al., 2022). Natural and human systems may suffer as a result of the increased frequency and intensity of these events brought on by climate change (Kassaye et al., 2024; Malede et al., 2024). Floods cause loss of life, property damage, disruption of infrastructure and economic activity (Wang et al., 2022). Furthermore, floods can contaminate freshwater supplies and accelerate soil erosion (Spalevic et al., 2020). In contrast, droughts lead to water scarcity, impacting agriculture, hydropower generation, and ecosystems (Kassaye et al., 2024). Droughts can also exacerbate desertification and the risk of wildfires (Di Baldassarre et al., 2016). The frequency, intensity, and duration of flood and drought events are driven by variations in climate, human interventions, and atmospheric conditions (Ekolu et al., 2022; Kassaye et al., 2024). Rapid water level increases due to heavy precipitation, leading to land inundation, population displacement, and infrastructure damage (Zaroug et al., 2014), while, extended periods with below-average rainfall, result in water scarcity, crop failure, and food insecurity. As the climate continues to change, understanding and managing flood and drought events will be critical for ensuring the sustainability of our water resources and societies (Brunner et al., 2021; Marengo and Espinoza, 2016). Previous studies have shown that under a warming scenario, around 37% of global land areas will experience an increase in flood intensity, whereas 43% will experience an increased drought intensity in the 21st century (Matano et al., 2023). About 10% of the world, which is highly populated, faces the risk of experiencing simultaneous increases in the frequency of both floods and droughts (Asadieh and Krakauer, 2017). These hydrological extremes directly and indirectly impact humans, including displacement and emerging refugee crises (Güneralp et al., 2015).

Despite the interconnectedness of floods and droughts, they have traditionally been studied and managed separately. However, a comprehensive understanding of both events is crucial for developing effective adaptation and management strategies. For example, a severe drought can lead to drier soils that are less able to absorb heavy rainfall, potentially causing worse floods. Thus, research is needed to develop integrated flood-drought management strategies that consider both events together (Fasihi et al., 2021). Additionally, little is known about how climate change affects the frequency and severity of floods and droughts extremes. A more comprehensive understanding of how factors like rising temperatures and changing precipitation patterns will specifically affect flood and drought events in the BNB is needed (Gelete et al., 2020). There might be a need for improved current methods to assess and predict droughts specific to the BNB's hydrological conditions (Ali et al., 2019). Therefore, evaluating the patterns and causes of flood and drought events is essential for overseeing the water resources throughout the entire Nile basin (Malede et al., 2022; Setegn et al., 2014). Furthermore, the basin is critical to the agricultural sectors of Ethiopia and Sudan since it supports irrigation and provides water for crop development (Awulachew et al., 2013). However, during the rainy season, soil erosion occurs in hilly regions, leading to loss of agricultural production and excessive sediments (Spalevic et al., 2020). Integrated water resources management among the shared countries requires a thorough understanding of flood and drought events (Davis, 2007).

The purpose of this review is to understand how a changing climate influences flood and drought extreme events in the BNB. Water security in the basin is seriously threatened by climate change. Hence, reviewing the impact of past and projected climate changes on flood and drought extreme events helps us to understand the evolving risks (McCartney et al., 2013). In this review, the consistency and discrepancies of research findings in flood and drought extremes have been addressed and examined. Reviewing existing studies into flood and drought extremes in the BNB helps to identify areas where further investigation is needed to improve our understanding and predictive capabilities. Therefore, the objective of this review is to assess the impacts of climate change on flood and drought extremes in the BNB by examining past and projected changes, identifying knowledge gaps, and informing policymakers and the sustainable development of effective adaptation strategies. This involves reviewing how rising temperatures, shifting rainfall patterns, and erratic weather events are influencing the frequency and intensity of floods and droughts spatially and temporarily. By understanding the evolving risks posed by a warming climate, researchers and policymakers can work together to build resilience and ensure the sustainable development and management of this vital water resource.

2. Description of the Blue Nile Basin

The BNB is a critical hydrological system situated in the northwestern Ethiopian plateau. As the most substantial tributary of the Nile River, it contributes approximately 60% of the river's total flow and covers an expansive area of around 176,000 km^2 (Samy et al., 2019). The BNB comes from Lake Tana, which is located between elevation ranges dramatically from 4023 m in the Ethiopian highlands to 382 m near the Sudanese border (Fig. 1). The headwaters of the Blue Nile River start at Lake Tana, which is in Ethiopia (Mohamed et al., 2022). Originating from Lake Tana in Ethiopia, the Blue Nile traverses through a series of gorges and rapids before joining the White Nile at Khartoum, Sudan, to form the main Nile River. Geographically, the BNB spans latitudes 7°0.71′N to 16°0.01′N and longitudes 32°0.40′E to 39°0.81′E (Fig. 1). The geography of the basin is varied, with hills located in the

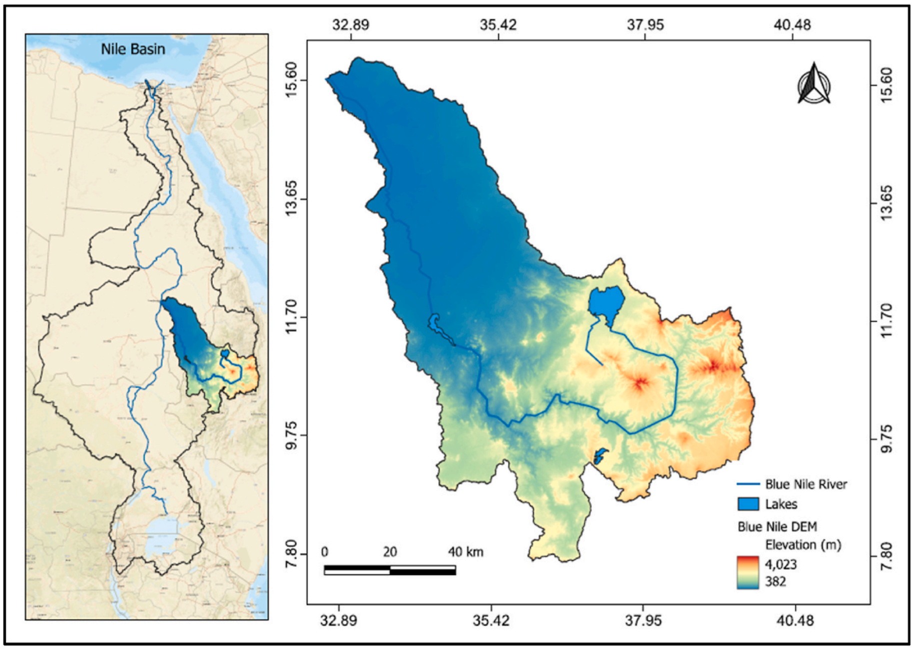

Fig. 1. Location of Blue Nile Basin showing elevation difference, Blue Nile River and Lakes.

northern section and lowlands in the western and southern sections (Gebremicael et al., 2013).

