Science of the Total Environment 630 (2018) 1309–1323

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Quantifying and evaluating the impacts of cooperation in transboundary river basins on the Water-Energy-Food nexus: The Blue Nile Basin

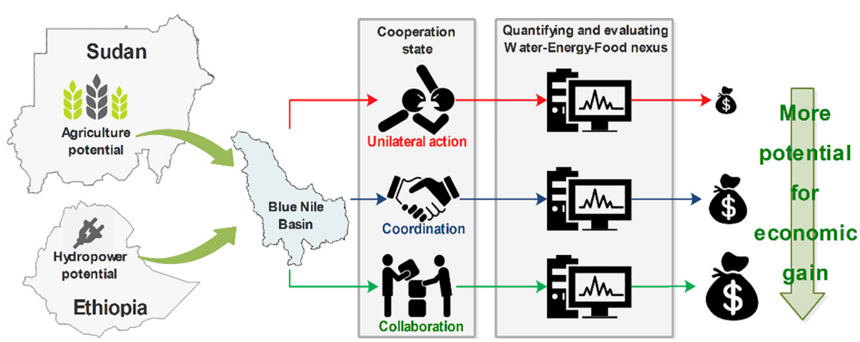
Mohammed Basheer [a,*], Kevin G. Wheeler [b], Lars Ribbe [a], Mohammad Majdalawi [c], Gamal Abdo [d], Edith A. Zagona [e]

[a] Institute for Technology and Resources Management in the Tropics and Subtropics (ITT), Technische Hochschule Köln, Betzdorferstr. 2, 50679 Cologne, Germany
[b] Environmental Change Institute, University of Oxford, South Parks Road, Oxford OX13QY, United Kingdom
[c] Agricultural Economics and Agribusiness Department, Faculty of Agriculture, The University of Jordan, Amman, Jordan
[d] Water Research Center (WRC), University of Khartoum, Nile street, 11111 Khartoum, Sudan
[e] Department of Civil, Environmental and Architectural Engineering, University of Colorado, 421 UCB, Boulder, CO 80309, USA

HIGHLIGHTS

- A daily model of the Blue Nile Basin is developed using RiverWare, HEC-HMS, and CropWat.
- Satellite-based rainfall products are a valuable asset in modelling WEF nexus.
- Changes in the economic gain from water, energy, and food are calculated for 120 scenarios.
- The overall economic gain of the basin increases with raising the cooperation level.
- Maximizing the overall economic gain requires transboundary management strategies.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 17 January 2018
Received in revised form 20 February 2018
Accepted 20 February 2018
Available online xxxx

Editor: D. Barcelo

Keywords:
Unilateral action
Coordination
Collaboration
Satellite-based rainfall products
Grand Ethiopian Renaissance Dam
RiverWare

ABSTRACT

Efficient utilization of the limited Water, Energy, and Food (WEF) resources in stressed transboundary river basins requires understanding their interlinkages in different transboundary cooperation conditions. The Blue Nile Basin, a transboundary river basin between Ethiopia and Sudan, is used to illustrate the impacts of cooperation between riparian countries on the Water-Energy-Food nexus (WEF nexus). These impacts are quantified and evaluated using a daily model that simulates hydrological processes, irrigation water requirements, and water allocation to hydro-energy generation and irrigation water supply. Satellite-based rainfall data are evaluated and applied as a boundary condition to model the hydrological processes.

The model is used to determine changes in the long-term economic gain (i.e. after infrastructure development plans are implemented and in steady operation) for each of Sudan and Ethiopia independently, and for the Blue Nile Basin from WEF in 120 scenarios. Those scenarios result from combinations of three cooperation states: unilateral action, coordination, and collaboration; and infrastructure development settings including the Grand Ethiopian Renaissance Dam and planned irrigation schemes in Sudan. The results show that the economic gain of the Blue Nile Basin from WEF increases with raising the cooperation level between Ethiopia and Sudan to collaboration. However, the economic gain of each riparian country does not necessarily follow the same pattern as the economic gain of the basin.

