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T01

Future changes in hydrological drought characteristics Over Pra River basin, Ghana

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Hydroclimatic extremes, such as droughts, are likely to change with global climate change, affecting water resources and socio-economic activities. This study analysed the characteristics and trends of hydrological drought over Pra River Basin, a major river basin in Ghana, West Africa and assesses the impact of projected future climate change. The study used high-resolution (5km x 5km) gridded precipitation, temperature and surface wind data for the historical period 1981-2020 and 13 bias-corrected CORDEX Africa regional climate data sets for the future period 2021-2100. The Vic hydrological model, RAPID and the Shuffled Complex Evolution - University of Arizona (SCEUA) optimisation algorithm were used to generate and calibrate streamflow. The Standardised Streamflow Index (SSI) was used to characterise drought based on runoff theory. The results show that the main Pra has relatively high drought duration of up to 5 months, with moderate to severe intensity. Historic trend show a decreasing severity, duration and intensity. Individual model projections show uncertainties in future changes in hydrological drought characteristics, but most models agree on a clear path for both RCP45 and RCP85 scenarios in different time periods. In the near future, RCP45 projects an increase in hydrological drought intensity, while RCP85 projects a decrease, and both scenarios suggest a reduction in drought duration and severity. In the medium to distant future, both scenarios predict a decrease in drought duration, intensity and severity. The results are important for integrated water resources management in the future.

T02

Advancing Water Security in Africa: A High-Resolution Modelled Discharge Data, 2000-2021

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Abstract:
In addressing the critical challenge of freshwater scarcity in Africa, exacerbated by climate change and population growth, our research introduces a novel approach through the development and application of the VegHydro dataset. Utilizing the VegET hydrological model and mizuRoute routing framework, we analyze river discharge across more than 63,000 river segments in Africa, leveraging satellite observations and in situ data for the period 2000-2021. This high-resolution dataset not only uncovers intricate hydrological patterns across diverse African landscapes but also sets a new benchmark for model reliability with performance metrics indicating strong correlations (R^2: 0.5-0.9), Nash-Sutcliffe efficiency (NSE: 0.6-0.9), and Kling-Gupta Efficiency (KGE: 0.5-0.8). Our findings quantify the continent's total annual average discharge at 3238.1 km^3/year, delineating significant contributions to various oceanic basins. Beyond numerical assessments, this work serves as a critical resource for stakeholders, providing a nuanced understanding of water availability's spatiotemporal variations. Such insights are pivotal for sustainable resource allocation, infrastructure planning, and enhancing climate resilience. The integration of remote sensing data addresses prevalent challenges in hydrological modeling within Africa, including data scarcity and quality. By offering a scalable and computationally efficient model, our research underscores the potential of digital innovations in bridging gaps in water resource management. The VegHydro dataset not only advances hydrological science but also catalyzes policy-making and operational decisions towards securing water for Africa's future.

T03

Projection of Climate Changes and Numerical Modeling of Climate in the Rheris Watershed-Morocco

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Abstract: Climate change is now widely recognized in the scientific community. Nonetheless, its impact on hydrological extremes is still a major concern. Half of the world's natural disasters are floods, and over the last ten years these hydrological hazards have become a major risk for the national territory, especially for areas located at the foot of the mountains. The research involves diverse types of meteorological data, ensuring the incorporation of both historical and climate model data to capture the complexity of precipitation patterns. This data is carefully evaluated for accuracy through rigorous validation procedures. The methodology used in the study involves statistical downscaling techniques to refine the spatial resolution of precipitation data and generate accurate projections. The Rheris basin is located in south-eastern Morocco, covering an area of 12,702 km², and is characterized by a semi-arid climate. The interest of the Downscaling precipitation modeling study in the Rheris watershed in southeastern Morocco in particular is undoubtedly linked to the high degree of climatic variability in the study area. The study's objectives are to assess the functioning of the river system in response to climate change through high-resolution rainfall projections. To achieve this, the study employs downscaling techniques to enhance the spatial resolution of precipitation data and generate accurate projections. The results demonstrate significant changes in the rainfall regime of the Rheris basin for the projected future periods, including variations in intensity and seasonality. The abstract highlights the importance of fine-scale precipitation data for understanding the evolving hydrological patterns and informing effective water resource management strategies. Moreover, it recommends the consideration of high-resolution precipitation projections in future water resource planning and management.

Keywords: Climate Change, Rheris Watershed, Climate Modeling, Impacts.

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T04

Comparative assessment of hydrological response of Upper Godavari Sub basin under CORDEX and CMIP6 climate models scenarios.

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Groundwater is a most vital resource for ensuring the water availability in the Upper Godavari sub basin, India, however, the rising water demand along with impeding anthropogenic activities has stressed this precious resource to a greater extent. Moreover, the predominating effect of climate change due to its irregular precipitation patterns has further exacerbated this stress. Hence, addressing these concerns requires a comparative assessment of the surface and groundwater resources under both present and future scenarios. Thus, the present study examines the status of the surface and groundwater dynamics using a SWAT-MODFOW integrated hydrological model. The individual surface and groundwater models are prepared in the SWAT and MODFLOW environment and are calibrated using the streamflow and the groundwater data. The calibration of the SWAT model is done in SWAT-CUP software and the groundwater is done in PEST module present in the Model Muse software. Then both the models are integrated using the linkages files for correct examination of the groundwater discharge, interaction of aquifers and streams. Likewise, for getting the future impact on the surface and the groundwater resource, CORDEX and CMIP6 climate models are considered. From a list of CORDEX and CMIP6 climate models the best climate models is selected based on the analysis of statistical indices such as R^2, MAE, RMSE, MSE, and NRMSE, correlated with IMD precipitation and temperature datasets and then is bias corrected using different methods such as empirical quantile mapping, Local intensity, Delta change (linear scaling and Variance scaling method. The empirical quantile method demonstrated more correlation of the bias corrected climate model with the IMD datasets. The bias corrected scenarios of the best selected climate models are then taken as input for examining the behavior of the upper Godavari sub basin under different climate scenarios. The result also highlighted the probable impact of decreased precipitation on the groundwater levels under SSP 370 and 585 scenarios. Hence, these results suggest a decisive need for redevelopment and mitigation strategies to address the declining groundwater reserves by framing sustainable policies both at organization and industry level.

Key words: climate change, hydrological model, SWAT, Nash-Sutcliffe efficiency (NSE), Root mean square error (RMSE) CMIP6, and CORDEX.

T05

Integrated Approach for Ensuring Sustainable Water Resources in Narmada River Basin under Land Use and Climate Change Scenarios

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The impact of climate change and anthropogenic activity on climatological parameters influence the hydrological processes and water resources availability. These issues in particular are disturbing the sustainable development planning and management of water resources. This study proposes an integrated approach to accurately measure the water budget of Upper Narmada Basin in India, which is crucial for sustainable water resource planning and management. The approach involves simulating hydrological responses under different land use land cover (LULC) and climate change scenarios. Regional scoring method was applied to select the best five climate models (MIROC5, CNRM-CM5, MPI-ESM-LR, GFDL-ESM2G, and IPSL-CM5A-MR) and they were coupled with a semi-distributed hydrological model. To account for the basin's heterogeneity, multi-site calibration and parameters sensitivity analysis were performed using Sequential Uncertainty Fitting (SUFI-2) algorithm. The calibrated model was then coupled with historical and futuristic land use scenarios (1990, 2000, 2010, and 2030) to compute hydrological sensitivity against land use change. The results show that precipitation is likely to intensify towards the late 21st century, and annual mean temperature could increase by 1.79 °C and 3.57 °C under mid and high emission scenarios respectively, at the end of the century. The basin's annual and monsoon flow is expected to increase during the 2050s (2041-2070) and 2080s (2071-2100). Additionally, the study identified the relationship between climate variables and water budget components to analyze the hydrological sensitivity of the basin under changing climate.

T06

Integrating downscaled CORDEX-South Asia regional climate models in urban flood modeling to quantify human health risk from conatamineted floodwaters

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Climate change poses a grave global threat, causing disruption to the entire water cycle, including altered precipitation patterns, rising temperatures, and sea level rise. As a result of these erratic changes, floods are becoming more frequent and severe in numerous regions across the world. While the adverse hydrological impacts of floods on the society are widely acknowledged and well-researched, their potential leading to the outbreak of waterborne infectious diseases and concerning human health risks, is lesser known. In **Delhi**, the national capital of India, urban flooding has caused extensive damage and numerous incidents. The major factors leading to this dismal situation along the **river Yamuna** are high population density, haphazard urbanization, inadequate drainage systems, and increasingly extreme rainfall due to climate change. To combat the adverse effects of flooding, city planners and water experts have begun using flood inundation mapping to identify flood-prone areas as a first step. However, the **severe microbial contamination of floodwaters** remains an ongoing issue.

For the first time, this study primarily aims to quantify the risks to **human health associated with contaminated urban floodwaters in a flood-prone region of Delhi** adjoining the Yamuna River. By developing a framework that integrates **climate and socio-economic changes**, the study provides quantitative and qualitative information about flood and human-health risks, both present and in the anticipated future. Hourly and sub-hourly hydro-meteorological data are collected, including rainfall, streamflow, sewer flow, and various water quality parameters. Future rainfall projections from **South Asia-CORDEX** under **RCPs 2.6 and 8.5** are **statistically downscaled** to higher resolution, while **SSPs 1 and 3 scenarios from the CMIP6 consortium** are considered to account for socio-economic scenarios. A set of flood inundation (depth, velocity, and inundated area) and hazard maps are derived from the **MIKE+ model**, an acclaimed 1D-2D coupled hydraulic model. The flood outputs from MIKE+ are fed to the **MIKE Eco-Lab** water quality model to map the water quality dynamics and the spread of Faecal Indicator Bacteria (FIB) in the domain. The human-health risk from FIBs is estimated based on the **β-Poisson dose-response model**. The proposed framework of fusing climate and socio-economic structures within a **hydraulic-cum-water quality** modeling environment is generic as it promises its demonstration for any other flood-prone region. Ultimately, the study aims to support the development of efficient resilience mechanisms that protect communities at risk and benefit developing and underdeveloped nations that face increasing flooding risks due to climate change and socio-economic changes.

Keywords: Climate change; CMIP6; CORDEX; Flood hazards; Human health risks; Urban floods.

T07

From Abundant to Scarce: Unravelling the Impacts of Climate Change on Water Demand in Boyo Watershed

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Abstract

Managing water for an equitable and sustainable distribution is critical to controlling human challenges like climate change and over-extraction [1]. This study aimed to assess how Boyo watershed's water demand has been affected by climate change. Procedurally, a sensitivity analysis and rainfall-runoff simulation were carried out using the HEC-HMS model, and the WEAP (Water Evaluation and Planning) model was used to distribute the water demand [2]. Three climate models were used to estimate future climatic data in the watershed [3]: MPI-CCLM4, ICHEC-RACMO22T, and CNRM-RCA4 for the baseline (1971-2000), mid-term (2041-2070), and long-term (2071-2100) climatic data were examined. In the meantime, the outputs of the CORDEX-Africa programs RCP4.5 and RCP8.5 scenarios were used for dynamically downscaled climate models. The findings show that the future available water will decrease causing extreme water shortage, the demand for water is also predicted to rise given the projected rise as a result of anticipated impacts of climate change in the study area. Therefore, sustainable usage, effective management, and fair allocation of water are not optional.

Keywords: **Climate Change, HEC-HMS, Boyo watershed, Water demand, WEAP.**

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T08

Flash Drought Evaluation Using Evaporative Stress and Evaporative Demand Drought Indices: A case study from Awash River Basin (ARB), Ethiopia

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Highlight

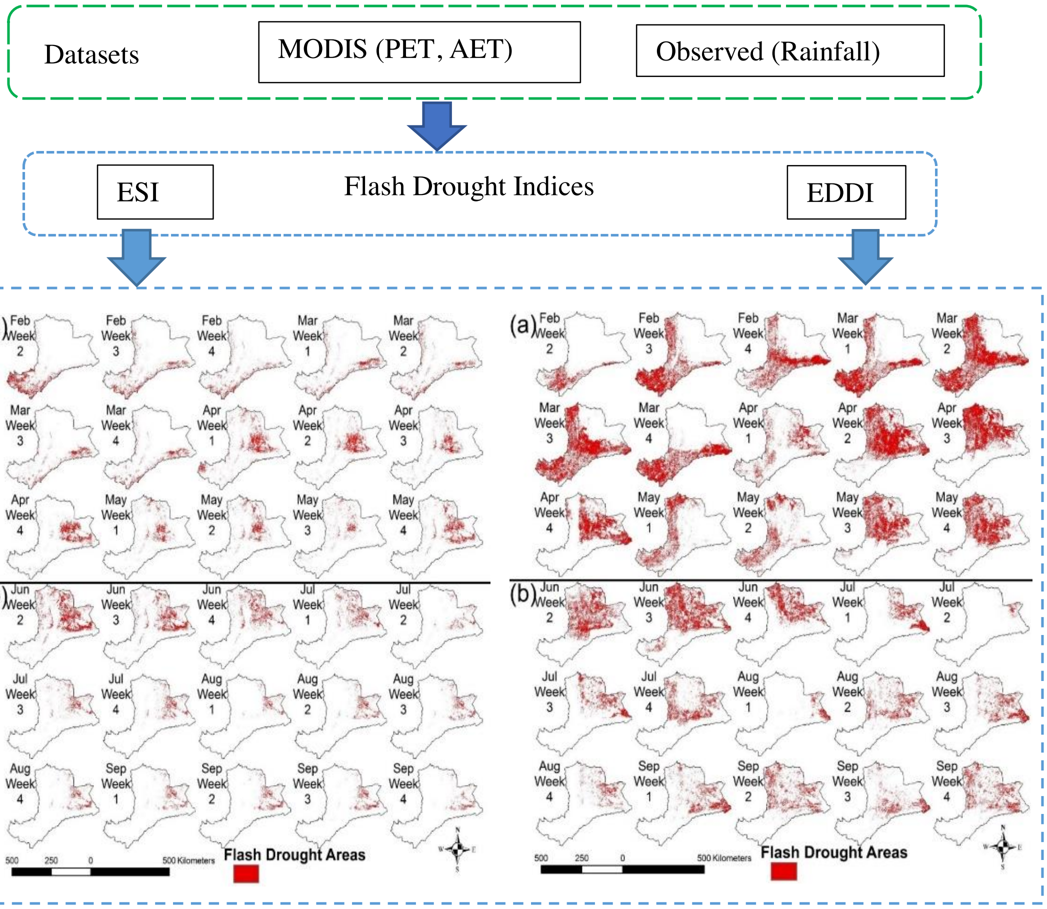
-Identifying flash drought is vital for drought early warning and monitoring.