The BNB experiences a distinct wet and dry season pattern (Ali et al., 2022). The primary rainy season occurs from June to September, contributing the majority of annual rainfall (Samy et al., 2019). Between March and May, there could be a short rainy season. The dry season typically spans from October to February, characterized by minimal precipitation. Rainfall distribution is uneven across the basin, with the southern highlands receiving over 2000 mm annually, while the northeastern regions experience significantly less rainfall, averaging around 800 mm. This creates a gradient of precipitation within the basin (Setegn et al., 2011). Global climate patterns like ENSO significantly impact rainfall in the Blue Nile. El Niño events tend to suppress rainfall, leading to drier conditions. Conversely, La Niña events can sometimes bring increased precipitation (Samy et al., 2019).

The basin's hydrology is highly dynamic, influenced by factors such as topography, rainfall patterns, and global climate phenomena like El Niño-Southern Oscillation (ENSO) (Hurni, 2010). The steep terrain and intense rainfall during the monsoon season make the BNB prone to flash floods. There has been a recent increase in the frequency and size of both droughts and floods in the BNB (El-Mahdy et al., 2021). Additionally, prolonged droughts have increased in frequency, negatively impacting the agricultural system (Mohamed et al., 2022). The basin also experienced three extreme major floods in 1988, 2006, and 2007, which were caused by complex, and heavy rainfall factors (Gelete et al., 2020). These climatic and hydrological characteristics underscore the BNB's vulnerability to hydrological extremes, making it a crucial region for studying the impacts of climate change on water resources.

3. Methods and data

A comprehensive systematic review and content analysis approach was employed to gather and analyze existing research on flood and drought extreme events within the BNB. Based on systematic review and content analysis (Ioana-Toroimac, 2018; Khirfan et al., 2020), we could extract and analyze information from a wide range of published articles. This methodology has been successfully applied in previous studies (Brunner et al., 2021; Hasan et al., 2018; Malede et al., 2022). Scopus is a comprehensive database encompassing a vast array of peer-reviewed literature, we acknowledge the possibility of missing relevant publications from other sources. To ensure a comprehensive literature review, we initially conducted preliminary searches in Google Scholar and Web of Science. Our findings indicated that a significant portion of the most relevant and impactful literature was readily available within the Scopus database. The Scopus database was queried using a combination of keywords related to floods, droughts, and the Blue Nile Basin (*TITLE-ABS-KEY((flood) OR (inundation) OR (overflow) OR ("hydrological extremes") OR (drought) OR (" dry period") OR (" shortage of water") AND ("Blue Nile " OR "upper Blue Nile " OR "Abbay " OR "Abay" OR "Nile"))*. This search initially obtained 2248 publications, including book chapters, research articles, review articles, and conference abstracts. The relevant information (authors, title, source, publication year, affiliation, abstract, keywords, and document type) was extracted into a CSV format.

After thoroughly reviewing publication titles, abstracts, and full text, we excluded irrelevant materials, such as studies undertaken outside of the basin and materials unrelated to flood and drought hydrological extremes, had no obvious link to the hydrological effects of floods and droughts, and concentrated on the non-hydrological effects of floods and droughts. This evaluation, which focused on observed hydrological extremes, excluded studies that did not have a connection to observed data or particular conditions within the BNRB, or those were grey literature or publications with insufficient peer review or methodological depth. In addition, the analysis did not include publications produced in languages other than English.

Fig. 2 shows the steps involved in searching for relevant articles in the database. The flowchart starts with an initial search in the database, which yields 1248 articles. Then, articles are excluded based on predefined screening criteria, including duplicates, old literature, language, and document type. This reduces the number of articles to 783. After this initial filtering, a further 243 articles are excluded due to a lack of information. Then, an additional 17 articles are removed because they have inadequate details regarding the methods used in the studies. Finally, the process concludes with 205 articles selected for detailed analysis. In addition to the database search methods, we also employed the "snowball" strategy, known for its effectiveness, to uncover additional literature. This strategy involves searching reference lists of existing research papers to identify new relevant sources and exploring

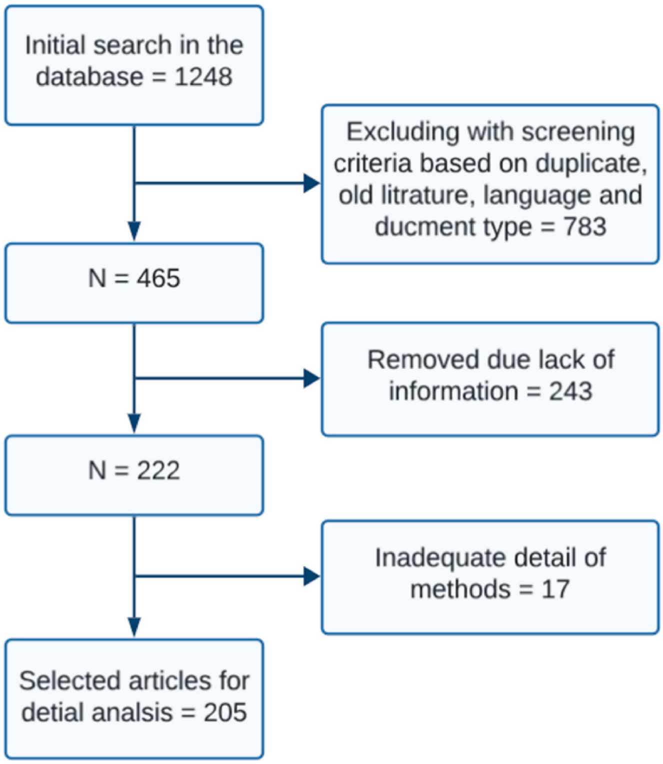

Fig. 2. Flowchart of the selected papers, where N stands for the number of articles.

papers that cite the paper under study (Vassar et al., 2016).

4. Publication trends and distribution

The publication trend and distribution in the BNB regarding flooding and drought extreme events are becoming more frequent. Fig. 3 illustrates the distribution of relevant articles recovered during 1990–2023, focusing on flood and drought extremes. There are vertical bars for each year between 1990 and 2023. The height of each bar represents the number of articles published in that year. Before 2010, the annual publication count for articles in this field was less than five. However, after 2010, there was a significant increasing trend in published articles, with the most articles published in 2019. There is a slight decrease in the number of articles published in 2023 compared to 2020. The number of articles published has increased recently, reaching about 20 articles per year. The increase in publications is attributed to the expansion of higher education, graduate program requirements for publication, and the rising frequency of flood and drought events (Taye et al., 2023).