* Corresponding author.
E-mail addresses: mohammed.basheer@th-koeln.de, mohammedadamabbaker@gmail.com (M. Basheer), kevin.wheeler@ouce.ox.ac.uk (K.G. Wheeler), lars.ribbe@th-koeln.de (L. Ribbe), mohammadmj@yahoo.com (M. Majdalawi), gabdo2000@yahoo.com (G. Abdo), edith.Zagona@colorado.edu (E.A. Zagona).

https://doi.org/10.1016/j.scitotenv.2018.02.249
0048-9697/

1. Introduction

The global pressure on Water, Energy, and Food (WEF) is projected to increase rapidly as a result of population growth, economic development, urbanization, and climate change (Bazilian et al., 2011; Hoff, 2011; Howells et al., 2013; Mohtar and Daher, 2012, 2016). The world population is estimated to reach 8.5 billion by 2030, 9.7 billion by 2050, and 11.2 billion by 2100 (UN, 2015a). In 2012, around 40% of the world population was affected by water scarcity, nearly 1.3 billion people lacked electricity, and approximately 2.7 billion people relied on traditional biomass as fuel (UNDP, 2015). In 2015, around 800 million people suffered from hunger, and around 160 million children under the age of five were believed to demonstrate stunted growth attributed to insufficient access to food (Bhattacharyya et al., 2015; UN, 2015b). The aforementioned WEF supply pressures, along with a growing understanding of the interlinkages between the three scarce resources, emphasizes the need to manage them jointly and more efficiently. The failure of fragmented management of the different WEF sectors has led to the emergence of the Water-Energy-Food nexus (WEF nexus) thinking which promotes an integrated and systematic approach for managing WEF (Al-Saidi and Elagib, 2017; Hoff, 2011).

Several researchers have studied the application of the WEF nexus approach on transboundary river basins (Bazilian et al., 2011; Karnib, 2017; Keskinen et al., 2015, 2016; Kibaroglu and Gürsoy, 2015; Pittock et al., 2016; Strasser et al., 2016). However, few have quantified and evaluated the interlinkages of WEF in transboundary river basins under different system operation settings (Basheer and Elagib, 2017; Jalilov et al., 2015, 2016; Jeuland et al., 2017). Although WEF in stressed transboundary river basins are subject to high pressure due to competition between riparian countries for the three resources, a systematic understanding of how cooperation between riparian countries impacts the WEF nexus is still lacking.

The Blue Nile, a transboundary river basin between Ethiopia and Sudan, is a major water contributor to the Nile River and encompasses ongoing, under construction, and/or planned irrigation schemes and hydropower dams. According to the surveyed literature, no study, until now, has been published exclusively on WEF nexus for the Blue Nile Basin. However, the construction of the Grand Ethiopian Renaissance Dam (GERD; see Fig. 1), a large storage dam currently under construction on the Blue Nile, has triggered many studies about water supply and hydro-energy generation of the Blue Nile Basin under different scenarios over different time horizons. Several published studies have quantified the short-term impacts of the GERD on water supply and hydro-energy generation of the Blue Nile Basin (i.e. the filling period of the GERD) (Keith et al., 2017; King and Block, 2014; Wheeler et al., 2016; Zhang et al., 2015, 2016). Other published studies quantified and evaluated the long-term benefits of the Blue Nile Basin from hydro-energy and food using hydro-economic models with monthly time steps (Arjoon et al., 2014; Block and Strzepek, 2010; Jeuland et al., 2017; Satti et al., 2015). Arjoon et al. (2014) evaluated the long-term impacts of the GERD on the economic benefits of Ethiopia, Sudan, and Egypt and concluded that the GERD would increase the minimum annual economic benefits of the three countries from 4.9 to 5.6 billion US$, provided that Sudan fully uses its water share according to the 1959 Nile Water Agreement (UN, 1964) and Ethiopia implements its planned irrigation schemes around Lake Tana. Similarly, Jeuland et al. (2017) examined the long-term impacts of the GERD on Ethiopia, Sudan, and Egypt and found that by maximizing the overall economic benefit of the three countries, the annual economic benefit to Ethiopia would increase from 253 to 1465 million US$ primarily due to hydro-energy generation, but the annual economic benefit to Sudan would decrease from 1691 to 1595 million US$ as a result of allowing the maximum generation of energy from all Nile dams and promoting downstream agricultural production in Egypt. Lastly, Satti et al. (2015) developed a hydro-economic model for Sudan without the GERD