-The extent of flash drought identified by EDDI is larger than those by ESI.

-The downstream basin having agropastoralists were highly prone to flash drought.

-Grassland areas were hotspots of high flash drought intensity.

Graphic abstract



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Abstract

Drought is one of the most devastating phenomena that affect the livelihood of most communities in Ethiopia as they have low adaptive capacity. Recent advancements in remote sensing and drought investigations have made it possible to identify a new type of flash drought that has rapid intensification with a short duration (i.e., less than 1 month unlike conventional droughts). This study intends to identify flash drought in the Awash River Basin (ARB) based on Moderate Resolution Imaging Spectroradiometer (MODIS) data of actual evapotranspiration (AET) and potential evapotranspiration (PET) using Evaporative Demand Drought Index (EDDI) and Evaporative Stress Index (ESI) indices. The Standardized Precipitation Index (SPI) correlation with EDDI and ESI were 0.76 and 0.79 respectively, implying that these indices can be used to characterize drought in the area in the absence of observed data. The flash drought result exhibited that agricultural lands, grasslands, vegetation areas, and irrigational croplands along the river were vulnerable to flash drought in the ARB. Using ESI, the area of ARB that experienced flash drought in 2002, 2008, 2009, 2012, and 2015 were 23 % (26355.9 km^2), 40 % (46449.5 km^2), 20 % (22943 km^2), 40 % (46074.8km^2), and 24 % (27559.5 km^2), respectively. These intense flash drought areas can be used as drought monitoring sites. The flash drought extent of EDDI is more compared to ESI because of ESI's dependency on vegetation coverages and soil moisture. The lowland downstream part of the ARB is highly prone to flash drought, particularly in the major rainy season (MRS) and the last two months of the minor rainy season (mRS). EDDI can discern the onset of flash drought better compared to ESI, but both can be used as a drought early warning mechanisms to minimize agricultural losses and drought-associated risks in the basin.

Keywords: Flash drought, Evaporative Stress Index and Evaporative Demand Drought Index

Practical Implications

Ethiopia is one of the most vulnerable countries to climate change and variability due to its high reliance on seasonal rainfed agriculture and low adaptive capacity. Agriculture is the essence of the Ethiopian economy that provides employment opportunities for 80% to 85% of the population and contributes 40% to 50% to the national gross domestic product (GDP) with 85 % export incomes (Yimere and Assefa, 2022; Worqlul et al., 2017). High rainfall variability and low adaptation capacity have been the main challenge in Ethiopia, which impacts agricultural productivity causing severe food security problems in the entire country (Gebissa et al., 2021). Improving climate extreme analysis and climate information/services for smallholder farmers are essential to increase agricultural production with effective adaptation strategies against extreme events. However, studies that quantify climate risks and provide climate services with adaptation strategies for smallholder farmers are very limited in Ethiopia. Without climate information to support drought watch, various extents, frequencies, and severities of droughts have caused great socioeconomic impacts on the livelihood of the Awash River Basin. Recent developments in remote sensing and drought research have shown possibilities to identify a new type of flash drought that has rapid intensification within a short duration (e.g., days, weeks) unlike the conventional drought lasting longer than one month. Evaporative Demand Drought Index (EDDI) and Evaporative Stress Index (ESI) were proposed in this study to quantify the characteristics of flash drought which can be used to evaluate the potential impact of drought on the agricultural sector. Since both indices are highly sensitive to climate variables (e.g., temperature and rainfall), they can be applied to access climate change impacts and also serve as precursors for conventional droughts by detecting flash droughts. Therefore, characterizing and identifying flash drought areas with EDDI and ESI have the advantages to provide valuable information for climate services and adaptation decision-making. For example, flash drought hotspots can be identified by both indices as vulnerable areas for drought impacts and require considerations for deploying monitoring instruments to detect the onset of future droughts. Smallholder farmers in the ARB are aware of increasing temperatures and the anomalous nature of rainfall, as well as their agricultural activities and productions have been compromised by frequent droughts. Considering drought in changing climate that may increase risks of food security in the ARB, developments of adaptation pathways should be informed with quantitative drought extents, frequencies, and severities. In addition, drought monitoring instruments should be deployed in flash drought-prone areas to detect drought onset and to support predictions of drought longevity.

1. Introduction

Drought is a complex climate extreme phenomenon mostly caused by a prolonged period of rainfall deficit (meteorological drought) followed by soil moisture deficit, which in turn leads to a loss of streamflow and water shortage (Wilhite, 2002; Van Loon, 2015; Wilhite and Pulwarty, 2017). It is one of the most devastating natural disasters due to its consequence on agricultural activities and water resources and has resulted in severe economic, environmental, and societal problems worldwide. Past studies have indicated that Ethiopia has been plagued by frequent, severe, long-lasting, and catastrophic droughts that influence the lives of millions of people through crop failure, water shortage, conflict, epidemics outbreaks, and death of human and livestock (Mera, 2018; Gebremeskel et al., 2019). For instance, in 2008 alone about 26000 livestock were lost in Borena district only, 14 million people were affected and the cost of humanitarian aid was estimated to be $1077.8 million US (World Bank, 2017; Mohammed et al., 2017). In recent years, the frequency and severity of droughts have increased in Ethiopia, which resulted in huge economic losses in 2002, 2003, 2004, 2005, 2006, 2008, 2009, 2011, 2012, 2015, and 2016 (MacDonald et al., 2019; Liou and Mulualem, 2019; USAID, 2018; Suryabhagavan, 2017; El Kenawy et al., 2016; Masih et al., 2014; Mays, 2014; Viste et al., 2013). These recent increases in drought severity and frequency in Ethiopia may be highly associated with global warming (Mera, 2018; El Kenawy et al., 2016).

Conventional droughts are generally slowly developing and receding phenomena with various longevity causing substantial socioeconomic impacts as their most common characteristics (Wilhite and Pulwarty, 2017; Svoboda et al., 2002, Wilhite, 2002). However, current studies have revealed a new type of flash drought, which has been defined based on its rapid rate of intensification (Ford and Labosier, 2017; Ford et al., 2015) or short duration from days to weeks due to atmospheric anomalies of rainfall deficit and high temperature that may further lead to soil moisture deficit (Yao, et al., 2018; Zhang et al., 2019; Mo and Lettenmaier, 2016; Hobbins et al., 2016; McEvoy et al., 2016; Otkin et al., 2014). Otkin et al (2018), which has distinct characteristics, unlike conventional drought properties of long-lastingness. According to Otkin et al (2018), flash drought can be identified based on its rapid rate of intensification (i.e., flash part) and moisture limitation (i.e., drought part). The onset and propagation of flash drought can occur rapidly when atmospheric anomalies such as rainfall deficit and high temperatures persist for several weeks (Christian et al, 2019; Svoboda et al., 2002). Flash drought has been largely affecting crop yields, water resources, natural ecosystems, and soil moisture (Christian et al, 2019; Otkin et al, 2018). Flash droughts can be easily intensified by human-induced climate change or increasing temperature and monitoring flash drought is indispensable to developing drought early warning systems that can minimize agricultural and economic losses. Detecting and monitoring the likely occurrences of flash and long-lasting droughts can help to minimize the disastrous impacts of droughts. Flash drought evaluations should be incorporated into conventional drought monitoring programs for early warning and proactive measures to lessen the overall drought risk.

Droughts have been frequent and catastrophic in the Great Rift Valley, eastern, and southeastern parts of Ethiopia, where the Awash River basin (ARB) is located (Thomas et al., 2019; Mera, 2018; Shiferaw et al., 2014). The ARB is the most populated and utilized basin in the country, which has been seriously affected by water scarcity and recurring droughts causing problems with food security (Hailu et al., 2017; Adeba et al., 2015; Edossa et al., 2010; Murendo et al., 2010). In recent years, better understanding, identification, and monitoring of droughts have been available by utilizing new technological advancements such as remote sensing products and drought indices (Yu et al., 2019; Christian et al, 2019; Otkin et al, 2018). Satellite datasets are cost-effective, vital in areas where ground-based datasets are not adequate, and important to provide better spatial information relative to observed data that requires interpolation (Sun et al., 2018; AghaKouchak et al., 2015). Therefore, monitoring and identifying flash drought using advancements in remote sensing outputs and newly developed flash drought indices is vital for the improvement of agricultural productivity.

Studies in Ethiopia or ARB have been mostly analyzing conventional droughts with rather less attention on the rapidly evolving flash droughts (MacDonald et al., 2019; Mera, 2018; Suryabhagavan, 2017; Edossa et al., 2010). Moreover, the effect of global warming was not well characterized by most of the previous drought indices. Recently, new drought indices have been proposed with information on atmospheric water demand or increasing temperature. Among those new indices, both Evaporative Demand Drought Index (EDDI) and Evaporative Stress Index (ESI) are highly sensitive to several climate variables including temperature, rainfall, and soil moisture which are important to characterize rapidly evolving drought events (Pendergrass et al., 2020; McEvoy et al., 2016; Otkin et al., 2014). In this study, we aim to identify flash drought using both ESI and EDDI drought indices. The commonly used drought index of Standardized Precipitation Index (SPI) calculated with rainfall data will be compared with both ESI and EDDI to examine whether the satellite data is applicable to better characterize drought in the basin or not. The objectives of this study include (1) validating the satellite output with SPI and evaluate flash drought in ARB using ESI and EDDI drought indices; (2) examining flash drought intensity; and (3) identifying flash drought hotspot areas in the basin.

2. Dataset and methods

2.1 Study area

The ARB lies in the east-central part of Ethiopia between 7°52’- 12°N and 37°57’- 43°25’E as shown in Figure1a. The Awash River has a length of 1200 km and a basin area of about 116,374 km^2 with an irrigation potential of 205,400 hectares (Dost et al., 2013). The elevation of ARB ranges from 215 m to 4185 m with the Awash River originating from the central highlands and meeting the Red Sea at Lake Abbe near Djibouti (Figure.1, b). About 24 million population (18 M people and 6 M livestock) are assessed to live in the ARB along with the major industries in big cities including the capital city of Addis Ababa, which makes the ARB the most utilized basin in the country (Hailu et al., 2017).

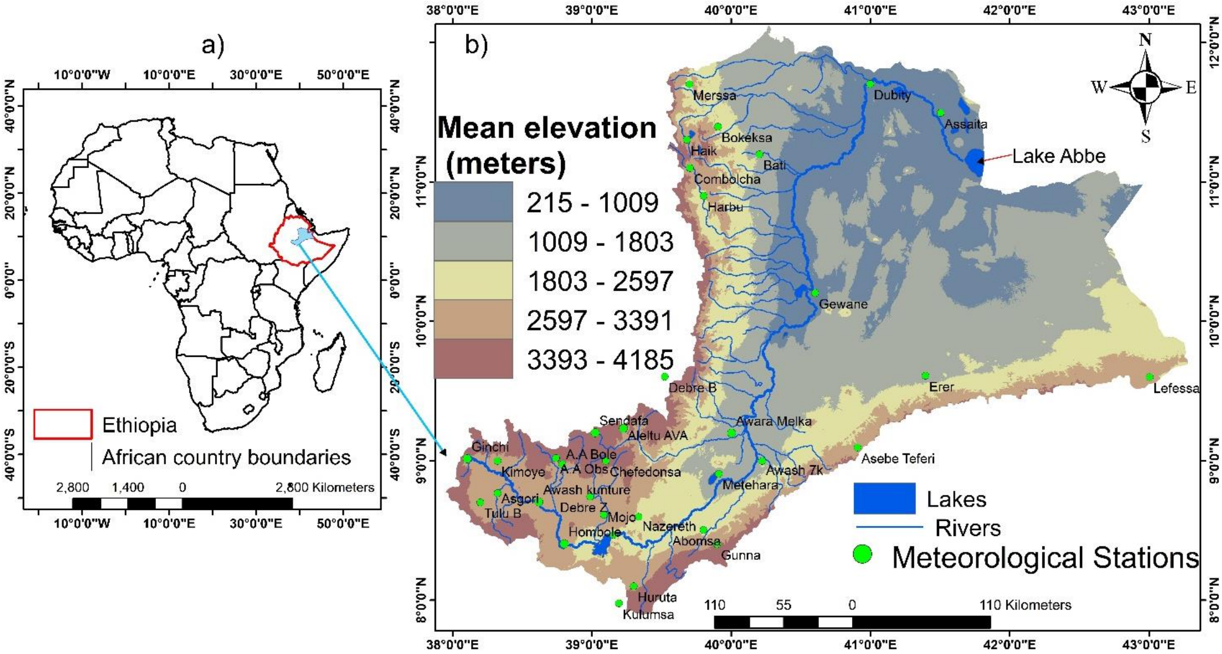

Figure 1. Study area location map: a) Africa, Ethiopia, ARB, b) Meteorological stations, Lakes, mean elevation, major rivers in the ARB.

Due to distinct seasonal rainfall amounts, the ARB has three seasons: (i) the main rainy season (MRS), nationally called "Kiremt" from Jun-Sep (JJAS), (ii) the minor rainy season (mRS), nationally known as "Belg" from Feb-May (FMAM) and (iii) the dry season, also called "Bega" from Oct-Jan (ONDJ) (Degefu et al., 2017). In addition to the rotation of the Earth around the sun, the monsoon system, and atmospheric circulation, the rugged topography also plays a significant role affecting regional rainfall distribution (Viste, 2012).

As indicated in Figure 2, based on data from 1986-2016, the mean annual rainfall in the upstream and northwestern peripheries of the basin is relatively high that varies from varies from 900-1300 mm. Similarly, the major rainy season rainfall is also comparatively high in the upstream and northwestern peripheries of the basin that varies from 620-930 mm, where as the minor rainy exhibited high rainfall in the northwest and southern peripheries of the basin. The highest monthly rainfall is indicated in July and August that is about 200 mm. The highest rainfall in most of the areas and seasons are associated with elevation that high elevated areas showed high rainfall compared to the lowland areas.