Table 1 shows the main journal sources along with frequently used keywords that appear in articles from various sources. The most frequent word is “Drought” which appears 80 times in articles from the Journal of Hydrology and Earth System Sciences, which contributed the highest number of publications. Other frequent words are “Climate change” (62 times), “Nile basin” (59 times), “Runoff” (40 times), “Blue Nile basin” (39 times), “Rivers” (38 times), “Rain” (35 times), “Nile River” (31 times), “Hydrology” (30 times), and “Floods” (28 times).

The sources of journals listed in the table include Hydrology and Earth System Sciences the first, the Journal of Hydrology second, Water (Switzerland) third, Extreme Hydrology and Climate Variability:

Table 1
Most relevant sources and frequent words.

Words	Occurrences	Sources	Articles
Drought	80	Hydrology and Earth System Sciences	14
Climate change	62	Journal of Hydrology	9
Nile basin	59	Water (Switzerland)	8
Runoff	40	Extreme Hydrology and Climate Variability: Monitoring, Modelling, Adaptation and Mitigation	5
Blue Nile basin	39	Advances in Meteorology	4
Rivers	38	Hydrological Processes	8
Rain	35	Quaternary Science Reviews	6
Nile river	31	Science of the Total Environment	5
Hydrology	30	El Nino: Historical and Paleoclimatic Aspects of the Southern Oscillation	5
Floods	28	Heliyon	5

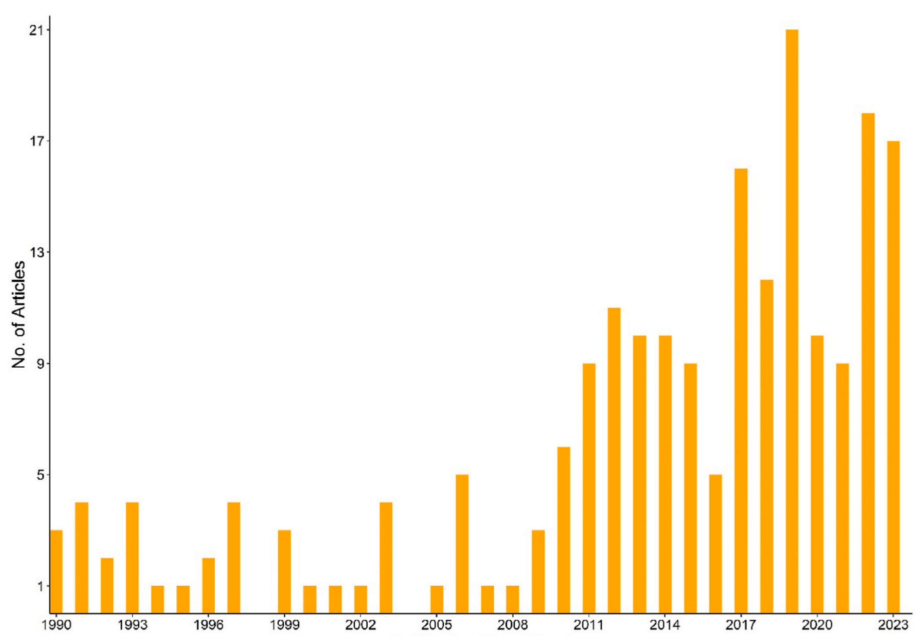

Fig. 3. The overall distribution of publications that were reviewed between 1990 and 2023.

Monitoring, Modelling, Adaptation and Mitigation fourth, Advances in Meteorology fifth, Hydrological Processes Sith, Quaternary Science Reviews seventh, and Science of the Total Environment eighth, and Heliyon ninth. This demonstrated that the majority of publications related to floods and droughts were published in hydrology and water-related journals. Fig. 4 demonstrates the Bibliometric analysis of collected published articles using keywords that provide for various routines from the Scopus database.

Table 2 displays the number of articles published by the five different publishers. It showed the majority of the articles used in the review were published by Elsevier, Springer, or MDPI. These three publishers contributed 84% of the articles used in the review. Elsevier provided 37% of the published works, while Springer and MDPI contributed 27% and 19% respectively (Table 2).

A co-occurrence plot of flood and drought information from 1990 to 2013 is displayed in Fig. 4 of the BNB. An "open-source bibliometrix R-package" program or software was utilized to map and evaluate Fig. 4, which created using the chosen literature associated with the studies of theme keywords (Aria and Cuccurullo, 2017). Bibliometrix is an open-source R-package designed for comprehensive bibliometric analyses, supporting a recommended workflow for science mapping. It facilitates data loading, analysis, and visualization, integrating effectively with other R-packages, and making it adaptable for evolving bibliometric needs. The plots are visualizations of how often words or phrases appear together or interrelated. For instance, precipitation affects how much water is in the BNB. Climate can affect precipitation patterns, which can in turn affect runoff and food security. It also helps researchers see how the frequency of these terms changed together throughout the research period (1990–2023).

Table 2
Distribution of articles based on most publishers.

Publisher	Number of articles	Percentage (%)
Elsevier	35	37.2
Springer	26	27.7
MDPI	18	19.2
Talor and Fransis	9	9.6
Copernicus	6	6.4
Total	94	100

5. Climate change trends in the Blue Nile Basin

5.1. Historical precipitation and temperature changes

Temperature and precipitation patterns in the BNB have changed significantly during the past century. For instance, a study by Mohamed and El-Mahdy (2021) showed that during the 68-year study period, there has been an increase in the BNB's maximum and minimum temperatures. It was discovered that the minimum and maximum temperatures increased by 0.037 and 0.025 °C per ten years, respectively. Furthermore, a study conducted from 1981 to 2010 found that maximum temperatures grew by 0.1 °C every decade, while minimum temperatures rose at a pace of 0.15 °C per decade (Mengistu et al., 2014). The annual and seasonal maximum and minimum temperature extreme indices showed a warming trend (Ali et al., 2022). Historical temperature findings highlight a consistent increase across various studies in the BNB.

Historical rainfall changes in the BNB reveal significant variability and trends. Some areas experience increasing rainfall patterns, while others face a decreasing trend. For example, a study by Mohamed et al. (2022) revealed that long-term investigations conducted between 1950 and 2018 revealed a notable decrease in seasonal and annual rainfall, especially during the Kiremt (rainy) season, with the frequency of drought events increasing. Additionally, analyses from 1981 to 2018 corroborate the above findings, indicating high inter-annual variability and a slight overall increase in annual rainfall, although winter rainfall trends are decreasing (Ayehu et al., 2021). Samy et al. (2019) also find a significant increasing trend in annual rainfall in the basin's eastern area and a significant decrease in the southwestern part. Overall, historical rainfall collectively highlights the complex interaction of increasing extreme rainfall events and decreasing seasonal averages in the basin. Table 3 presents a compilation of studies investigating historical rainfall and temperature trends in the BNB. The table summarizes key findings from different research projects conducted in various parts. In general, the majority of research shows that the BNB is clearly trending upward in terms of both maximum and lowest temperatures. Rainfall patterns are inconsistent, some studies show increasing rainfall, while others report decreasing trends or high variability.