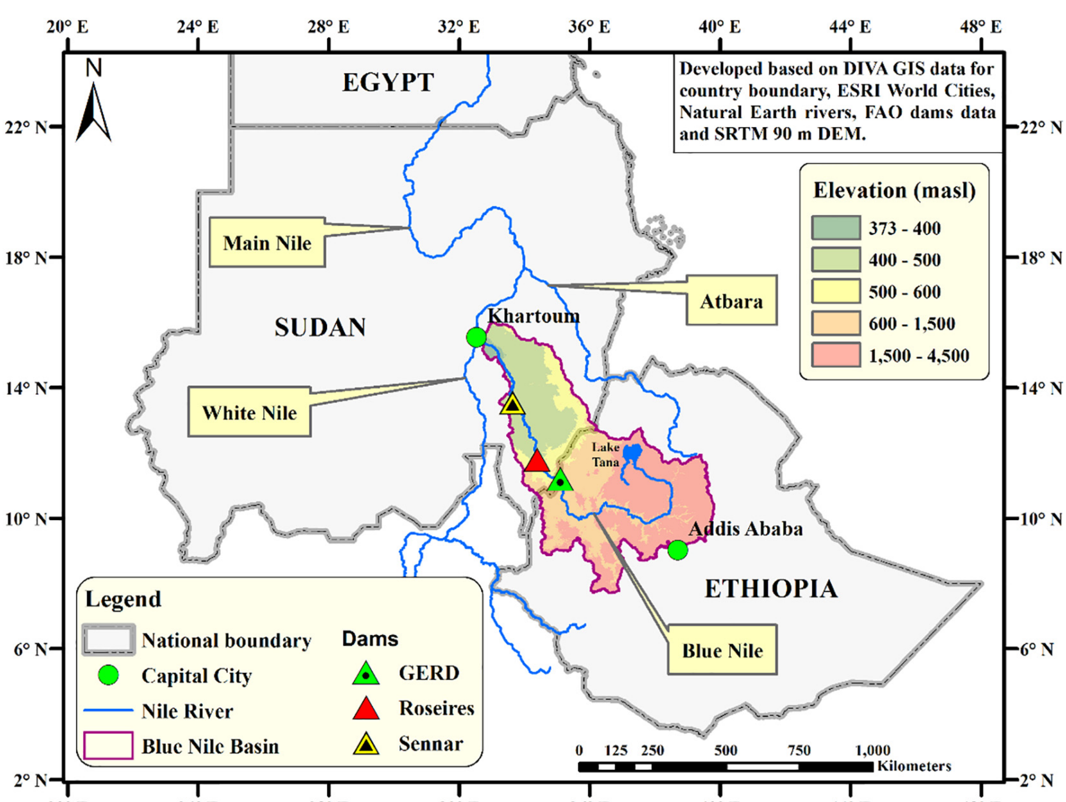


Fig. 1. Topography and dams in the Study area. Note: GERD = Grand Ethiopian Renaissance Dam; GIS = Geographic Information System; ESRI = Environmental Systems Research Institute; FAO = Food and Agriculture Organization; SRTM = Shuttle Radar Topography Mission; DEM = Digital Elevation Model.

implemented in Ethiopia and found that expanding irrigated agriculture in the Sudanese part of the Blue Nile Basin would result in decreasing the overall economic benefit to the Blue Nile Basin unless the energy price in Sudan drops due to hydropower development in Ethiopia. The shortcomings of some of the previous studies include the use of deterministic flow scenarios to model WEF, the use of monthly models to quantify the impacts on WEF, and the lack of knowledge regarding the economic value of evaporation losses from reservoirs. Moreover, no attempt has been made to quantify and evaluate the impacts of varying degrees of cooperation between riparian countries on the WEF nexus.

This study investigates the impacts of varying levels of cooperation between riparian countries on the WEF nexus. We quantify and evaluate these impacts for the Blue Nile, which is transboundary river basin between Ethiopia and Sudan. The change in the long-term economic gain (i.e. after infrastructure development plans are implemented and in steady operation) for Ethiopia and Sudan, and for the Blue Nile Basin, is calculated for 120 scenarios which are subject to 27 hydrologic traces (a total of 3240 simulations). Evaporation losses, hydro-energy generation, and irrigated agriculture are the three components considered in determining the economic gain from water, energy, and food respectively. The impact on Egypt, which is located downstream of Ethiopia and Sudan, is calculated in terms of change in the outflow of the Blue Nile Basin. The simulations are performed using a daily model that includes hydrological processes, irrigation water requirements, and water allocation to hydro-energy generation and irrigation water supply. The performance of four satellite-based rainfall products (SRPs) that cover the study area is evaluated and the best performing one is used as a boundary condition to model the hydrological processes.

2. Study area

2.1. Extent and general features

The study area extends over the Blue Nile Basin from the location of the GERD to Sennar Dam (see Figs. 1 and 2). It is bound by the Ethiopian highlands in the southeast and the Sahara Desert in the north and northwest. This part of the Blue Nile Basin was selected because it