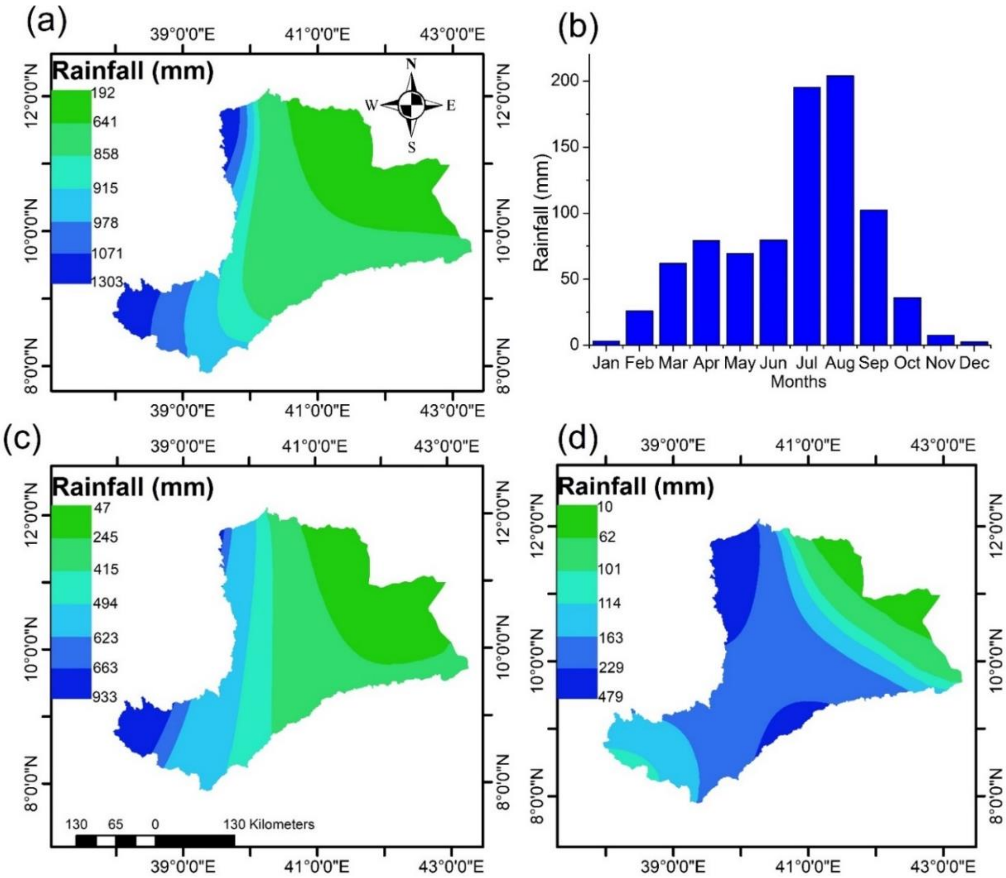

Figure 2. Spatial average annual and seasonal rainfall distribution of ARB from (1986-2016): a) annual rainfall, b) average monthly rainfall, c) major rainy season rainfall, d) minor rainy season rainfall.

2.2 Data

2.2.1 MODIS data

The potential evapotranspiration (PET) and actual evapotranspiration (AET) data measured by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra satellite of the National Aeronautics Space Administration (NASA) were obtained from the United States Geological Survey (USGS) web service (https://e4ftl01.cr.usgs.gov/MOLT/MOD16A2.006/). The MODIS Terra dataset of MOD16A2 with an 8-day temporal scale (8-day average) was used in this study with a spatial resolution of 500 m (Running et al., 2017). The downloaded .TIF format data was processed using R and ArcGIS software. The AET and PET data used for this study were obtained from 2002-2017. The MOD16A2 product of AET was computed using the Penman-Monteith equation, while the Priestley–Taylor equation was used to calculate the PET (Mu et al., 2007; Mu et al., 2011). The detailed flow chart of generating AET and PET products of MOD16A2 can be found in the MODIS user's guide (Running et al., 2017; Priestley and Taylor, 1972).

2.2.2 Observed Meteorological datasets

The observed rainfall data for 15 years (2002-2016) were obtained from 35 stations of the National Meteorological Institute (NMI), Ethiopia (Figure 1). The data obtained from NMI were preprocessed and quality checked.

2.3 Flash Drought Indices

2.3.1 Evaporative Stress Index (ESI)

Based on the definition of flash drought given by Otkin et al. (2018), a methodology of characterizing flash drought suggested by Christian et al. (2019) was adopted in this study (Figure 3). Unlike slow-developing conventional droughts to be examined in monthly or longer time scales, flash drought investigation should be carried out in shorter time scales such as daily and weekly. Drought indices of ESI and EDDI were used to identify flash drought based on the MODIS Terra products of average weekly AET and PET in this study. The MODIS data were processed from 2002-2017 with flash drought analysis carried out in selected recent drought years. Evaporative Stress Index (ESI)

The ESI is computed as a ratio of AET to PET (Anderson et al., 2016; Sur et al., 2015; Anderson et al., 2011). It is defined as

$$ESI = \frac{AET}{PET} \qquad (1)$$

The ESI is further standardized to be the Standardized ESI (SESI) computed as:

$$SESI = \frac{ESI - \overline{ESI}}{\sigma_{ESI}} \qquad (2)$$

where the $\overline{ESI}$ and the σ_{ESI} stands for the average and the standard deviation of ESI, respectively, for the whole study period from 2002 to 2017. In practice, standardization is a useful process for a more easy and robust comparison of different climatic regimes and growing seasons over multiple years (Christian et al., 2019).

Additionally, the standardized ESI change (ΔSSESI) anomalies were computed over selected weeks:

$$\Delta SSESI = \frac{\Delta SESI - \overline{\Delta SESI}}{\sigma_{\Delta SESI}} \qquad (3)$$

where the ΔSSESI is the standardized change in SESI, the ΔSESI is the change in SESI, the $\overline{\Delta SESI}$ is the average change in SESI for the entire period investigated in this study and the $\sigma_{\Delta SESI}$ is the standard deviation of the SESI considering all available years in the dataset.

The ESI is sensitive to moisture stress that indicates terrestrial water availability (Zhang et al., 2019). The ESI value ranges from zero to one that is associated with dryness or wetness conditions of the land surface. The larger (positive) ESI means the atmospheric demand of evapotranspiration is well fulfilled by vegetation and existing soil moisture, whereas lower (negative) means land surface hardly fulfilled any of the atmospheric evaporative demand (Christian et al., 2019). The positive ESI value indicates less or no drought occurrence, whereas the negative ESI value shows the occurrence of drought for a given location and period (McEvoy et al., 2016). Normalization by PET helps to minimize the AET variation due to the seasonal difference of available energy as well as vegetation coverage, which provides weightage to currently available moisture for the vegetation regardless of previous moisture conditions (Farahmand, 2016; Anderson et al., 2016).

2.3.2 Evaporative Demand Drought Index (EDDI)

EDDI is a newly proposed drought index only relying on potential evapotranspiration (PET) (Hobbins et al., 2016). It measures the drying potential of the atmosphere that induce vegetation stress on the ground (McEvoy et al., 2019). In other words, it is used to monitor the atmospheric evaporative demand that leads to the onset and development of droughts when the extreme atmospheric anomalies like high temperature or rainfall deficit persist for several weeks (Christian et al., 2019). EDDI is a useful index to indicate rapidly evolving (developing over a few weeks) and sustained (months or years) drought events (Hobbins et al., 2016). It is highly recommended for flash drought analysis because of its inter-dependency on rainfall, soil moisture, and topography (McEvoy et al., 2019). Moreover, recent studies have showed that places around the world have been experiencing more frequent drought because of the rising global temperature (Ford et al., 2015; Otkin et al, 2014; Zhang et al., 2019). EDDI can easily indicate the early onset and development of rapid drying conditions prior to other indicators namely, rainfall, soil moisture, and AET (McEvoy et al., 2019). First, PET was standardized like that of SESI, which is computed as follows (Hobbins et al., 2016):

$$EDDI = \frac{PET - \overline{PET}}{\sigma_{PET}} \qquad (4)$$

where, EDDI represents standardized PET, PET represents the potential evapotranspiration in weekly time scale, $\overline{PET}$ is the long-term mean of weekly PET from 2002-2017 and σ_{PET} is the standard deviation of long-term PET. Secondly, the standardized PET (EDDI) change anomalies were computed over specific weekly intervals:

$$\Delta SEDDI = \frac{\Delta EDDI - \overline{\Delta EDDI}}{\sigma_{\Delta EDDI}} \qquad (5)$$

where, ΔSEDDI is the standardized change in EDDI, ΔEDDI is the change in EDDI, $\overline{\Delta EDDI}$ is the average change in EDDI for all years available in the dataset and $\sigma_{\Delta EDDI}$ denotes the standard deviation of EDDI for all years available in the dataset.

Based on the approach proposed by Christian et al., (2019), a flash drought phenomenon is identified to have: (1) a minimal length of five negative SESI /EDDI changes, correspondent to a length of six weeks (i.e., 30 days), (2) a final SESI/EDDI value below the 20^{th} percentile from the average SESI/EDDI, (3) week-to-week changes in SSESI/SEDDI must be below the 40^{th} percentile between individual weeks, and (4) the mean changes in SSESI/ SEDDI must be below the 25th percentile for the entire weeks. It is noted weeks are equal to pentads in their approach. The earlier two criteria focus on drought impacts on vegetation related to soil moisture depletion that fulfills the drought component, whereas the final two focus on the speedy intensification to fulfill the flash component of drought (Christian et al, 2019). The minimum six pentads were suggested to smooth out the short-term fluctuation in SESI/EDDI and to eliminate the short-term dry spells. The SESI/EDDI value below the average for a longer period of time that is below the 20th percentile threshold fulfill the drought component. The third criterion (40th percentile) threshold is less strict and it is used to isolate deteriorating conditions (< 40th percentile) from that of improving conditions (>40th percentile) in individual pentads. Moreover, it is possible that some weeks in SESI/EDDI will exhibit very quick development, whereas others will experience slower intensification. However, these issues in third criterion can be corrected by the average change in SSESI/EDDI must be below the 25th percentile during the flash drought event (Christian et al, 2019).

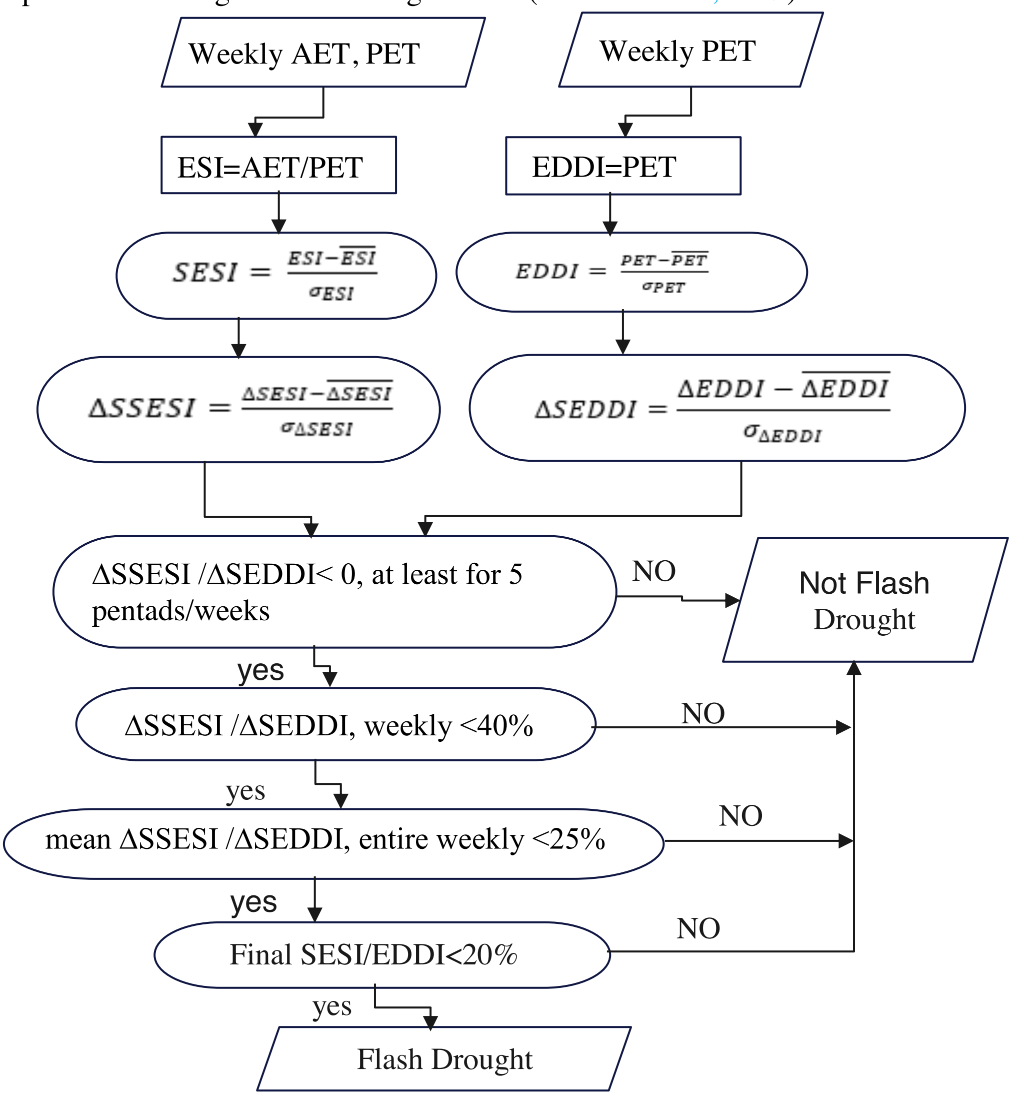

Figure 3. General methodology of flash drought based on ESI and EDDI.

2.3.3 Standardized Precipitation Index (SPI)

The SPI index proposed by McKee et al. (1993) to characterize rainfall deficit in multiple time scales was used to detect drought for different areas (Munagapati et al., 2018). Several studies in Ethiopia have used the SPI to evaluate meteorological droughts (Teweldebirhan et al., 2019; Suryabhagavan, 2017; Zeleke et al., 2017; Viste et al., 2013). Since SPI is normalized to the required location with various time scales, it is commonly accepted and applied worldwide for different applications (Masih et al., 2014). The SPI is not only flexible but also solely requires rainfall data making it is suitable for complex topography and climatic regions (El Kenawy et al., 2016). The standardized or normalized average monthly rainfall data obtained from 35 meteorological stations of the ARB was used to compute the SPI values and then compared with MODIS based ESI and EDDI drought indices for verification. Correlations between the SPI and the ESI and the EDDI were evaluated to check how the ESI and EDDI indices obtained from the MODIS data capable to characterize droughts in the basin.

As shown in table 1, the EDDI, SPI, and ESI drought severity class were scaled on constant and equal ranges. These drought severity classes are used to describe the extent or magnitude of drought events over the ARB.