5.2. Projected precipitation and temperature changes

The future of the BNB's climate is uncertain, but projections point towards a trend of increasing temperatures and changes in precipitation patterns (Getachew and Manjunatha, 2021; Mohamed et al., 2022). Many studies predict that temperatures will rise across the basin (Mengistu et al., 2021; Takele et al., 2022; Wedajo et al., 2024). For example, a study by Worqlul et al. (2018) forecasts that the minimum and maximum temperatures will increase by 3.6 °C and 2.4 °C, respectively, by the end of the twenty-first century. In a similar vein, Chakilu et al. (2023) recorded the greatest monthly temperature variation in the 2080s, with maximum temperatures varying from 2.93 °C to 5.17 °C. The minimum temperature also will increase by 4.75 °C in the 2080s, with a more significant trend. Both RCP 4.5 and RCP 8.5 scenarios show

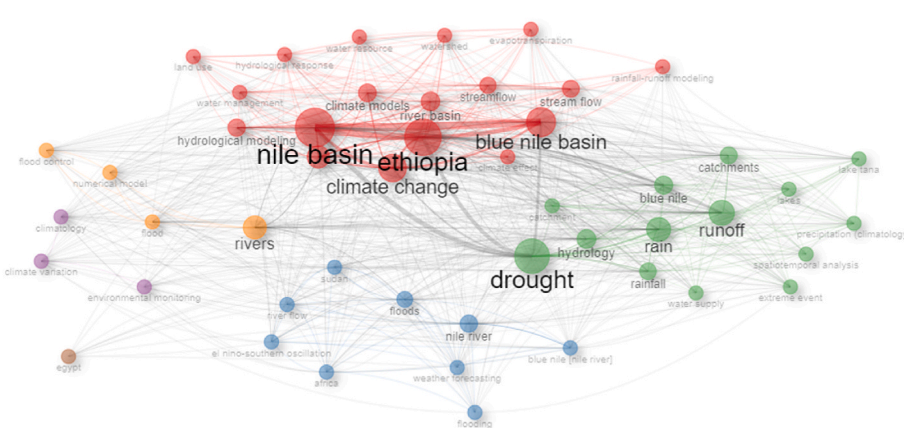

Fig. 4. Co-occurrence plot of flood and drought research in Blue Nile Basin from 1990 to 2023 (the nodes indicate how often the keyword appears in documents, while the colours of the nodes signify the cluster to which the keyword is assigned).

Table 3
An overview of studies on historical precipitation and temperature variations in the BNB.

Study location	Study period	Main finding	Reference
BNB	1950–2018	Extreme temperature variability revealed a marked rise in yearly minimum and maximum temperatures.	Mohamed and El-Mahdy (2021)
UBNB	1970–2000	By the 2080s, temperature extremes are predicted to rise by a maximum of 5.17 °C and a minimum of 4.75 °C.	Chakilu et al. (2023)
BNB	1981–2010	Historical temperature extremes have demonstrated a monotonically increasing tendency, with observable evidence pointing to rising temperatures.	Tedla et al. (2022)
UBNB	1953–2014	The historical temperature extremes have shown a monotonically increasing tendency, and there is apparent evidence of rising temperatures.	Samy et al. (2019)
BNB	1964–2003	There is no apparent seasonal or yearly rainfall trend.	Tesemma et al. (2010)
Jemma sub-basin	1980–2021	Significant seasonal variations and a downward trend in rainfall	Gonfa et al. (2021)
Jemma sub-basin	1980–2014	Increasing trend in mean annual temperature and no significant trends in precipitation and streamflow	Lebeza et al. (2023)
Gumara catchment	1976–2005	Precipitation increases up to 13.7%, temperature by 1.01 °C.	Andargachew and Fantahun (2017)
UBNB	1982–2017	Actual summer precipitation in 2018 was slightly below the long-term mean but within the range of "near normal."	Blum et al. (2019)
Muger subwatershed	1980–2019	Low variability in annual and summer areal rainfall. Seasonal rainfall distribution showed strong irregularity throughout the years.	Moshe and Beza (2024)
Didessa sub-basin	1986–2014	Variability in rainfall and temperature rise were verified by observed climatic data.	Chala et al. (2020)
BNB	1992–2001	Future mean flows will be higher and the potential for future floods to be more severe	Nawaz (2010)
BNB	1951–1997	Different patterns of precipitation variability are revealed by sub-seasonal study.	Berhane et al. (2014)
UBNB	1965–2012	El Nino followed by La Nina leads to extreme floods. El Nino starting in April–June results in upper catchment droughts.	Zaroug et al. (2014)
UBNB	1901–2013	Annual rainfall data in the Upper Blue Nile River Basin is homogeneous at 95%.	Elzeiny et al. (2019)

a rise in maximum and minimum temperatures (Wubneh et al., 2022).

Conversely, precipitation trends in the basin are not consistent patterns (Getachew and Manjunatha, 2022; Tariku et al., 2021). Some models indicate a slight increase in the total annual precipitation (Ayehu et al., 2021), but others suggest a decreasing trend in the BNB (Alemayehu et al., 2022; Takele et al., 2022). For instance, the two months with the highest percentage of rainfall in the basin are July and August (23.32% and 22.65%, respectively) (Samy et al., 2019). Studies such as Tilahun et al. (2023) showed that the ensemble mean of the six RCMs forecasts a decrease in precipitation and a rise in temperature for both the RCP4.5 and RCP8.5 typical concentration scenarios. Overall, the basin faces a future with likely warmer temperatures and a more erratic precipitation pattern. Table 4 provides a detailed overview of projected rainfall and temperature conditions in the BNB. The table presents a warming trend in the BNB and increasing climate variability, with a potential implication for water resources. Increasing climate variability causes a shift towards more extreme precipitation events (Tabari, 2020). Some areas experience intense downpours leading to floods, while others see longer periods with little to no rain, intensifying droughts. Overall, the projected increases in temperature are significantly larger than the historical trends, indicating a more rapid warming trend in the future. However, the historical variability in precipitation patterns is likely to continue, with the potential for more extreme events like floods and droughts.

6. Flood and drought extreme events in the Blue Nile Basin

6.1. Occurrence of flood extreme events

Flooding has become an increasingly significant challenge in the BNB, driven primarily by climate change and its associated alterations in precipitation patterns. Numerous studies have investigated the occurrence, extent, and potential future of floods in the basin (Chakilu et al., 2023; Desalegn et al., 2016; Zaroug et al., 2014). Researchers have employed hydrological and climate models to simulate and predict flood inundation, and depth (Alaminie et al., 2021; Worku et al., 2021),

Table 4
A summary of research findings on projected precipitation and temperature changes in the BNB.