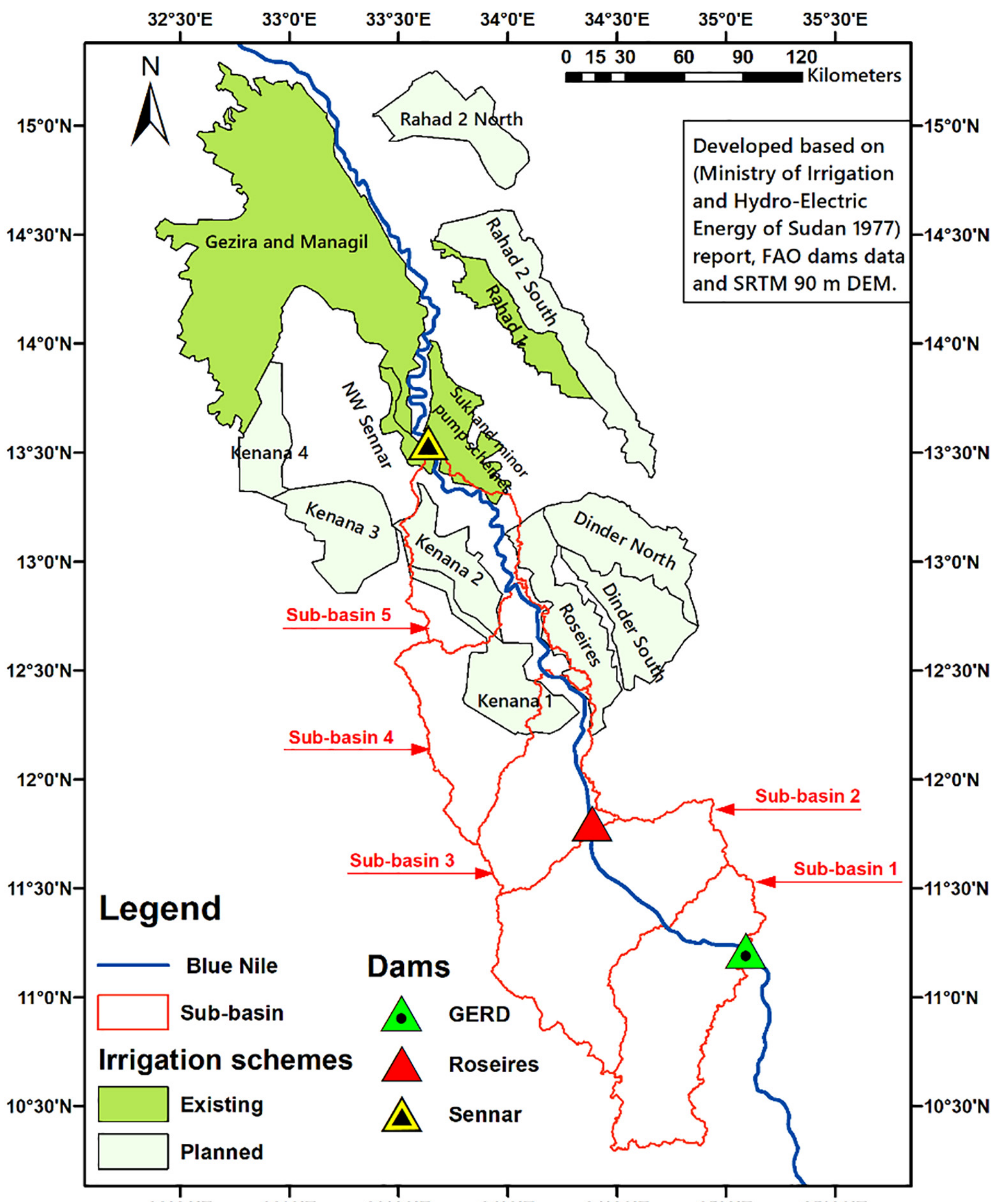


Fig. 2. Irrigation schemes and sub-basins in the study area. Note: GERD = Grand Ethiopian Renaissance Dam; FAO = Food and Agriculture Organization; SRTM = Shuttle Radar Topography Mission; DEM = Digital Elevation Model.

Table 1
cultivable area and start year of irrigation schemes located in the study area.
Source: Ministry of Water Resources, Irrigation, and Electricity of Sudan (MoWRIES).

Status	Scheme name		Cultivable area (ha)	Start year
Existing	Gezira		882,000	1925
	Managil extension			1966
	Suki		36,500	1971
	North West Sennar		21,000	1972
	Rahad 1		122,000	1977
Planned	Left bank schemes	Kenana 1	110,000	–
		Kenana 2	118,000	–
		Kenana 3	150,000	–
		Kenana 4	78,000	–
	Right bank schemes	Roseires	123,000	–
		Dinder South	24,000	–
		Dinder North	106,000	–
		Rahad 2 South	132,000	–
		Rahad 2 North	136,000	–