Table 1. Drought severity classes of drought indices values (McKee et al., 1993)

Drought condition		SPI / ESI/ EDDI
Extreme drought		≤ -2
Severe drought		-1.5 to -1.99
Moderate drought		-1.0 to -1.49
Near normal	Mild drought	-.99 to -0.5
	Normal	-0.5 ≤0 ≤ 0.5
	Mild wet	0.5 to .99
Moderate wet		1.0 to 1.49
Very wet		1.5 to 1.99
Extremely wet		≥2.0

3. Results and discussion

3.1 Pattern of AET and PET in Awash River Basin

Figure 4 presents the spatial distribution of monthly average AET and PET in the ARB using MODIS products from 2002-2017. High monthly average AET that varied in a range of 0.5 mm/day to 5 mm/day was observed in the upstream, northwest, and southwest peripheries of the basin with a high basin area of 58.5% (68085.7 km^2) in August and reduced to the coverage area of about 31.6% (35253.2 km^2) in February (Figure 4a). On the other hand, the AET in the downstream (semi-arid to arid) part of the basin had a range of 0 mm/day to 0.5 mm/day for a high basin area of 57.5 % (66923.3 km^2) in February, while it was low in August covering 27.9 % (32473.3 km^2) of the basin area. Specifically, the highest monthly average AET in a range of 3 mm/day to 5 mm/day was observed in the forested and shrub-lands of the upstream basin with coverages of 2934.4 km^2 in September and 881.6 km^2 in August and the lowest coverage in March (74.5 km^2). The AET in a range of 1.5 mm/day to 5 mm/day was high in August, September, and October and covered 33.8% (39380.9 km^2), 32.4% (37700.5 km^2), and 19.8% (23029.1 km^2) of the basin area, respectively, and it had the lowest coverage of 3% (3095.5 km^2) in March. Because of the sufficient rainfall in the MRS, the growth of agricultural crops and natural vegetation cover in the upstream, northwest, and southwest peripheries of the basin, which explain the larger monthly AET as compared to the downstream part of mostly arid or semi-arid bare land with inadequate rainfall. In most of the basin, the lowest AET range of 0 mm/day and 1 mm/day was observed in December, January, and February months. The spatial pattern of AET in the ARB is highly correlated with the spatial patterns of rainfall such that the elevated and high rainfall (humid) area of the basin shows the highest AET relative to the downstream low rainfall (arid, semi-arid) part of the basin.

As shown in Figure 4b, the spatial pattern of PET is contrary to that of AET such that the highest PET is exhibited in the downstream or central part of the basin and the lowest PET is shown in the upstream part of the basin. The spatial pattern of PET corresponds to the temperature pattern, while the AET pattern resembles the rainfall. The monthly spatial PET of the entire basin was in the range of 2 mm/day to 10.5 mm/day. The lowest PET range of 2 mm/day to 4.5 mm/day was exhibited in June, July, August, and September with the basin area of 212.7 km^2, 9316.6 km^2, 5449.3 km^2, and 258 km^2, respectively, which mainly occurred in the upstream basin (i.e., low temperature due to high elevation) during the MRS (i.e., high rainfall). The highest PET with a range of 9.5 mm/day to 10.5 mm/day occurred in May and June mainly found in the downstream basin covered 17.4 % (20299.2 km^2) and 21.9 % (25492.7 km^2) of the basin. Afterwards, the PET range of 8.5 mm/day to 9.5 mm/day occurred in March, April, May, September, and October with the basin area of 31.9 % (37131.7 km^2), 31.4 % (36573.6 km^2), 29.9 % (34818.5 km^2), 27.3 % (31732.1km^2), and 26.2 % (30532.6 km^2), respectively. Overall, the highest PET occurred in the downstream basin mainly covered by rangeland (grassland). Similar to those observed in AET, the lowest PET occurred in December and January due to the lowest temperature throughout the entire basin. It is noted the white color in the spatial map without AET and PET values were caused by urban areas, barren lands, sparse vegetation (rock, tundra, desert), and cloud coverage of MODIS satellite images.

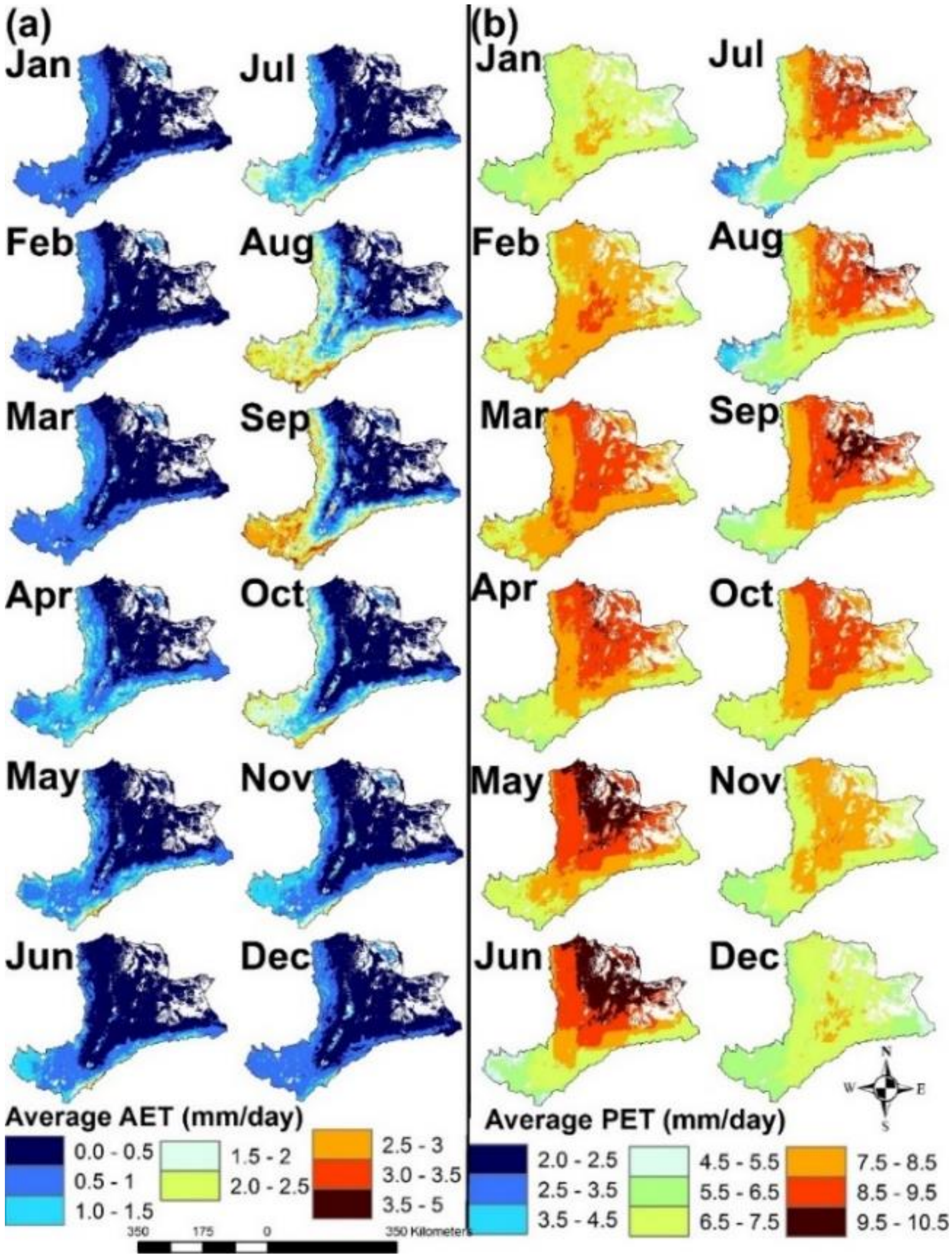

Figure 4. Monthly (a) actual evapotranspiration and (b) potential evapotranspiration of ARB from 2002-2017.

3.2 SPI comparison with ESI and EDDI

The most widely used SPI drought index was computed using the basin average rainfall from 35 meteorological stations. The basin monthly average AET and PET were used to generate ESI and EDDI indices. As explained in the previous section, both AET and PET were highly affected by seasonal rainfall. It is expected that ESI and EDDI will highly correlate to the SPI. The time series of EDDI, ESI, and SPI were shown in Figure 5. The result showed that the three indices were quite consistent with each other to capture the most extreme, severe, and moderate drought years, as well as the wet years. The SPI correlation with EDDI and ESI were 0.76 and 0.79, respectively, which implies that the MODIS satellite products are suitable of characterizing dry and wet conditions in the

ARB. The correlation between EDDI and ESI was 0.89. Considering monthly time series were used in this study, the number of drought events might increase with a shorter time resolution as the indices (e.g., SPI, ESI, and EDDI) quickly changed between wet and dry months. However, the most devastating drought years were 2000, 2004, 2005, and 2006. 2008, 2009, and 2012.

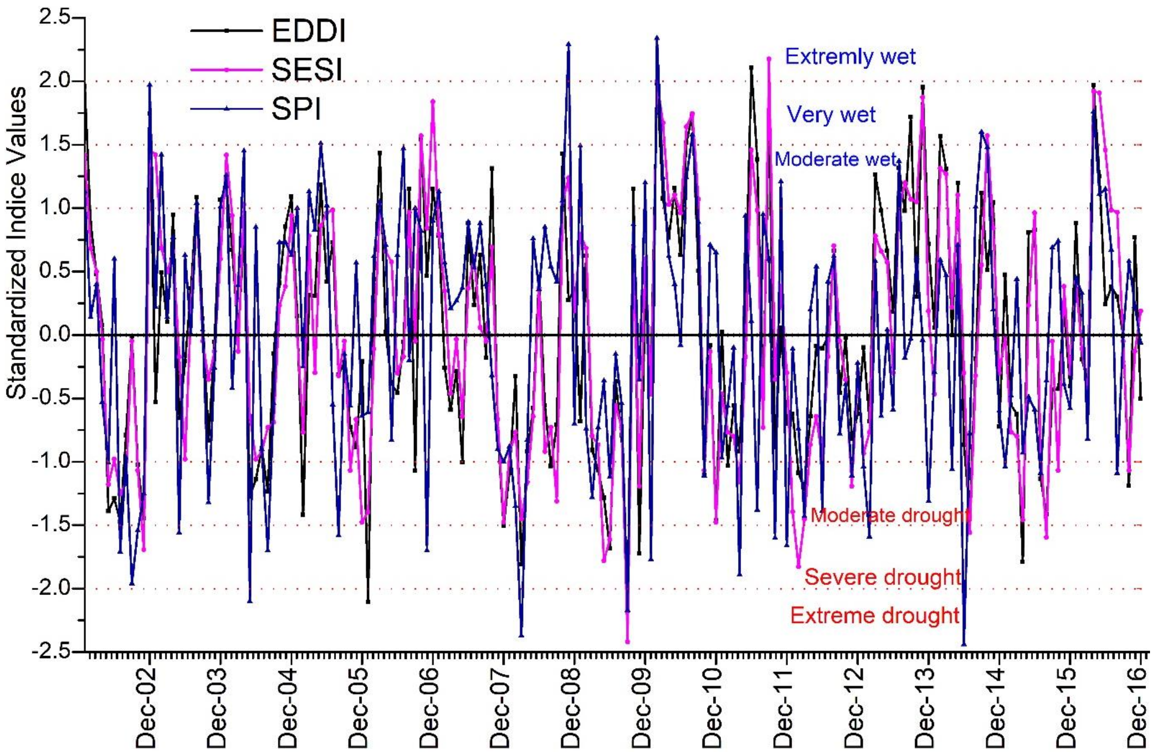

Figure 5. Comparison of monthly based drought indices of EDDI, SESI and SPI.

3.3 Evaluating flash drought using ESI and EDDI

The shorter duration of weekly ESI and EDDI can indicate the early onset of drought that cannot be detected by conventional drought analysis with monthly data. Flash drought in the ARB was examined during the two growing seasons of the mRS (Feb-May) and the MRS (June-Sep) because the evaporative stress is less sensitive to drought in non-growing seasons (Christian et al., 2019). Recent historical drought years of 2002, 2008, 2009, 2012, and 2015 were used to evaluate the spread of flash drought over the ARB. Figures 6 and 7 showed the spatial evolution of flash drought in 2008 historical drought, which were results of flash drought areas identified by weekly ESI and EDDI drought indices and followed the criteria of flash drought as mentioned in Christian et al. (2019).

3.3.1 ESI based evolution of 2008 flash drought

The distributions of flash drought in 2008 mRS and MRS with weekly ESI were depicted in Figures 6a and 6b, respectively. The flash drought in 2008 mRS started from the second week of February in the upstream basin and expanded to the northwestern and southwestern peripheries and along with the river (Figure 5a). The downstream part of ARB experienced less flash drought in February and March. During April and May, the flash drought over the upstream basin has become less and shifted to the downstream part, particularly the northeastern and southeastern basin. However, the flash drought extent varied quickly from one week to another. The upstream basin experienced flash drought during the first two months of mRS. It is noted the area along the river were vulnerable to flash drought throughout the entire mRS due to the presence of better vegetation coverage and high temperature. The shift of flash drought in April and May might be caused by the erratic minor rainfall started in the downstream basin to trigger the grassland to grow. Figure 6b presented the spread of flash drought during the MRS. Unlike the spatial shifts of flash drought observed in 2008 mRS (Figure 5a), the downstream basin was mainly identified to experience flash drought during the MRS. Moreover, the flash drought in the MRS extended in June and the first week of July were larger than those of other weeks.