Study location	Study period	Main finding	Reference
UBNB	2020s, 2050s, and 2080	The lowest temperature is expected to rise by 4.75 °C and become more visible in the 2080s.	Chakilu et al. (2023)
BNB	2050s and 2080s	Temperature and precipitation levels are expected to rise annually.	Tariku and Gan (2018)
UBNB	2050s and 2090s	Projections of temperature increases, and rainfall decreases in the basin	Taye and Willems (2013)
UBNB	2030s,2050s, and 2080s	Future climate scenarios show increasing trends in precipitation and temperature	Mekonnen and Disse (2018)
UBNB	2030s and 2070s	While BCC-CSM-2MR indicates a modest increase in rainfall, MRI-ESM2-0 predicts a temperature rise.	Alaminie et al. (2021)
BNB	2080s and 2100s	No consensus on precipitation changes and temperature increases predicted.	Elshamy et al. (2009)
UBNB	2020s,20250s and 2080s	Maximum and lowest temperature trends are rising, whereas stream flow and precipitation trends are falling.	Daba and Rao (2016)
Abay Basin	2020s,2040s and 2070s	Increasing trend in temperature, but no clear trend in rainfall.	Awetu and Kenea (2023)
Lake Tana basin	2020s	An increase in extreme precipitation and temperature events is expected since the 2020s.	Moges and Moges (2019)
UBNB	2050s, and 2080s	The minimum temperature is expected to rise to 5.92 °C, while the maximum temperature is expected to rise from 1.38 °C to 3.59 °C. However, there was no clear trend in the precipitation prediction over the basin.	Getachew and Manjunatha (2021)
UBNB	2030s and 2050s	Temperature trends upward and is statistically significant, whereas rainfall has a declining trend and is not statistically significant.	Takele et al. (2022)
Kessie Watershed	2050s and 2080s	Mean annual precipitation and temperatures indicate a little increase for the future for all outputs from the climate model.	Amognehegn et al. (2023)
BNB	2040s and 2080s	Changes in precipitation occur in different stations, locations, and times.	Gamal et al. (2024)
UBNB	the 2030s and 2070	Maximum and minimum temperature increases in all months and seasons	Gebre and Ludwig (2015)

revealing the potential for more frequent and severe flood events in the future (Ragab and Negm, 2016; Robi et al., 2019). These studies have also demonstrated how climate variability affects the frequency of floods in the basin (Lazin et al., 2023). The relationship between El Nino and La Nina events was studied by Zaroug et al. (2014), who suggested that the timing and temporal patterns of such events could affect the likelihood of extreme floods and droughts. According to an examination of discharge measurements at the Blue Nile and the El Niño index from 1965 to 2012, there is a 67% chance that a severe flood will occur.

Many researchers have studied the impact of floods on the Blue Nile Basin. For instance, Desalegn et al. (2016) found that river floods in the Fogera floodplain, caused by heavy rainfall and overflow of rivers and backwater effects from Lake Tana, have significantly damaged human life and property in the UBNB. Similarly, Worku (2015) indicated the vulnerability of developing countries like Ethiopia to climate change, including the increasing frequency of extreme rainfall and the projected impacts of floods on crops, water resources, and socio-economic challenges. Moreover, the flooding in the upper parts of the BNB has led to increased soil erosion, resulting in the loss of nutrients and the expansion of water hyacinth at Lake Tana (Dile et al., 2018).

The region is experiencing more flooding and drought due to adverse climate changes that are upsetting hydrological cycles (Endalew, 2024). Projections indicate that there could be an increase in total precipitation, particularly during the rainy season, which would increase the frequency and intensity of extreme rainfall events (Tedla et al., 2022a). Additionally, the regional climate models indicate that changes in precipitation patterns will affect runoff, thereby complicating flood management strategies (Abdelmoneim et al., 2023; Zahran et al., 2024). Fig. 5 presents a comparison of flood inundation depth across different climate models in the basin. It shows high flood inundation maps for historical and projected simulations that were taken from the WEB-RRI model, showing a rise in all GCMs. It also indicated the projected elevations of the inundation zones for CMCC -CMS, ACCESS1.0, CESM1, (CAM5), MPI-ESM-LR, and MPI-ESM-MR to be 2208, 14782, 2618, 753, and 1838 km^2.

Altered precipitation patterns in the basin significantly impact flood dynamics. Research findings indicate that climate is likely to intensify flooding due to increased variability in precipitation, which is leading to more frequent and intense flood events. For instance, a study by Liu et al. (2021) predicts specific flood occurrences in 2020, 2025, and 2030, highlighting the basin's vulnerability to hydrological changes driven by precipitation fluctuations. Similarly, Phy et al. (2022) suggest that changes in precipitation could lead to varying flood magnitudes, with significant alterations expected by the 2060s. Overall, the increased precipitation and the management of water resources will be crucial in shaping flood dynamics in the Blue Nile Basin.

6.2. *Occurrence of drought extreme events*

The BNRB has experienced frequent drought conditions (Abdelmoneim et al., 2023; Ali et al., 2022). Previous studies indicate that precipitation patterns will become increasingly variable, with potential decreases in dry season rainfall and increases during the rainy season, which leads to risks of both floods and droughts (Tedla et al., 2022a). The regional climate models suggest that future scenarios could see annual precipitation changes ranging from −18.3% to +13.6%, with severe drought conditions (Lazin et al., 2023). The influence of climate phenomena, such as the El Niño-Southern Oscillation, further complicates drought propagation (Nigatu et al., 2024). There have been severe and extreme droughts observed in the years 1984, 2002, 2009, and 2015 (Dilnesa, 2020). In the highlands, the drought reached its peak in July 2015, whereas in the lowlands, it peaked in June 2015 (Kebede et al.,