contains all current and foreseeable infrastructure development plans in the Basin. The Blue Nile River, which contributes around 60% of the annual flow of the Main Nile, starts in the Choke Mountains of Ethiopia. The river descends from the Ethiopian highlands while other tributaries join the mainstem from an altitude of above 4000 m asl. Further downstream, the Blue Nile crosses the Ethiopian-Sudanese border at an elevation of around 500 m asl, then flows northwest to the city of Khartoum at less than 400 m asl (ENTRO, 2009; Melesse et al., 2011; Ribbe and Ahmed, 2006; Sutcliffe and Parks, 1999). The White Nile, which originates at Lake Victoria, joins the Blue Nile at Khartoum to form the Main Nile. The combined flows then flow in the north direction to join the Atbara tributary and onwards towards Egypt and ending in the Mediterranean Sea (ENTRO, 2009; NBI, 2012). The flow of the Blue Nile, measured at El-diem gauge near the Ethiopian-Sudanese border, is highly seasonal with more than 80% of the annual flow occurring from July to October (Awulachew et al., 2008; Conway, 1997). The annual flow of the Blue Nile at El-diem gauge ranges approximately between 21 BCM and 74 BCM with an average of around 49 BCM (Wheeler et al., 2016).

2.2. Irrigation schemes

Fig. 2 shows existing and planned irrigation schemes in the study area. Large-scale irrigation in the study area commenced in 1925 with the construction of Gezira Scheme and Sennar Dam that stores and diverts water into the irrigation canals (see Section 2.3) (MoIHES, 1977; NBI, 2012). In the late 1960s the Managil extension of Gezira was constructed (Melesse et al., 2011; Sutcliffe and Parks, 1999). The Gezira and Managil represent more than 50% of the irrigated area in Sudan and remain the only existing gravity-fed schemes based on the Blue Nile (MoIHES, 1977; Plusquellec, 1990).

Irrigation development in the study area continued in the 1970s with the construction of Suki, North West Sennar, and Rahad 1 schemes. The three schemes are pump-fed from the Blue Nile reach between Roseires and Sennar dams (IWMI, 2012; MoIHES, 1977).

Looking forward, nine irrigation schemes are planned to be constructed in the study area. All the schemes would be irrigated by gravity through two canals diverting water from Roseires Reservoir. The nine schemes are divided into two groups: (1) the left bank schemes which include Kenana 1, Kenana 2, Kenana 3, and Kenana 4; (2) the right bank schemes which include Roseires, Dinder South, Dinder North, Rahad 2 South, and Rahad 2 North (MoIHES, 1977). Table 1 shows the cultivable area and the start year of existing and planned irrigation schemes in the study area.

2.3. Dams and hydropower

Figs 1 and 2 show the locations of dams in the study area. Sennar Dam was constructed in 1925 to supply Gezira irrigation scheme by gravity from head works located on the east side of the dam. In 1962, two 7.5 MW turbines were installed in a power station on the west side of the dam to utilize downstream outflow for hydro-energy generation (MoIHES, 1977; MoIHPS, 1968). Soon after, the need for additional storage to satisfy the irrigation water demands of Managil extension (see Section 2.2) led to the construction of Roseires Dam. Roseires Dam was constructed in two stages. The first stage was completed in 1966 with a Full Supply Level (FSL) of 480 m asl, and the second stage was completed in 2013 to add 10 m of elevation (DIU, 2016; MoIHPS, 1966, 1968). Most recently, in 2011, the Ethiopian government announced the construction start of the GERD, which, by its completion, will be the largest hydro-energy generation dam in Africa and the tenth largest globally (Salman, 2016). The GERD is located in Ethiopia 20 km upstream of the Ethiopian-Sudanese border (Salini Impregilo, 2016; Salman, 2016; Swanson, 2014). The roller compacted concrete dam will have a height of 145 m and the reservoir will be supplemented by a saddle dam that is 5 km long and 50 km high (IPoE, 2013; MIT, 2014).

Table 2 summarizes the key features of Sennar Dam, Roseires Dam, and the GERD.

3. Methodology

3.1. Modelling

In this study, a daily model was developed for the Blue Nile from the GERD to Sennar Dam (Fig. 3) that simulates the major hydrological processes, irrigation water requirements, and water allocation to hydro-energy generation and irrigation water supply. The model uses the historical Blue Nile flow record for 1983 to 2012, except 1997, 1998, and 1999 due to data gaps (see Section 3.5). The Blue Nile flow at El-diem gauge near the Ethiopian-Sudanese border was used as inflow to the GERD. The outflow from the GERD joins seasonal inflow from sub-basins 1 and 2 (see Fig. 2) before it enters Roseires Reservoir. Roseires Dam diverts the irrigation water demands of nine planned irrigation schemes located on the left and the right banks of the Blue Nile.