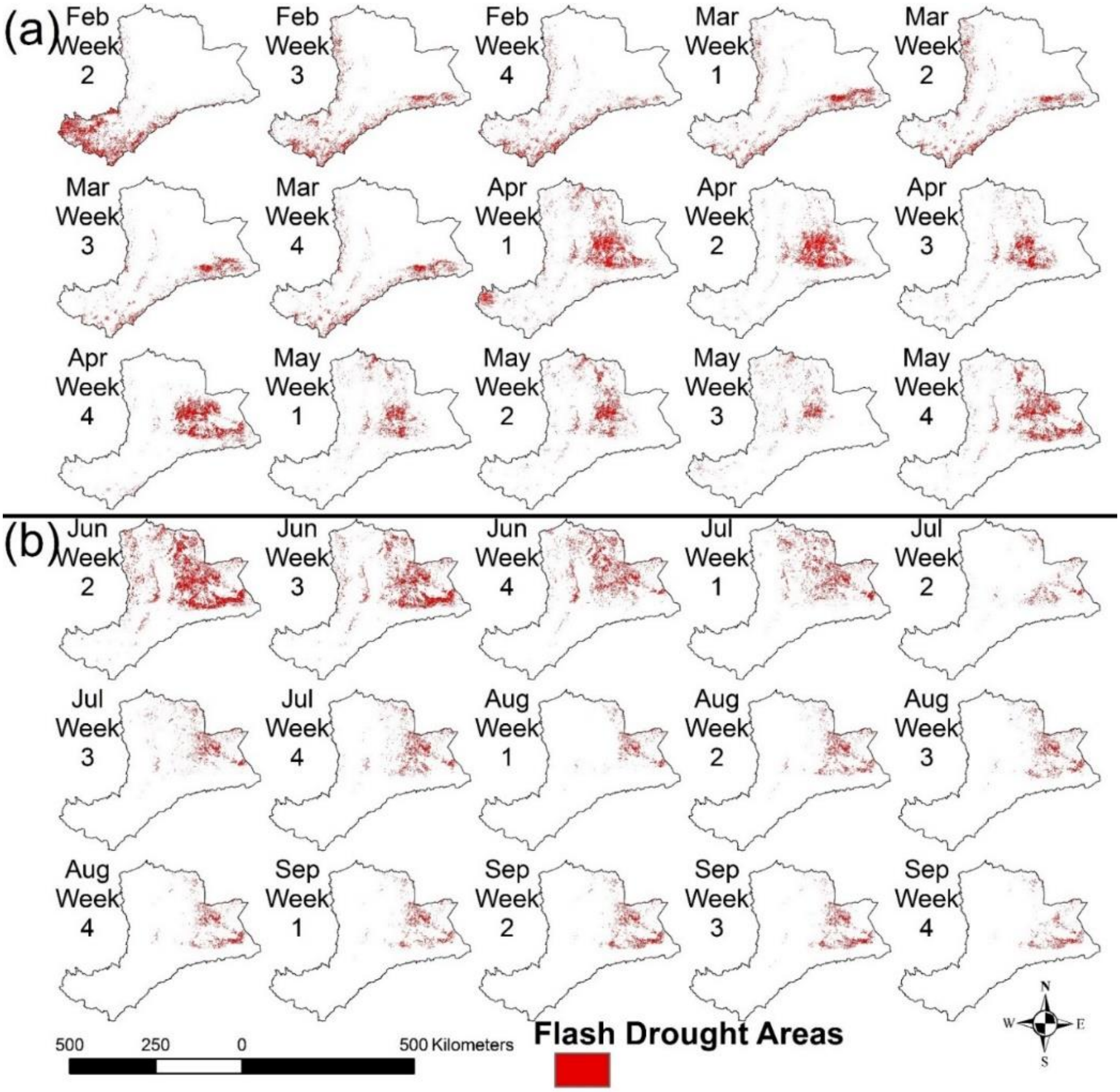

Figure 6. Spread of flash drought over the Awash River basin using weekly ESI in the case of 2008 historical drought: (: (a) during the mRS (February - May), and (b) during the MRS (June - September).

3.3.2 EDDI based evolution of 2008 flash drought

The spread of flash drought in 2008 mRS and MRS with weekly EDDI were depicted in Figures 7a and 7b, respectively. Similar to the ESI results, the EDDI results identified the mRS flash drought of 2008 began in the second week of February mainly over the upstream and southwestern basin. Starting from the third week of February till the fourth week of March, the flash drought expanded over the larger area of the basin, except for the downstream part of the basin. Similar to the ESI results, the EDDI flash drought shifted to the downstream basin during April and May, except for the first and second week of May. The area coverage of flash drought identified by the EDDI were larger than those by the ESI. As shown in Figure 7b, the MRS flash drought was observed in the semi-arid part of the downstream basin. The MRS flash drought observed in the downstream basin was smaller in the first week of August and the first and second week of July as compared to those of the other weeks. Weekly flash drought identified by ESI and EDDI showed similar shifts in spatial distributions from one week to another, but their areal coverage was quite different of having larger flash drought areas by the EDDI.

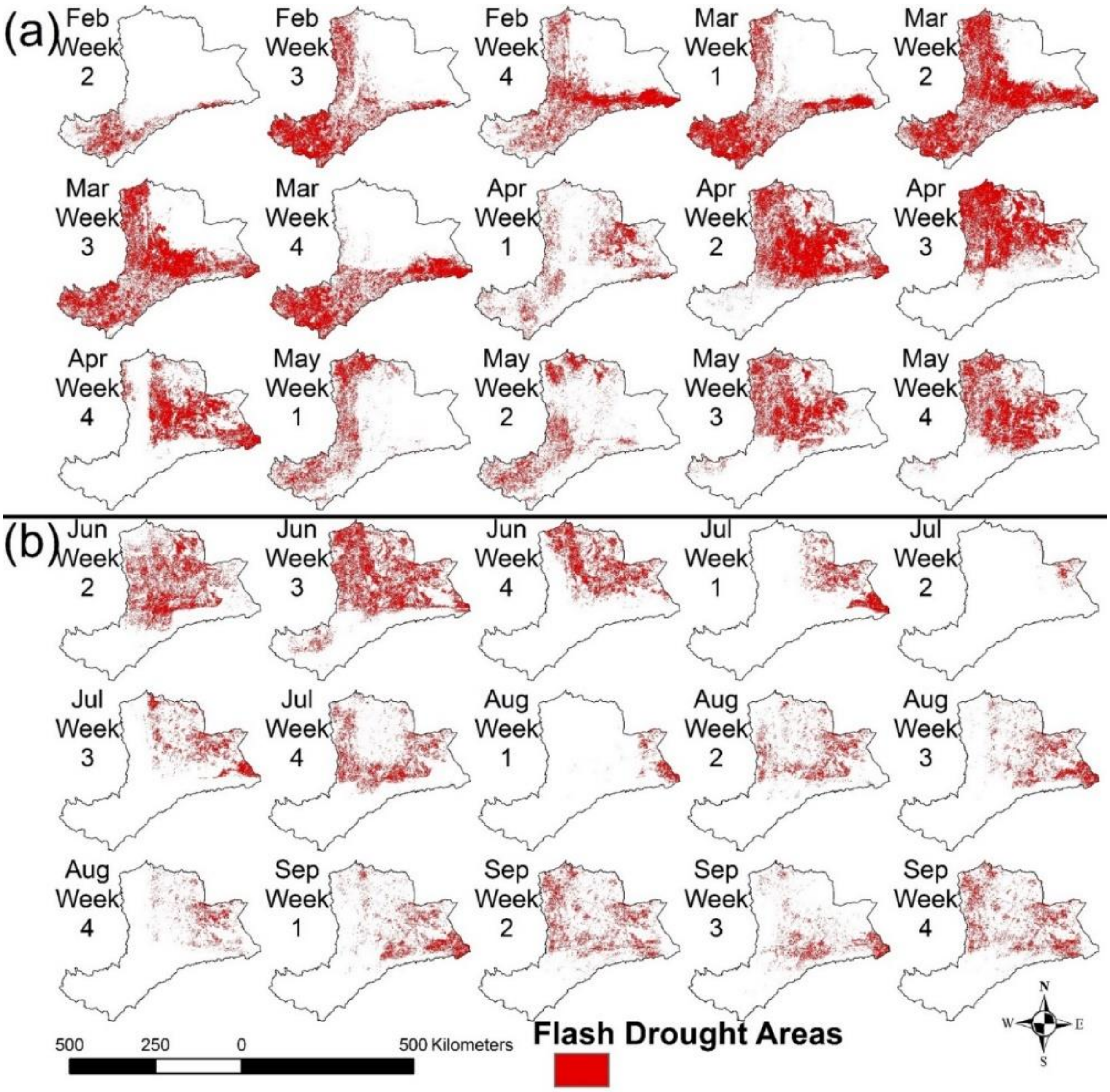

Figure 7. Spread of flash drought over the Awash River basin using weekly EDDI in the case of 2012 2008 historical drought: (a) during the mRS (February - May), and (b) during the MRS (June - September).

3.3.3 Flash drought intensity based on ESI

Following the fourth criterion of flash drought given by Christian et al., (2019) that the mean changes in SSESI/ SEDDI must be below the 25th percentile for the entire pentads, it is able to indicate the rapid intensification of flash drought. As depicted in Figures 8 and Table 2, the flash drought intensity was classified based on the mean changes in SSESI/SEDDI. Flash drought intensity was classified as an exceptional, extreme, severe, and moderate flash drought if the mean changes in SSESI/ SEDDI were respectively < 10th percentile, between 10th and 15th percentile, between 15th and 20th percentile, and between 20th and 25th percentile, respectively.

The ESI-based flash drought intensity of 2002, 2008, 2009, 2012, and 2015 droughts using the mean change in SSESI (< 25th percentile) were presented in Figure 8 and Table 2. The exceptional and extreme flash drought intensity mainly exhibited in the highland and humid (i.e., upstream, southwestern, and northwestern) parts of the basin with the most dominant land-cover types of agricultural crops, grasses, and shrublands. Additionally, the exceptional and extreme flash drought distribution observed in the lowland (i.e., downstream) part of the basin were directly linked to the rangelands (grasslands) of the area. The exceptional and extreme flash drought intensity in 2008 and 2012 extended over the ARB were larger than those of the other drought years. For example, the exceptional and the extreme flash drought covered 5.77 % (6711.5 km^2) and 10.13 % (11792.1km^2), respectively, of the basin area in 2008 drought (Table 2). The upstream (agricultural lands), irrigated croplands along the river, and the downstream (grasslands) part of the basin experienced a prevalence of flash drought. Overall, the area of the ARB that experienced flash drought in 2002, 2008, 2009, 2012, and 2015 are 23 % (26355.9 km^2), 40 % (46449.5 km^2), 20 % (22943 km^2), 40 % (46074.8km^2), and 24 % (27559.5 km^2), respectively.

Table 2. ESI based categories of flash drought intensity and their area (km^2) coverage in ARB in the cases of 2002, 2008, 2009, 2012 and 2015 recent drought years

Categories of flash drought intensity	Historical droughts years					Commonly affected areas
	2002	2008	2009	2012	2015	
Moderate flash drought	4423.5 (3.80%)	8663.8 (7.44%)	5427.6 (4.66%)	9960.4 (8.56%)	8391.4 (7.21%)	17.6 (0.02%)
Severe flash drought	11308.9 (9.72%)	19282.1 (16.57%)	10150.1 (8.72%)	19196.7 (16.50%)	9444.9 (8.12%)	1375 (1.18%)
Extreme flash drought	7942.2 (6.82%)	11792.1 (10.13%)	3792.7 (3.26%)	12003.1 (10.31%)	6827.3 (5.87%)	948 (0.81%)
Exceptional flash drought	2681.3 (2.30%)	6711.5 (5.77%)	3572.6 (3.07%)	4914.6 (4.22%)	2895.9 (2.49%)	14.4 (0.01%)
Total area	**26355.9 (23%)**	**46449.5 (40%)**	**22943 (20%)**	**46074.8 (40%)**	**27559.5 (24%)**	**2355 (2%)**

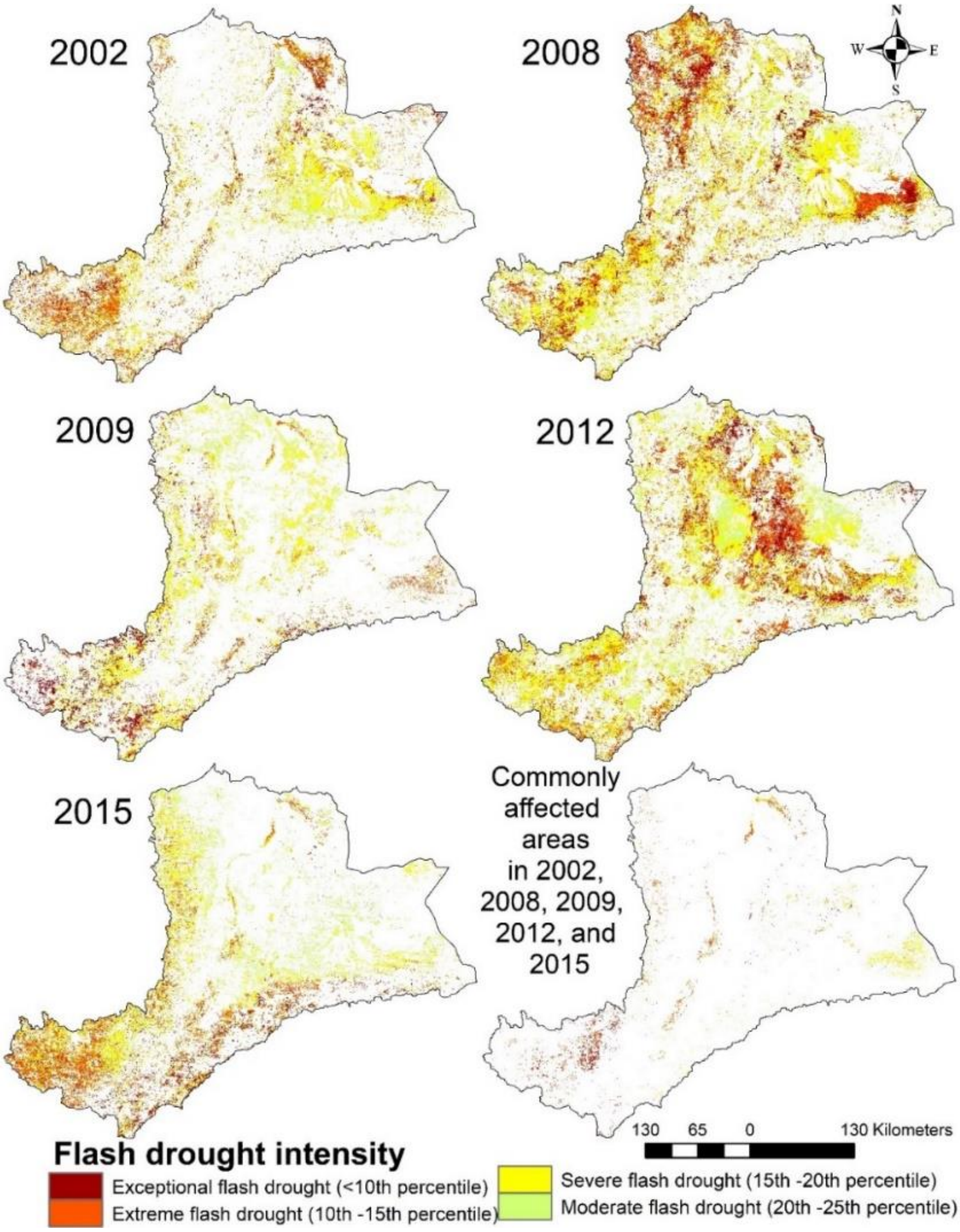

Figure 8. ESI based flash drought intensity over the ARB using the mean changes in SSESI below 25th percentile threshold in the case of 2002, 2008, 2009, 2012, and 2015 recent drought years.