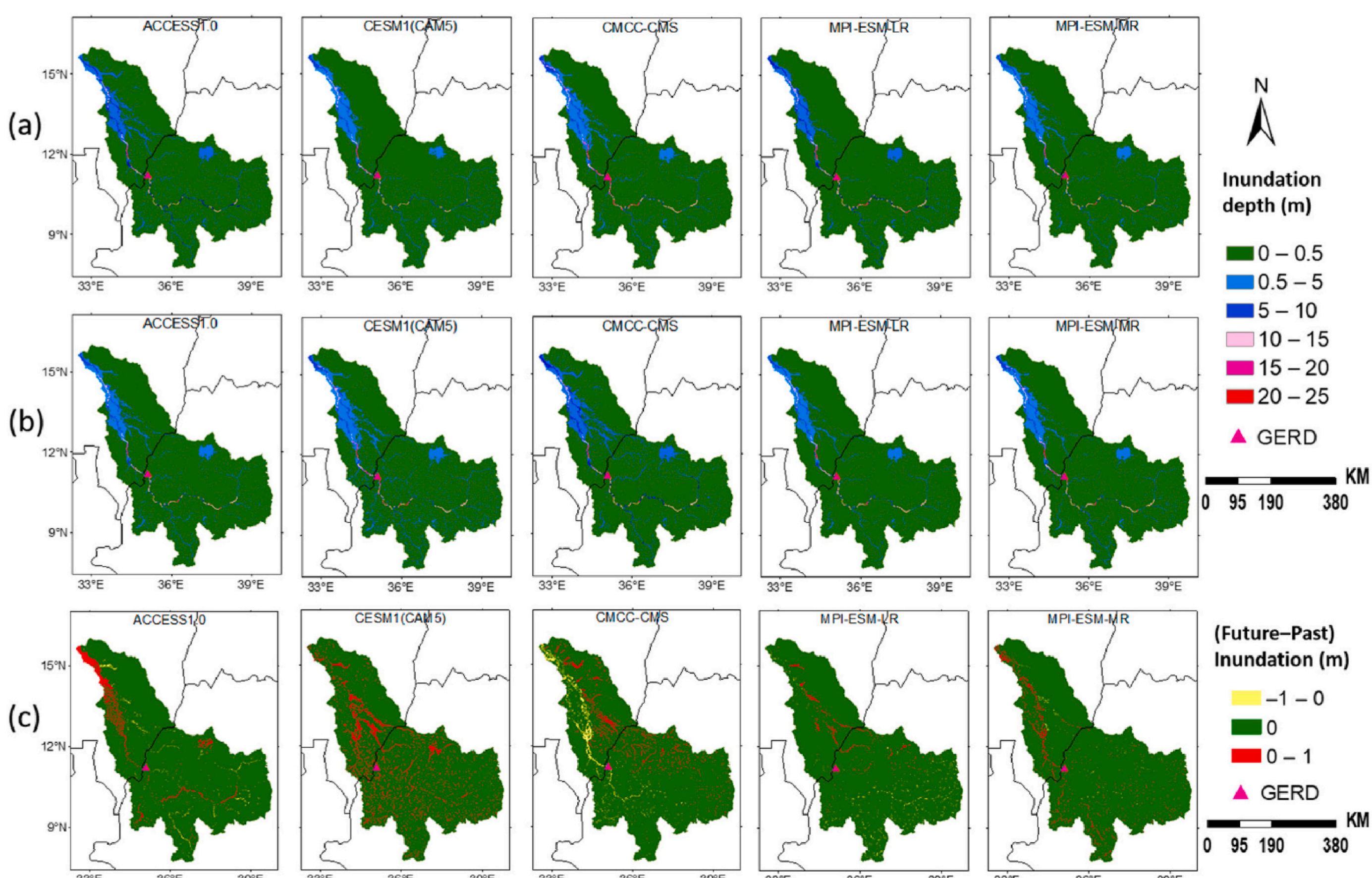

Fig. 5. Map of high flood inundation from GCM simulations: (a) historical, (b) projected (Tedla et al., 2022a).

2019). Additionally, severe drought conditions were identified in 1984/1985, 1989/1990, 1990/1991, and 1991/1992 (Bayissa et al., 2019; Dilnesa, 2020). The study also found that severe to extreme meteorological droughts were not typical throughout the whole basin, except for the north and northeast regions.

Droughts have had significant consequences on both the human and economic sectors. Crop destruction, property loss, community disruption, and other socioeconomic problems are only a few of the negative consequences that drought has on the socioeconomic sector (Kebede et al., 2019). Floods and droughts in the basin cause large financial losses and crop yield declines that affect farmer livelihoods and agricultural production. Studies indicate that adverse climatic events, particularly droughts, lead to substantial crop losses, with an average reduction in total crop production by 29% across affected areas (Zenda, 2024). The specific studies in the Blue Nile basin reveal that farmers can incur annual losses of approximately USD 220 per hectare due to nutrient loss from soil erosion, exacerbated by these climatic extremes (Erkossa et al., 2015).

Both droughts and floods collectively result in economic losses exceeding $5.1 billion, affecting 145 to 170 million people in Africa (Wollburg et al., 2024). In the Blue Nile basin, soil erosion leads to significant financial losses, with farmers losing around USD 370 per hectare annually due to nutrient depletion (Elnashar et al., 2021). Droughts are identified as the primary risk to crop yields, with a 1% increase in drought risk correlating to a yield decline of 14.5 kg/ha for sorghum (Elagib et al., 2023). Floods, while less damaging, can still cause yield losses; however, they may also enhance yields under certain conditions (Kim et al., 2023). Droughts are identified as the primary risk to crop yields, with a 1% increase in drought risk correlating to a yield decline of 14.5 kg/ha for sorghum (Leng and Hall, 2019). Floods, while less damaging, can still cause yield losses; however, they may also enhance yields under certain conditions (Kim et al., 2023).

It also threatens agricultural livelihoods and water resources, which are crucial for the economy (Ali et al., 2022). The UBNB experiences recurring drought events, with severe drought conditions observed in certain areas (Bayissa et al., 2021). There are certain years when the drought is more severe and lasts longer than previous periods of meteorological drought (Hailesilassie et al., 2023). This drought escalated into a famine due to prolonged dry periods in the preceding years, which had been the driest on record (Hassen, 2008). The BNRB is characterized as a drought-prone area, and efforts are needed to enhance farming practices and implement improved early warning systems.

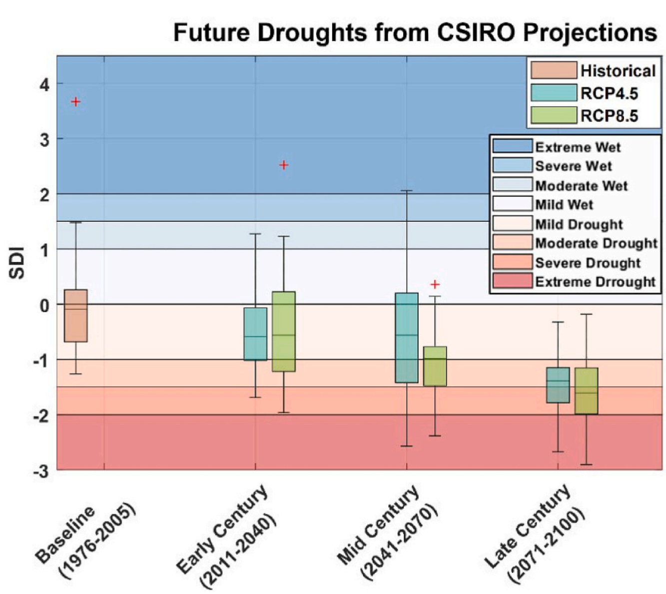

Fig. 6. Future drought compared to the baseline period based on CSIRO model estimates (Lazin et al., 2023).