Table 2
Main characteristics of dams located in the study area.
Source: Ministry of Water Resources, Irrigation, and Electricity of Sudan (MoWRIES).

Characteristic	Sennar dam	Roseires dam after heightening	GERD
Dam status	Existing	Existing	Under construction
Full supply level (m asl)	421.7	490	640
Minimum operating level (m asl)	417.2	469	590
Total storage volume (MCM)	640 (in 1985)	5909 (in 2012)	74,010
Live storage volume (MCM)	420 (in 1985)	5850.7 (in 2012)	59,010
Dead storage volume (MCM)	220 (in 1985)	58.3 (in 2012)	15,000
Surface area at FSL (km^2)	160 (in 1985)	564.5 (in 2012)	1904
Surface area at MOL (km^2)	95 (in 1985)	26.3 (in 2012)	703
Installed power capacity (MW)	15	280	6000

Note: GERD = Grand Ethiopian Renaissance Dam; FSL = Full Supply Level; MOL = Minimum Operating Level.

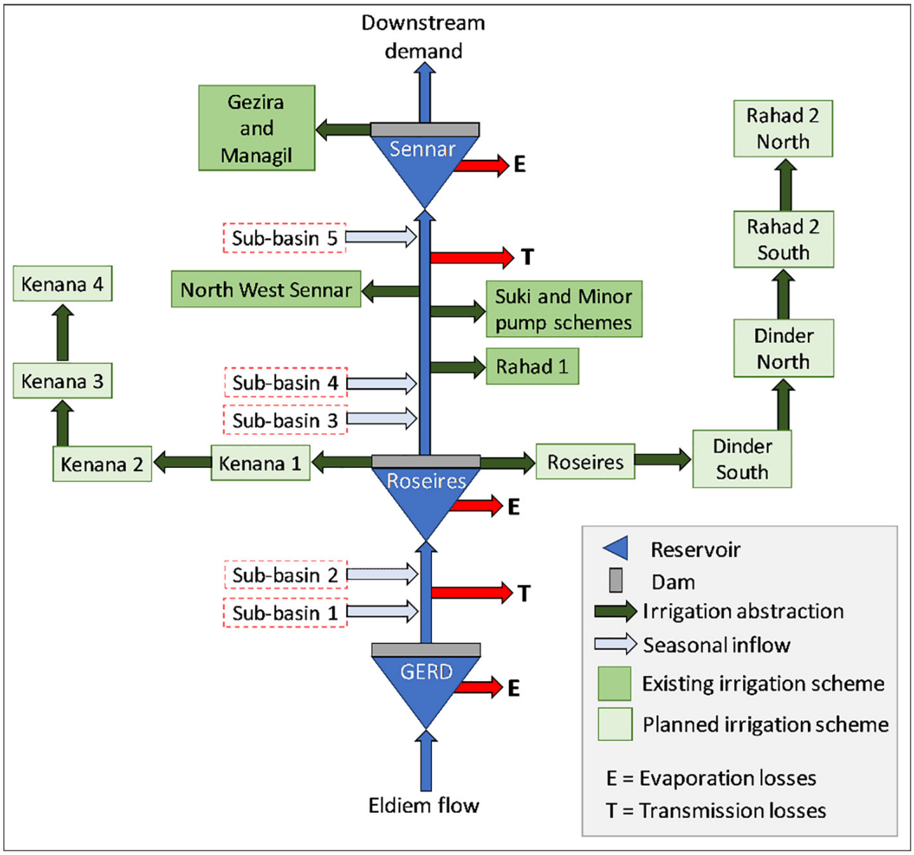


Fig. 3. Schematic of the model developed for the study area. Note: GERD = Grand Ethiopian Renaissance Dam.

Downstream from Roseires Dam, inflows from sub-basins 3 and 4 join the outflow from Roseires Dam before three existing irrigation schemes abstract their irrigation water demands. Seasonal inflow from sub-basin 5 joins the Blue Nile flow before it enters Sennar Reservoir, which provides the irrigation water demands of Gezira and Managil schemes. The outflow from Sennar Dam meets part of the demands of the downstream water users in Sudan and Egypt. Evaporation losses from the GERD, Roseires, and Sennar reservoirs, as well as transmission losses due to deep percolation in the study area, are included in the model.