3.3.4 Flash drought intensity based on EDDI

Figure 9 and Table 3 presented the EDDI-based flash drought intensity of 2002, 2008, 2009, 2012, and 2015. The results of EDDI are similar to those of ESI, except the areal extent of flash drought identified by EDDI were generally larger than those by the ESI. Similarly agricultural and grassland areas were highly affected by flash drought. Overall, most of the basin experienced flash droughts with different intensities from one year to another. During 2002, the exceptional and extreme flash drought coverages were larger than those of other years and covered 19.56 % (22758.3 km^2) and

22.05% (25657.1 km^2) of the basin, respectively.

Several flash drought studies were conducted in the United States and they found that agricultural lands and grasslands were highly vulnerable to flash drought because of the shallow root system and high rate of evapotranspiration (Otkin et al, 2014; Mo and Lettenmaier, 2016; Otkin et al, 2018; Christian et al., 2019). Moreover, comparatively agricultural lands were more prone to flash drought than grasslands. Our results generally agreed with their findings, the ARB were highly vulnerable to flash drought over upstream agricultural land, irrigation cropland along the river, and downstream grasslands. High temperatures and densely vegetated areas were also exposed to flash drought risks due to the increase in evapotranspiration from the vegetation (Zhang et al., 2019). Semiarid plain regions are sensitive to land-atmosphere interaction, such as the decreased evapotranspiration caused by reduced soil moisture will limit the local source of boundary layer moisture to restrict atmospheric moisture advection. As a result, the atmosphere remains dry to increase the evaporative demand and the dry soil keeps altering the ambient environment to be less supportive of convective rainfall and intensifies flash drought (Basara and Christian, 2018; Christian et al., 2019). They also reported that regions that lack soil water availability and have sparse vegetation could not be susceptible to flash drought.

EDDI is mostly vital for flash drought early warning because it is independent of rainfall and soil moisture with less uncertainty related to topography and regional convective activities (Hobbins et al., 2016). EDDI is also sensitive to two distinct land-surface atmosphere interactions (Hobbins et al., 2016; McEvoy et al., 2016): (1) The surface moisture limitation that leads to declining of ET and increasing of PET indicates a sustained drought, and (2) the increases of ET and PET from increased energy availability that results in surface moisture limitation to trigger a flash drought. PET can rise in all drought cases and could be the first sign of drought (Hobbins et al., 2016). The flash drought extent under EDDI is larger as compared to ESI in the ARB because of the first condition that under a water-limited environment, ET and PET respond in the opposite direction, which indicates a sustained drought.

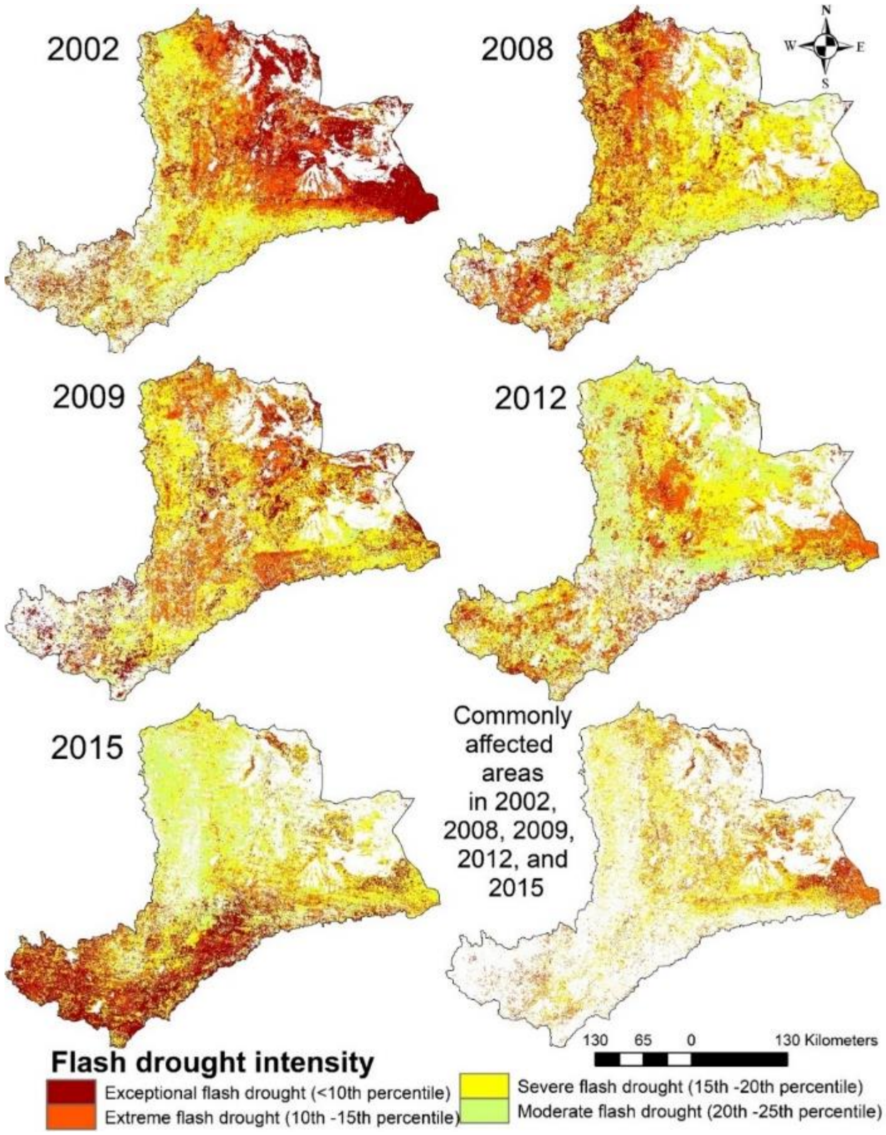

Figure 9. EDDI based flash drought intensity over the ARB using the mean changes in SEDDI below 25th percentile threshold in the case of 2002, 2008, 2009, 2012, and 2015 recent drought years.

Table 3. EDDI based categories of flash drought intensity and their area (km^2) coverage in ARB in the cases of 2002, 2008, 2009, 2012 and 2015 recent drought years

Flash drought intensity	Historical droughts years					Commonly affected areas
	2002	2008	2009	2012	2015	
Moderate flash drought	14558.8 (12.51%)	15151.9 (13.02%)	11315.7 (9.72%)	24346.2 (20.92%)	21118.9 (18.15%)	807.5 (0.69%)
Severe flash drought	20065.9 (17.24%)	34395.8 (29.56%)	29968.7 (25.75%)	28097.3 (24.14%)	27136.8 (23.32%)	21150.4 (18.17%)
Extreme flash drought	25657.1 (22.05%)	23009.3 (19.77%)	21228.9 (18.24%)	20569.9 (17.68%)	10464.6 (8.99%)	12592.8 (10.82%)
Exceptional flash drought	22758.3 (19.56%)	11285.2 (9.70%)	15026.3 (12.91%)	5696.8 (4.90%)	18765.9 (16.31%)	1285.5 (1.10%)
Total area	**83040.1 (71.4%)**	**83842.2 (72.05%)**	**77539.6 (66.63%)**	**78710.2 (67.64%)**	**77486.2 (66.58%)**	**35836.2 (30.79%)**

3.4 Conventional drought using ESI and EDDI from 2002 to 2017

Besides the weekly flash drought analysis, the conventional drought was examined from 2002 to 2017 to check whether the flash drought extends to full-blown conventional drought or not. As shown in Figures 10-14, most of the considered flash drought events such as 2002, 2008, 2009, 2012, and 2015 were extended to conventional drought regardless of drought months and spatial extent. The month of May exhibited more frequent drought as compared to other months of the mRS (i.e., February, March April, and May) as shown in Figures 10 and 11. Similar to the flash drought results, the spatial extent and severity of conventional drought identified by the EDDI were much larger than those by the ESI. For example, the spatial pattern of conventional drought was similar to those of flash drought identified in February and March, mainly over the upstream (south-west) and peripheries of the basin. In the month of April and May, almost the entire and north-eastern (downstream) part of the basin experienced more drought compared to other parts of the basin.

The month of June exhibited more frequent drought following by September than those of other months in the MRS (i.e., June, July, August and September) as shown in Figures 14 and 13. The conventional drought pattern in the MRS is similar to the results of flash drought that the north-eastern (downstream) part of the basin experienced more drought during July, August and September, whereas in June the entire basin revealed more drought.

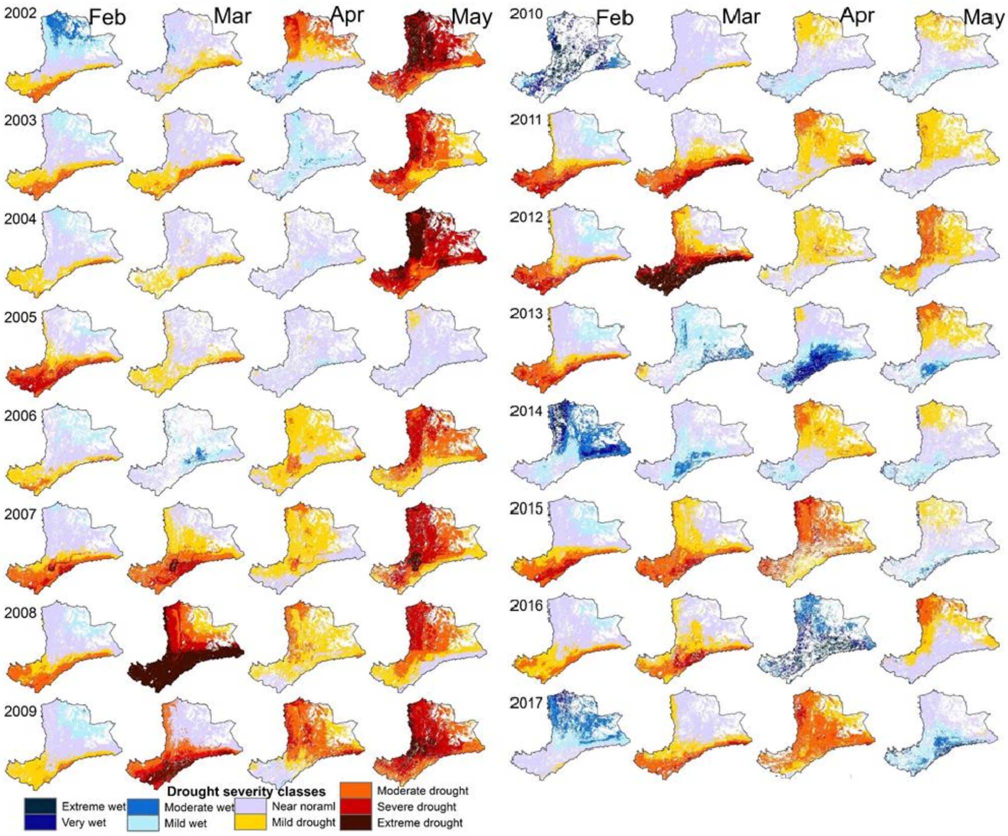

Figure 10. Monthly EDDI based full blown of conventional drought in the mRS during (2002-2017).

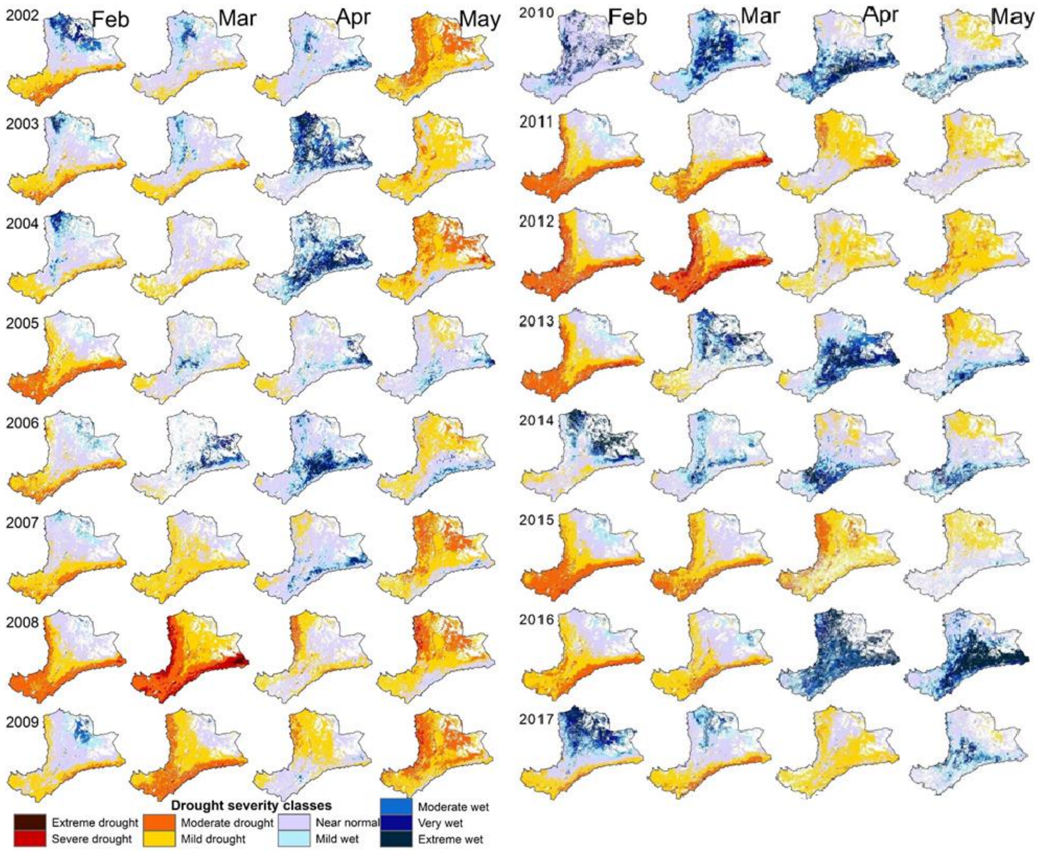

Figure 11. Monthly ESI based full blown of conventional drought in the mRS during (2002-2017).