Fig. 6 presents historical and projected drought conditions using the Standardized Drought Index (SDI) based on the CSIRO projections. SDI measures drought severity ranging from extremely wet to extremely dry conditions. The historical period shows a wide range of drought conditions, with some years experiencing severe drought and both RCP4.5 and RCP8.5 scenarios suggest an increase in drought severity and frequency in the future, with the most severe droughts projected towards the end of the century under the RCP8.5 scenario. Overall, drought in the BNB has wide-ranging impacts on both human well-being and the economy, emphasizing the need for effective drought monitoring and management strategies.

Ineffective management of water and land in upstream areas negatively impacts runoff yields and degrades the quality of water that reaches downstream regions (Alemu and Kidane, 2014). The lack of a well-structured river basin management system, combined with insufficient water storage capacity and significant spatial and temporal variability in rainfall, restricts farmers to cultivating only one crop per year. This limitation often leads to crop failures due to dry spells and droughts. Furthermore, severe soil erosion further diminishes farmland productivity.

Extreme hydrological events, such as floods and droughts, frequently occur at both local and basin-wide levels. For example, the devastating drought of the early 1980s had a severe impact on much of the Ethiopian highlands, while the intense flooding that occurred in August and September of 1988 caused widespread destruction in Sudan (Sutcliffe et al., 1989). These extreme events disrupt agricultural productivity, threaten livelihoods, and strain water resources, necessitating effective management strategies. Floods, with increasing frequency and intensity, lead to soil erosion and loss of arable land (Getaneh et al., 2024), while droughts reduce crop yields, directly affecting food security and income for farmers (Tedla et al., 2022a).

Soil erosion remains a significant challenge in the Ethiopian highlands, contributing to increased sedimentation in reservoirs and lakes (Alemu and Kidane, 2014; Awulachew et al., 2007). The sustainability of dams in this region is uncertain due to severe soil erosion and sediment deposition, both of which are results of poor upland management and extensive land degradation (Alemu and Kidane, 2014; Descheemaeker et al., 2006; Haregeweyn et al., 2006).

The harmful effects of severe soil erosion extend to both upstream and downstream communities (Alemu and Kidane, 2014), particularly in Ethiopia's highlands. To address these challenges, it is essential to implement practical and cost-effective in-situ soil and water conservation strategies.

7. Synthesis and knowledge gap

Increased temperatures and altered precipitation patterns are leading to more flooding events, particularly during the rainy season (Endalew, 2024). On the other hand, drought conditions are becoming more severe due to prolonged dry spells and reduced rainfall, affecting agricultural productivity and water availability (Abdelmoneim et al., 2023; Zahran et al., 2024). Climate change is causing more fluctuations in river flow, with higher peak flows during floods and lower flows during droughts (Lamichhane et al., 2024). Increased temperatures enhance evaporation, leading to more severe droughts and potentially more intense rainfall events (Kiros et al., 2022). Changes in rainfall distribution, including shifts in timing and amount, contribute to both flood and drought occurrences (Gebrehiwot and Van Der Veen, 2013). Studies indicate that a rising trend in heavy precipitation leads to more floods (Tedla et al., 2022a). Overall, the BNB is experiencing a multi-faceted interaction of climate change factors that are increasing the likelihood and severity of both floods and droughts.

Flood and drought extremes in the BNB reveal a knowledge gap that needs further investigation. Firstly, there is a lack of comprehensive data on the socio-economic impacts of these extremes, particularly how they affect local communities and agricultural practices (Gebeyhu, 2024). Additionally, existing studies often focus on hydrological modelling without adequately addressing the interaction between water resources, climate variability and land use changes, which can exacerbate flood and drought conditions (Endalew, 2024; Nigatu et al., 2024). These models should be capable of simulating extreme events with higher accuracy. Moreover, the role of climate change in altering precipitation patterns and its subsequent effects on water resource management remains underexplored (Shiferaw et al., 2024).

There is also a need for more localized studies that consider the unique geographical and climatic conditions of the Blue Nile Basin, as current research tends to generalize findings from broader regions (Abdelmoneim et al., 2023). Developing effective early warning systems for both floods and droughts is crucial for disaster risk reduction. Addressing these gaps will enhance our understanding of flood and drought dynamics and inform more effective management strategies.

8. Implications and the need for action

Increased flood and drought extremes in the BNB pose significant threats to the environment, society, and water resources. Intense rainfall associated with floods can lead to severe soil erosion, reducing soil fertility, loss of agricultural productivity, destruction of infrastructure, and adversely affecting local communities and their livelihoods (Tedla et al., 2022a). Floods can transport pollutants into water bodies, contaminating water sources and harming aquatic life. It is a significant disturbance that affects aquatic ecosystems and the services they provide to the ecosystem (Talbot et al., 2018). Conversely, droughts can aggravate water scarcity, impacting agricultural productivity and food security, which is critical for the basin's population (Ali et al., 2022). Prolonged droughts can accelerate desertification, leading to land degradation and loss of vegetation cover.

These hydrological extremes are likely to increase due to climate change, leading to unpredictable water availability and increased competition for resources (Elagib et al., 2021). This variability can strain existing water management systems, necessitating adaptive strategies to mitigate adverse effects on both human and ecological systems (Mastrandrea and Bohn, 2023). Furthermore, the socio-economic implications include heightened vulnerability among marginalized communities, who may lack the resources to cope with such environmental stresses ("Investigating extreme hydrological risk impact on water quality; evidence from Buffalo catchment headwater, Eastern Cape, South Africa," 2023). Thus, a comprehensive approach is essential to address these challenges and promote resilience in the BNB.

The BNB faces a significant challenge for extreme flood and drought events in Fig. 7. These need robust adaptation and mitigation strategies. Studies indicate that climate variability is increasing these hydrological extremes, which impacts water resources and agricultural productivity in the area (Mohammed, 2024). Effective adaptation strategies, such as improved water management practices, the development of resilient infrastructure, and the implementation of early warning systems, are essential to enhance resilience against these climatic threats (Abdelmoneim et al., 2023; Lazin et al., 2023). Moreover, mitigation efforts, including reforestation and adopting sustainable land use practices, can help reduce the severity of floods and droughts by improving soil moisture retention and regulating water flow (Bi et al., 2024). However, the integration of local knowledge and community involvement in these strategies is crucial for their success, as highlighted by studies emphasizing participatory approaches (Endalew, 2024). Thus, a comprehensive framework that combines both adaptation and mitigation is vital for addressing the multifaceted challenges posed by climate extremes in the Blue Nile Basin.