Flow estimates from sub-basins 1, 2, 3, 4, and 5, used rainfall data from the best performing long-term (with at least 30 years of record) daily satellite-based rainfall product (SRP) (see Section 3.2). Various hydrologic assumptions and methods were invoked including soil deficit and constant loss calculations for infiltration, simple canopy interception, average monthly evapotranspiration, and a Snyder unit hydrograph (HEC, 2008, 2000, 2015). All the hydrologic parameters were spatially lumped, thus spatial variation within each sub-basin was not considered. Irrigation water requirements of planned schemes were estimated using FAO Penman-Monteith equation (Allen et al., 1998). Evaporation losses from the reservoirs were calculated using average monthly evaporation coefficients for each reservoir. For each river reach in the study area, a constant loss percentage and a constant travel time were used to simulate transmission losses and lag time respectively. Average monthly values of water abstraction by existing irrigation schemes were assumed to be their irrigation water demands. Due to unavailability of daily rates of some inputs (i.e. surface evapotranspiration, reservoir evaporation coefficients, and irrigation water demands of existing schemes), their monthly rates were uniformly discretized into daily rates.

Several modelling tools were used in simulating the hydrological processes, irrigation water requirements, and water allocation. The Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS) was used to simulate rainfall-runoff of the five sub-basins (HEC, 2000, 2008, 2015). HEC-GeoHMS was used to delineate the sub-basins, determine their geometric characteristics, and construct inputs to HEC-HMS (HEC, 2000, 2008, 2015). Irrigation water requirements for the different cropping patterns of planned schemes were calculated using CropWat (FAO, 2015). Average values for climatic parameters required by CropWat were obtained from New_LocClim (FAO, 2014; Grieser et al., 2006). Water allocation in the study area was modelled using RiverWare, a general river and reservoir simulation software (Zagona et al., 2001). RiverWare can simulate hydrologic and hydraulic processes of several kinds of objects such as storage reservoirs, river reaches, diversion structures, and canals. The rule-based simulation provides the ability to simulate the operational policies of river systems using logical statements rather than embedded logic to drive the simulation and the Multiple Run Management (MRM) utility provides the ability to run a model using ensembles of stochastically generated hydrologic inputs and system operations policies (Zagona et al., 2001, 2008).

The outflows from Roseires and Sennar dams were used to calibrate and validate the model. Due to data gaps, a fourteen year period, from 1983 to 1996, was used to calibrate the model at both sites. A ten year period was then used to validate the model at Roseires Dam (2000 to 2003 and 2007 to 2012) and a thirteen year period at Sennar Dam (2000 to 2012). The model was calibrated using parameters from Sub-basins 1–5 which include the initial and maximum storage of plant canopy, the initial and maximum deficit of soil moisture, the constant infiltration rate of soil, the standard lag, and the peaking coefficient. The performances of the model at Roseires and Sennar dams in both the calibration and validation periods were assessed according to the performance recommendations of Stern et al. (2016). They provided performance ranking for daily models based on quantitative comparison of simulated and observed flow values using three statistical performance metrics: coefficient of determination (R^2), the Nash-Sutcliffe coefficient of efficiency (NSE), and the Mean Error Percentage (MEP).

3.2. Evaluation of satellite-based rainfall products

To investigate the daily performance of SRPs, their pixel values at the locations of ground rainfall gauges were compared with the concurrent available records of daily rainfall of the gauges (from January 1999 to March 2007; see Section 3.5). To measure the difference between the pixel values and the ground observations, eight performance metrics were used. Those metrics can be categorized into two groups: (1) error metrics that include the Root Mean Square Error (RMSE; Chai and Draxler, 2014), the Mean Bias Error (MBE; Legates and McCabe, 1999), the Mean Absolute Bias Error (MABE; Chai and Draxler, 2014), and R^2 (Legates and McCabe, 1999) (2) categorical metrics that include the Frequency Bias (FB; Zambrano-Bigiarini et al., 2017), the Probability of Detection (POD; Toté et al., 2015), the False Alarm Ratio (FAR; Diem et al., 2014), and the Equitable Threat Score (ETS; Ebert et al., 2007).

3.3. Simulation scenarios

To investigate the impacts of cooperation levels between Ethiopia and Sudan on the WEF nexus, 120 scenarios were examined (Fig. 4). The scenarios were based on 30 agricultural development plans that were tested using four reservoir operation configurations including a baseline (i.e. without the GERD) and three cooperation states with the GERD online, as described below. Each of the scenarios was subjected to 27 hydrologic traces which resulted in a total of 3240 simulations.