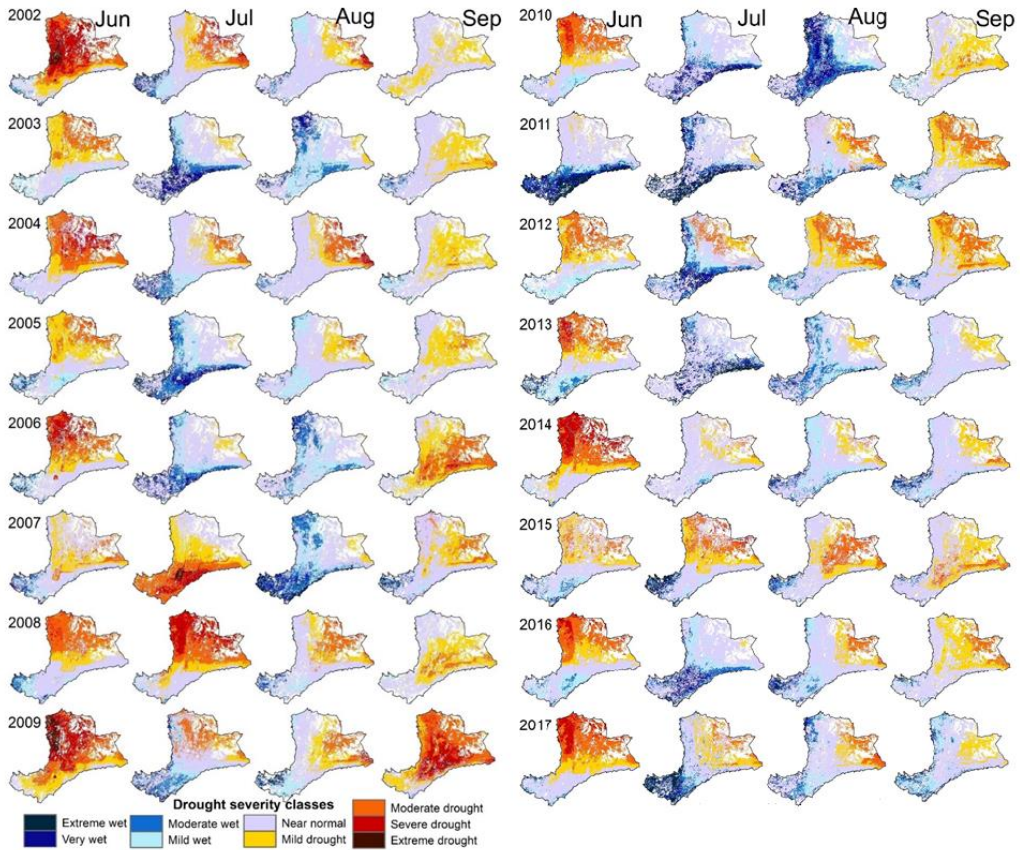

Figure 12. Monthly EDDI based full blown of conventional drought in the MRS during (2002-2017).

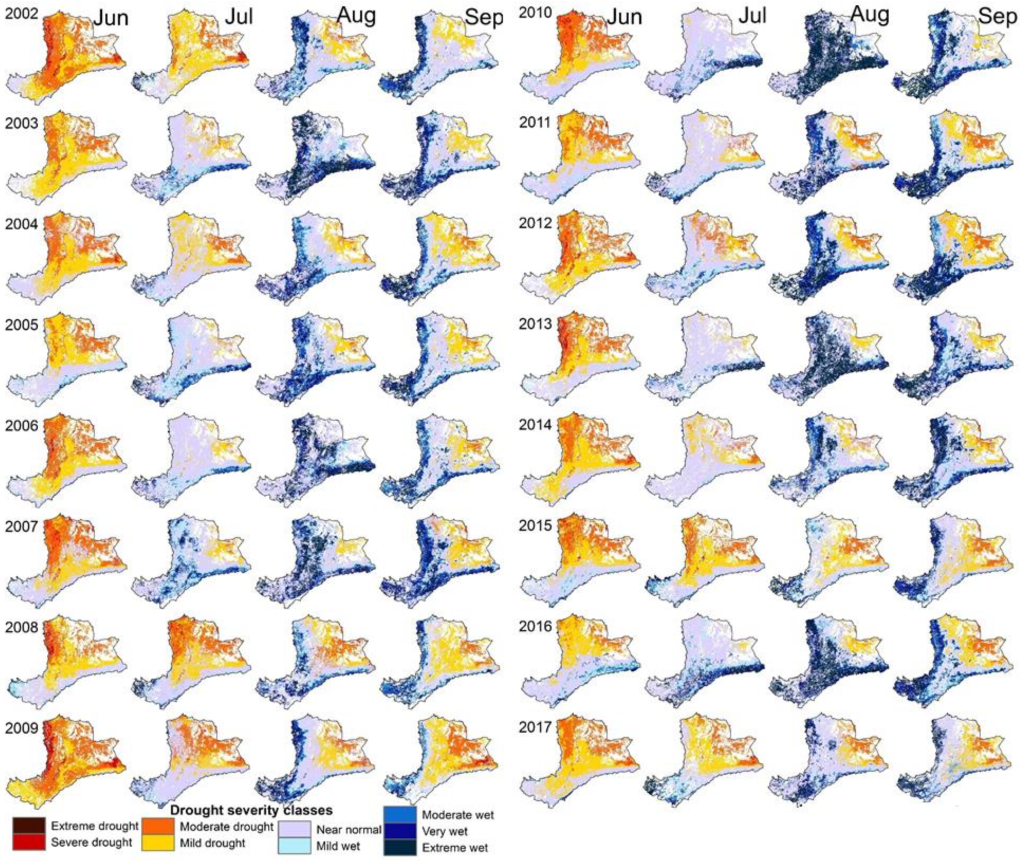

Figure 13. Monthly ESI based full blown of conventional drought in the MRS during (2002-2017).

4. Conclusions

The most severe droughts in recent years over the ARB were evaluated with the flash drought indices and approaches proposed by Christian et al, (2019). The distributions of flash drought during the mRS and the MRS in 2008 were identified with both EDDI and ESI. Flash droughts that rapidly intensify within a week were also examined. Mostly observed in February and March, the upstream, northwestern, and southwestern peripheries of the ARB experienced flash drought in 2008 with the spatial coverages mainly correlated with agricultural crops and grasslands. During April and May, the flash drought in the upstream basin became less and expanded to the downstream, particularly the northeastern and southeastern basins. During most weeks of the MRS, the downstream basin was identified to experience flash drought. Since the EDDI is solely dependent on PET and it can intensify with increasing temperature regardless of rainfall and soil moisture, the flash drought extent identified by the EDDI were generally larger than those by the ESI. Based on different drought intensities, flash droughts were classified as exceptional, extreme, severe, and moderate flash droughts. The exceptional and extreme flash droughts mainly exhibited in the highland and humid (i.e., upstream, southwestern, and northwestern) parts of the basin with dominant land-use types of agricultural crops, grass, and shrublands. Additionally, the exceptional and extreme flash droughts were found in the lowland downstream part of the basin with grasslands as the dominant land-use types. The irrigated croplands along the river were also identified to be highly vulnerable to flash drought. Early identification of flash drought expansion based on AET and PET under rising temperatures will be very helpful for developing drought monitoring. Particularly the EDDI is more sensitive to warming temperatures having the advantage of detecting the early onset of flash drought, which is vital for developing drought early warning. Using a shorter time resolution, the flash drought analysis can detect the early onset of drought as compared to the conventional drought analysis with a longer time resolution. By incorporating flash drought evaluations into drought monitoring and early warning will be very helpful to enhance proactive risk management strategies and minimize potential losses of agricultural production and increase food security.

5. Limitation of the study and recommendation

The lack of adequate and reliable observed data was the main challenge in this study. The meteorological stations are sparse especially in the downstream part of the ARB and without having long-term observed data. Thus, increasing the density of meteorological stations would be helpful for future drought evaluation and monitoring in the basin, especially over areas vulnerable to flash drought. Verification of the satellite data was difficult due to the lack of observed evapotranspiration and soil moisture data. For areas with rapid intensification of flash drought, it is recommended to deploy instruments to support analysis of flash drought with daily soil moisture, rainfall, and temperature data. Soil moisture evaluation at different depths in response to EDDI and ESI indices will enhance early detectability of flash drought that improve drought monitoring and predictions. Further investigations are suggested to understand effects of different land-use and land-cover types on the onset and evolution of flash drought, and the interactions between them. Examining flash drought response in relation to the ENSO and extreme events and incorporating climate projections to assess climate change impacts will be more important for minimizing the drought risk in the basin.

Authors' contributions

Yitea Seneshaw Getahun: process and analysis the data, data interpretation, and drafted the first version of the manuscript. Ming-Hsu Li: guided how to analysis the data, revised the paper and amended the manuscript.

Competing interests

The authors do not have any conflict of interest.

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T09

Contribution of the cryosphere changes to the increase streamflow on Lhasa river basin in Tibetan Plateau

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Abstract: Over the past few decades, the Lhasa River basin (LRB), which originates in the south Tibetan Plateau and covers an area of 32,896 km^2, has experienced increased streamflow, temperatures, and precipitation along with cryospheric degradation. Glacial meltwater is an important source for the river runoff in LRB. Based on the VIC_glacier model, this study simulated the runoff process in the Lhasa River Basin from 1990 to 2010. The results show that: (1) compared with the original VIC model, the VIC_glacier model shows good performance in streamflow simulation. The correlation coefficient between the observed daily streamflow and the simulation was close to 0.8, and the Nash efficiency coefficient is above 0.75. (2) From upstream to downstream, the contribution rate of glacial meltwater to runoff was 21.4% (Punduo Station), 17.7% (Tangjia Station), and 14.5% (Lhasa Station), respectively. (3) The annual changes of both glacial runoff and non-glacial runoff showed "single-peak" shape , and reached its peak in August. (4) From 1990 to 2010, the annual glacier runoff showed an increasing trend, which was consistent with the change of air temperature in the same period. However, there is a opposite trend between the contribution of annual glacial meltwater to runoff and the annual precipitation. The findings could provide a scientific basis for water resources management in the Lhasa River Basin.

T10

Evaluating the Effects of Climate Change on Water Availability using Water accounting Plus (WA+) Framework in the Wardha River Basin: Insights from a Spatially Calibrated Hydrologic Model

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This research provides an in-depth analysis of the water resources within the Wardha River Basin, employing the Water Accounting Plus (WA+) framework in conjunction with hydrological modelling to comprehensively address the challenges of sustainable water management in the face of climate change. The study uses the Variable Infiltration Capacity (VIC) model to simulate water fluxes, stocks, and flows across the historical period of 2003-2022 and projects these into the near future of 2023-2050. This projection utilizes data from an extensive ensemble of five Global Climate Models (GCMs) from CMIP6 projections, ensuring a robust analysis of potential climate change impacts on the basin's hydrology.

The integration of VIC outputs with the WA+ framework enables evidence-informed reporting on the hydrological dynamics of the Wardha River basin, offering insights into water flows, consumption patterns, and the interplay between land use and water management. This dual approach not only overcomes the limitations associated with data scarcity in transboundary basins but also provides a nuanced understanding of manageable and unmanageable water flows, enhancing the granularity of water resource assessments [1].

Findings from this study highlight a projected increase in the long-term net inflow to the basin, with a significant portion of this inflow subject to evaporation, leaving a modest fraction available for human and ecological needs. The analysis underscores the critical role of evaporation in the green water cycle and identifies the current and potential future water uses, emphasizing the agricultural sector's dominant consumption [2]. Furthermore, the study anticipates shifts in exploitable and available water fractions under future climate scenarios, stressing the importance of adaptive strategies to mitigate impacts and sustain water security.

This research contributes significantly to the field by integrating climate change projections with water accounting and hydrological modelling, offering a pioneering approach to water governance in transboundary basins [3]. By providing a comprehensive and standardized assessment of water resources, the study supports evidence-based decision-making, facilitating the development and implementation of effective management policies and strategies to address the challenges posed by climate change and socio-economic developments in the Wardha River basin.

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T11

Past and future hydrological extremes analyses over the Senegal River Basin (West Africa)

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Abstract

The aim of this study is to evaluate historical simulations from a highly distributed hydrological model CHyM (Cetemps Hydrological Model), and to assess the potential changes of extreme river discharge over the Senegal River Basin (SRB). The hydrological model was forced with 20 CMIP6 (Coupled Model Intercomparison Project Phase 6) runoff simulations to investigate the ability of CHyM to reproduce river flow characteristics and to assess the impacts of climate change on extreme stream flows under two different Socio-economic Pathways (SSPs) scenarios (SSP1-2.6 and SSP5-8.5). The evaluation of the hydrological model during the historical period, shows a good agreement between simulated and observed mean river discharges at eight (8) hydrometric stations in the SRB. The CHyM was able to reproduce the flow regimes during the low and high flows periods. Moreover, similar agreement was also found in the annual peak flow recurrence curves. However, in some hydrometric stations, the model overestimates the magnitude of both mean and peak river discharge. With regards to the future, decreasing trends were found in mean precipitation and mean river discharge from 2015 to 2099, even though slight increases were projected in the near future. The eastern basin will face the highest increase of temperature (up to 5.5°C) in the far future under SSP5-8.5 scenario. As for the extreme flows' changes, the high flows (95th percentile) are likely to increase significantly (13.54 -21.26 %) in coming decades at all hydrometric stations, and they are characterized by a strong interannual variability. Furthermore, the assessment of the impacts of global warming levels (GWLs) on annual peak flows that have 100 years return period (Q100), has revealed increasing flood risk due to rising GWLs (from 8% up to 21%, under 1.5 and 3.0 °C, respectively). The results of this study can be used to better plan the mitigation of the negative impacts of flood risk over the Senegal River Basin.

Keywords: Senegal River Basin**,** Hydrological modelCHyM , extreme flows

T12

Analyzing Historical and Projected Seasonal Climate Variability and Its Influence on Natural Surface Waterbodies: A Case Study of Coastal City Khulna, Bangladesh

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The IPCC sixth assessment report emphasizes that human-induced greenhouse gas emissions are causing alterations to climate variables such as temperature and precipitation worldwide, leading to an escalation in extreme weather events and impacting water and food security [1]. The geographic position of Bangladesh makes it highly susceptible to natural disasters, earning it a reputation as one of the world's most disaster-prone countries [2]. Floods, droughts, heatwaves, and cyclones inflict significant harm on crops, livestock, and communities almost every year [2, 3]. During the monsoon season, floods can have a severe impact on crops and domestic animals in Bangladesh, resulting in significant losses to the agrarian economy [4]. Additionally, these floods can adversely affect food security in the region [5]. Alternatively, during the dry season, increased temperatures paired with reduced precipitation levels can lead to more frequent drought occurrences [6]. These events have the potential to cause natural surface waterbodies to dry up, worsening water scarcity issues [6, 7].
This study systematically assesses seasonal variations in two climate parameters, such as temperature and precipitation, using historical and projected future datasets. The analysis utilizes observed data from the Bangladesh Meteorological Department (BMD) and projected data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) dataset. To comprehend the influence of climate variability on natural surface waterbodies, changes are estimated through Landsat imagery analysis. The findings of this study can serve as valuable insights for policymakers and administrators in formulating and executing effective water management strategies to promote sustainable development.