Large-scale water storage infrastructure, such as the Grand Ethiopian Renaissance Dam (GERD), is essential for regulating river flow and reducing the risks of flooding and drought (Mengistu et al., 2021). The construction of check dams, percolation ponds, and rainwater harvesting systems improves water retention and ensures availability during dry periods (Alemayehu et al., 2020). Additionally, implementing reforestation, terracing, and soil conservation techniques helps minimize runoff and soil erosion, which in turn reduces flash floods and enhances water infiltration (Gebregziabher et al., 2012).

Satellite-based monitoring and community-driven early warning systems also bolster preparedness for extreme weather events (Taye et al., 2015). Moreover, practices such as agroforestry, conservation agriculture, and crop diversification help mitigate vulnerability to unpredictable rainfall patterns (Deressa et al., 2009). Strengthening water governance, fostering transboundary cooperation, and engaging local communities all contribute to more effective water resource management (Biratu et al., 2023).

Promoting alternative income sources, such as livestock farming, handicrafts, and small-scale trade, helps reduce reliance on rain-fed agriculture (Biratu et al., 2023), Indigenous water management practices, including traditional irrigation systems, enhance local resilience (Adimassu et al., 2014). Lastly, training farmers in climate-smart agriculture and sustainable water management supports long-term adaptation to changing environmental conditions (Belay et al., 2017).

A sustainable approach to addressing flood and drought risks in the Blue Nile Basin necessitates a holistic perspective that considers economic, social, and environmental dimensions, guided by Integrated Water Resources Management (IWM) principles. IWM emphasizes equitable access to water resources, efficient utilization, and the protection of water ecosystems. Key institutions, such as the Nile Basin Initiative (NBI), the Eastern Nile Technical Regional Office (ENTRO), the International Water Management Institute (IWMI), and national agencies in respective countries, play crucial roles in promoting IWM principles through collaborative efforts, capacity building, and knowledge sharing. The Cooperative Framework Agreement (CFA) on the Nile Basin, though not yet fully ratified, provides a framework for equitable and sustainable water resource utilization among riparian states. Furthermore, the active involvement of local communities, through the

Fig. 7. (a) Farming fields in the Robit district affected by seasonal drought (Manyazewal, 2022) and (b) flooding that devastated rice production in the Fogera plain of the Upper Blue Nile Basin (Dawit and Abebaw, 2020).

implementation of community-based adaptation measures, is essential for building resilience and ensuring the long-term sustainability of water resources in the basin. These collective efforts, guided by IWM principles and underpinned by regional cooperation, are crucial for mitigating the impacts of climate change and ensuring the sustainable development of the Blue Nile Basin.

The Eastern Nile Subsidiary Action Program (ENSAP), established in 2002, includes Egypt, Ethiopia, and Sudan (Haileslassie et al., 2009; Misgan, 2013). Its long-term objectives are to (a) promote efficient water management and prevent significant harm, (b) foster cooperation among Eastern Nile countries, (c) support poverty eradication and economic integration, and (d) move from planning to implementation. ENSAP oversees various projects, including flood preparedness, the Baro-Akobo water resource initiative, the Ethiopia-Sudan transmission interconnection, and irrigation and watershed management efforts (Bahri et al., 2011; Misgan, 2013).

The Nile Basin Initiative (NBI) promotes regional cooperation through the Cooperative Framework Agreement (CFA), aiming to establish a legal framework for the sustainable management of the Nile River basin (GWP, 2009). The CFA focuses on public education about water rights, national planning processes, and integrating climate change into water sector development plans (Eyasu, 2005; Misgan, 2013).

Effective river basin management is essential for reducing poverty and conflicts while preventing environmental degradation. Integrated River Basin Management (IRBM) supports decision-making, especially in the upper Nile basin, home to over 180 million people. Strong institutions and stakeholder participation enhance cooperation and peaceful relations among countries. Transboundary water cooperation is vital for reducing poverty and preserving resources (Teshome B, 2008). Negotiations should emphasize benefit-sharing over water-sharing to avoid disputes.

9. Conclusion

Climate change is causing floods and droughts to be more frequent and severe in the BNB. Observational evidence and climate model predictions show that higher peak rainfall levels result in an increased frequency and intensity of flash floods and riverine floods. Floods in the basin significantly impacted the livelihood of the community. It is a major challenge in the Eastern Tana sub-basin, which is placed in the upper BNB, causing displacement and damage to human life and property. Alongside the increased floods, the basin is also facing more severe and prolonged droughts. The drought severity and duration are higher in some years, such as 1984, 2002, 2009, and 2015. The El Niño and La Niña climate phenomena have a substantial impact on rainfall patterns in the region, which in turn contributes to drought and flood events. The intricate and dynamic effects of climate change on the basin require constant monitoring and the application of adaptation measures.

Climate change is intensifying the frequency and severity of both floods and drought extreme events, which is a significant challenge to the basin's agriculture, water resources, infrastructure, and overall socioeconomic development. It is anticipated that future precipitation patterns and drought extremes will grow more unpredictable, directly affecting the amount of water available. In areas with little data, analyzing flood frequency has proven difficult; yet, the generalized extreme value distribution has shown reliable for predicting floods. Community awareness of water scarcity, extreme events, and responsible water usage practices is important for water resource management. Policymakers, researchers, and communities can develop effective plans to reduce risks and ensure the sustainable management of the basin's vital resources by developing a deeper understanding of these hydrological extremes.

Understanding flood and drought extremes in the BNB is crucial for effective water resource management and adaptation planning. Improve early warning systems for floods and droughts, allowing for timely interventions. Develop infrastructure and policies to withstand extreme events, reducing damage and losses. Finally, assessing the changes in precipitation and temperature extremes and their impact on hydrological extremes using hydrological models can provide valuable information for future sustainable water resource management.

CRediT authorship contribution statement

Demelash Ademe Malede: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Vetrimurugan Elumalai:** Formal analysis, Methodology, Supervision, Visualization, Writing – review & editing. **Tesfa Gebrie Andualem:** Writing – review & editing, Visualization, Conceptualization. **Yilkal Gebeyehu Mekonnen:** Methodology. **Mesenbet Yibeltal:** Writing – review & editing, Writing – original draft. **Girum Getachew Demeke:** Writing – review & editing, Visualization. **Tena Alamirew:** Writing – review & editing, Visualization. **Shimelash Molla Kassaye:** Writing – review & editing, Visualization. **Yonas Gebreslasie Hagos:** Writing – review & editing, Visualization. **Anmut Enawgaw Kassie:** Writing – review & editing, Visualization. **Mulatu Kassa:** Writing – review & editing, Validation. **Gizachew Sewagegn Berihun:** Writing – review & editing, Visualization. **Ram L. Ray:** Writing – review & editing, Visualization.

Data availability statement

The Data that support this study are available from the corresponding author upon reasonable request.

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Declaration of competing interest

The authors declare that they have no competing interests. All authors have contributed significantly to the work, and the manuscript has not been submitted elsewhere for publication.

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Data availability

Data will be made available on request.

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