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T13

Implication of bias correction on quantification and allocation of uncertainties on hydropower projections under different Global Warming Levels

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Hydropower is the world's largest producer of renewable energy. It represents more than 43% of the low-carbon energy and its potential is more affected by the hydrological regime. Hydropower projections are subject to uncertainties that arise from different sources in the impact modeling chain. For any science-based decision making, the realistic assessment of the uncertainties is of paramount importance. This study assesses the implication of the bias-correction on the total uncertainty on hydropower projections and its effect on uncertainty decomposition under 1.5° and 2.0°C global warming levels (GWLs). Raw and Bias-corrected precipitation and temperature from 17 CORDEX-Africa members combined 09 general circulation models (GCMs) and five regional climate models (RCMs) under two representative concentration pathways (RCPs) 4.5 and 8.5 were used to run two calibrated Lumped-conceptual hydrological models (HMs) (HBV-Light and HYMOD). An analysis of variance (ANOVA) decomposition was used to quantify the uncertainties related to each impact modeling chain step for hydropower potential calculation process, namely RCP scenarios, GCMs, RCMs and HMs. The results revealed that the bias-correction technique doesn’t significantly affect the sign and the magnitude of the change signal as well as the total uncertainty in hydropower projections. However, the uncertainty decomposition based on ANOVA reveals that the bias-correction affects the contribution of each uncertainty source to the total uncertainty. In addition, the bias-correction significantly reduces the uncertainty arising from the residual errors. Under 1.5°C GWL, climate models (GCMs and RCMs) significantly contribute to the total uncertainty, while under 2.0°C GWL, all the four main sources of uncertainty significantly contribute to the total uncertainty which is no longer the same when we use the raw data. This finding brings more insight to the importance of the bias-correction on hydrological and hydropower projections for decision-making.

T14

Advancing Water Resource Modeling through Generative AI Technologies

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Water resource modeling is crucial for efficient freshwater management, yet conventional hydrological models struggle to accurately represent the complex and ever-changing hydroclimate systems. The research investigates incorporating generative artificial intelligence (AI) tools into water resource modeling to improve prediction capabilities and enhance our understanding of water dynamics. Generative AI, which includes generative adversarial networks (GANs) and recurrent neural networks, could be used to model hydroclimate processes that are uncertain and make accurate predictions. The study intends to improve the accuracy of water resource estimates, evaluate potential effects of climate change, and strengthen decision support systems for sustainable water management using generative AI. This research brings together a thorough review of current hydroclimate models, generative artificial intelligence (AI) methods, and their uses in related fields. The results will highlight the significant effect th. at generative AI can have on water resource modeling, contributing to important changes in adaptive water resource planning and policy development.

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T15

Combined impacts of climate and land use changes on water resources in Kenya, A Case study of Kisii County River Basins. Part 1: Contemporary Period.

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Abstract

Climate variability and change (CVC), and land use-land cover changes (LULCC) are some of the factors that affect water resources, affecting different sectors of the economy and livelihoods in various parts of the world. This study looked at how CVC, and LULCC have affected water resources in Kenya from 1981 to 2023 using Kisii County as a case study. The study objective was to diagnose how LULCC and CVC have affected river regimes in Kisii County focusing on two basins in the County; Marani and Bomachoge Chache. The data used in this study comprised geospatial data of rivers and stream networks from World Resource Institute (https://www.wri.org/data/kenya-gis-data) used for mapping and assessing streams and river changes over the years. Rainfall and temperature data from Climate Hazard Infrared precipitation with stations and minimum and maximum temperatures from Kenya Meteorological department were used to assess rainfall and temperature changes over the years for two rainfall regimes experienced in the region; March-April-May (MAM) and September-October-November-December (SOND). Other data (observed LULCC, river regime changes) used was gathered through pre-tested questionnaire. Purposive sampling was used to select interviewees. Mann Kendall statistic was used to determine whether the trend of rainfall and temperature observed is significant. Chi-square test was used to determine whether there was significant variation from respondents on the changes in river regimes and wetlands. 362 responses were recorded. Analysis of Landsat over the years indicate changes in land use type with agriculture and build-up areas increasing in areal coverage while forest and grasslands decreasing. This was confirmed by 70.7 % of the respondents who indicated that the river regimes and wetlands have decreased over time while only 29% were of different opinion. The computed chi square value was 62.2 at 1-degree freedom which indicated a significant decrease in river levels and wetlands in Kisii County. This observation is in line with Mironga (2005) who indicated that Kisii wetlands are under threat due to intensified agricultural activities. Further 78.5% of the respondents indicated that the river volumes had declined to a large extent. This was a significant observation with a chi square value of 83.3 at 1-degree freedom ($P<0.05$). This is a clear indication that most wetlands are seriously under threat. From the analysis, rainfall has not shown any significant change in Kisii County while temperature (min, max & avg) trend has been significantly increasing over the years at 95% confidence level. This could explain the observed reduction in river levels, due to enhanced evapotranspiration interfering with the hydrologic cycle. Our second part of this work aims to conduct model simulations at convective permitting scale to compare the model results with these findings. We hope to inform policy changes in favor of water resource conservation which is key in various sectors of the economy.

Key words: Climate variability, Climate change, river regimes, LULCCC, wetlands.

T16

Coupling EM-DAT Reported Flash Floods with IMERG Precipitation Data

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Flash floods significantly impact societies and their economies. The latest entry of a major flash flood in the Emergency Database is the Democratic Republic of the Congo, with 201,000 USD in total damages, around 20,000 affected people, and 2,970 deaths (Updated 2023-09-26), as the [2]. Riverine floods typically affect most people, but flash floods have a higher mortality per incident [1], making them extremely dangerous. This research investigates the global distribution and economic impact of flash floods using the EM-DAT database from 2001 to 2020. We introduce a method for georeferencing the EM-DAT entries locating and characterizing each possible flash flood. This study also identifies the Mediterranean Basin, Central South Asia & Georgia, and Southeast Asia as regions most susceptible to flash floods. We found that the spatial distribution of flash floods, aligns with the regions affected by monsoonal rainfall patterns.

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T17

A systematic analysis of Regional Climate models in determining Flooding at Basin Scale using Global Hydrodynamic model

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Analyzing global weather patterns is necessary to comprehend flood hazards resulting from climate change. The advancement of climate science has been beneficial in the creation of global flood models (GFMs). Although they are widely used, general circulation models (GCMs) are not very good at capturing local characteristics and extreme occurrences. Higher temporal and spatial scales are provided by regional climate models, or RCMs. In this study, a high-resolution GFM for the flood-prone Mahanadi River basin in India is driven by CORDEX RCMs. Bias-corrected RCMs are compared using APRODITE. Rainfall data and spatial inputs are employed in the two-dimensional GFM LISFLOOD-FP. MODIS satellite imagery is used to validate the model's outputs. The study advances our understanding of RCMs' capability for regional flood mapping in data-scarce areas.

Due to simultaneous climate changes and global changes in weather patterns, it is imperative that one understands the mechanisms underlying the dynamics of flood hazards. Hydrologists and flood modellers have historically depended on General Circulation Models (GCMs) to incorporate the consequences of climate change through GFMs, such as precipitation, runoff, etc. However, GCMs may become less useful when trying to explain local and regional variables, like topography and land-surface features, because of their coarse resolution, which ranges from 100 to 300 km. Additionally, several research point out that GCMs might not be able to replicate extreme occurrences at long time scales. As they can capture weather and climate processes at larger spatial and temporal scales, Regional Climate Models (RCMs), which are available at sub-GCM resolutions, are an appropriate substitute in these circumstances. A group of high-resolution RCM ensembles known as the Coordinated Regional Climate Downscaling Experiment (CORDEX), a part of the World Climate Research Program. Already known for their spatial and temporal capabilities to accurately capture floods at regional sizes, it is less clear how effective they are at inundation levels. In order to capture flood data over the Mahanadi River basin, India's most severely impacted area by flooding, at high resolutions (35 km x 35 km), this study, for the first time, takes into account a suite of CORDEX South Asia RCMs.

The RCMs are bias adjusted and compared with APRODITE to guarantee that gridded estimations are accurate. The General Extreme Value (GEV) distribution is fitted to the rainfall data from 1980 to 2020 to derive design rainfalls for various return periods. The rainfalls are sent to LISFLOOD-FP, a two-dimensional GFM, together with geomorphic (river width, depth, etc.) and spatial (Digital Elevation Model, Land use Land Cover) inputs to determine flood inundation statistics for

the area. By comparing historical flood maps from MODIS satellite photography, the model results were also confirmed. The study increases our knowledge of RCMs' capacity for regional flood inundation mapping in situations with scant station-level data, which is a significant challenge in many data-scarce or ungauged flood-prone watersheds in low- and middle-income countries.

Keywords: CORDEX; LISFLOOD-FP; Flood hazards; Mahanadi River Basin; MODIS; Regional Climate Models;

T18

How Far Can We Rely on CORDEX RCMs to Quantify Climate Change Impacts on Flood Risk- A Hydro-climatic Modeling Approach over a Severely Flood-Prone Coastal Multi-Hazard Catchment in India

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In the wake of climate change, along with global warming, global flood events have witnessed a notable surge in both intensity and frequency. While General Circulation Models (GCMs) have enhanced our comprehension of atmospheric processes, their application in regional flood mapping poses significant challenges due to their coarse spatial resolution. Previous research endeavors have commonly utilized GCMs and their downscaled versions to integrate hydro-climatological data. However, these models often exhibit substantial discrepancies in capturing flood statistics at the regional level. In light of these limitations, high-resolution Regional Climate Models (RCMs) present a promising alternative. Nevertheless, their efficacy in accurately representing transformations in flood risk remains an unexplored territory. In an attempt to answer these riveted research questions, this study, for the first time, explores the fidelity of a set of RCMs (**RegCM4.7, COSMO & REMO2015**) from the Coordinated regional climate downscaling experiment (**CORDEX**) Consortium for flood risk quantification. The proposed framework is demonstrated over the sensitive flood-prone deltaic stretches of the Lower Mahanadi River Basin (India), which is known to witness a complex interplay of multiple flood drivers like extreme rainfall, storm tides, and riverine flows. The rainfall projections from these RCMs are divided into historical (1990-2019) and future scenarios (2060-2099). Design rainfalls for 1 in a 100-year return period are calculated using a set of probability distributions. Design rainfall, along with other ancillary datasets (high-resolution Digital Elevation Model, land use land cover, design discharge, and design storm tides), are fed as an input to the MIKE+ 1D-2D hydrodynamic flood model to derive 1 in 100-yr flood hazard map at the inundation scale. To understand the hidden characteristics of vulnerability, a comprehensive set of 24 physical and socio-economic indicators is considered in a Shannon-entropy and TOPSIS framework. A novel concept of ***Bivariate Choropleth*** is utilized to understand the marginal and compound contributions of hazard and vulnerability. A superlative performance of COSMO was observed over other RCMs in capturing hydro-climatological behaviors. A conspicuous rise in flood hazards is noticed in future scenarios, primarily across the coastal stretches. The findings of this study assist in identifying potential hotspots that are expected to witness serious flood risk (high hazard and vulnerability) in the future. The study also recommends appropriate climate-resilient adaptation measures to mitigate vulnerability for future periods, ultimately reducing risk.

Keywords: Bivariate Choropleth; CORDEX; Flood Risk; Lower Mahanadi River Basin; MIKE+; TOPSIS

T19

Investigating climate change effects on hydrology in the Great Alpine region through high resolution convection permitting regional climate modelling and hydrological modelling

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High resolution climate simulation holds promise for enhancing the representation of local hydrological processes, as the impact of climate on hydrology is expected to be better captured at finer scales. In this context and with an uptake in the utilization of high resolution regional climate models in the last decade, a regional climate model ensemble for the Great Alpine region, at the convection permitting (CP-RCM) resolution (> 3 km), has been released. This ensemble has been made available through the CORDEX Flagship Pilot Study on Convective phenomena at high resolution over Europe and the Mediterranean (FPSCONV) [1,2].
In order to investigate possible enhancements of hydrological descriptions, the CETEMPS hydrological model (CHyM) [3] was used coupled off-line with the different CP-RCM ensemble members. The model has been run in two distinct settings: one using temperature and precipitation inputs from the driving CP-RCM, and the other directly employing the runoff. Validation of the hydrological simulation ensemble has been conducted against data from local monitoring stations situated in the Po River and central Italian river basins, employing metrics such as the Kling–Gupta efficiency (KGE). The climate change projections are compared with previous lower resolution simulation driven by convection parametrized regional climate models from the Euro-CORDEX ensemble [4].

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T20

Title: Climate change adaptation at Nile Basin Initiative

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Nile Basin countries are already experiencing the effects of climate variability and change. There is evidence for increase in temporal variability of rainfall in recent years. Yet, there is a large degree of uncertainty in establishing concrete climate trends and impacts, particularly in the Nile Basin. Furthermore, upper and lower Nile Basin are projected to experience quite different precipitation trends (increase e.g., in the upper Blue Nile, decrease further downstream). Blue Nile and White Nile have different flow regimes and different natural storage capacity, so that the impacts of increasing variability will be different. Changes in frequency and intensity of extreme climate events in the Nile Basin offer a very complicated picture. In some countries, mean annual rainfall is projected to increase slightly and decrease in others. Shifts in rainfall seasonality — including delayed onset and decreased duration of the rain season — will cause an increase in frequency and intensity of extreme rainfall events, flooding and soil erosion. The Nile Basin is also likely to experience an increase in mean annual temperature of around 1.5-2°C by the 2050s. Droughts are projected to become more frequent and intense across the entire region. The prolonged dry season and increased temperatures will intensify droughts and their impacts on agriculture and therefore vulnerable communities in the eight countries. Frequent severe droughts affect the livelihoods and food security of millions of people, leading to a famine, migrations and even death. Addressing these and similar challenges is crucial for effective adaptation to climate change and enhance resilience of the basin countries' economies. Moreover, the early warning systems are in their nascent stages of development. Every dollar invested in disaster mitigation and climate-resilient infrastructure 6 dollars are saved. Hydro-meteorological hazards account for 90% of natural disasters in East Africa region. It enables NBI to foster cooperation in the Nile Basin around the topic of better informed decision making consider current and future available resources. NBI developed strategy, policies, action plan, tools, and knowledge products to mitigate the impact of climate change. Over the past several years, the NBI has built its capacity in the generation data, information, and provision of climate services. The NBI will share its experience in this conference on climate change adaptation. The NBI stakeholder database was >3000 who regularly receive our products. More than 35,000 people have benefited from capacity development in hydroclimate areas. Many professionals were trained in application modern hydroclimatic analytical tools, and relevant technologies. Increased recognition and relative uniformity in consideration of trans-boundary water resources management and development in the member States.