Sadoff and Grey (2005) noted that cooperation in transboundary river basins is not a simple binary, but should be considered as a continuum that can occur in different levels including unilateral action, coordination, collaboration, and joint action. Based on these categories, we developed three cooperation states for the study area: unilateral action, coordination, and collaboration. In the unilateral action state, it was assumed that Ethiopia independently operates the GERD to maximize its annual energy generation regardless of the downstream implications. In the coordination state, Ethiopia was assumed to maximize the annual energy generated by the GERD and to provide information to Sudan in advance on the Blue Nile flow to be expected at the Ethiopian-Sudanese border (i.e. GERD outflow). Coordination would enable Sudan to operate Roseires Dam at its maximum possible FSL without being concerned about unexpected releases from the GERD that would cause dam overtopping. In the collaboration state, we assumed that Ethiopia would share information with Sudan on the GERD outflow in addition to giving the first priority to releasing, at least, the water demands of Sudan and the second priority to maximizing the benefits from energy generation by the GERD.

In this study, 30 agricultural development plans were examined, which result from 10 implementation setups of planned irrigation schemes in Sudan tested using three cropping patterns. The implementation of the planned irrigation schemes was assumed in the following order: No scheme, Kenana 1, Kenana 2, Kenana 3, Kenana 4, Roseires, Dinder South, Dinder North, Rahad 2 South, and Rahad 2 North. The three cropping patterns (Table 3) are based on seven crops suitable for cultivation in the study area. Cropping pattern 1 assumes the same percentage of cultivated area for all crops; cropping pattern 2 distributes the cultivated area between crops based on the weight of their annual gross margin (see Section 3.4 for information about gross margin

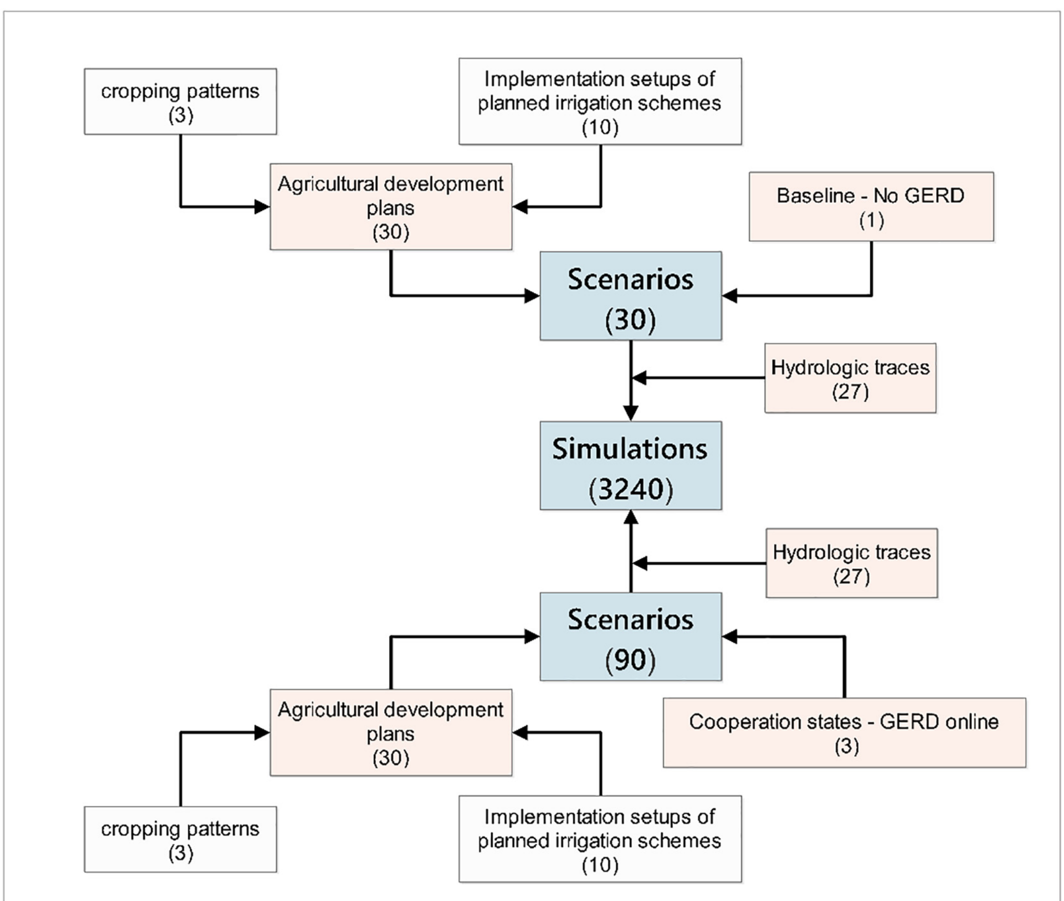


Fig. 4. Scenarios developed for the study area. Note: GERD = Grand Ethiopian Renaissance Dam.

Table 3
Gross margin of crops and cropping patterns.

Crop	Annual Gross margin (US$/ha)	Cropping Pattern 1	Cropping Pattern 2	Cropping Pattern 3
Cotton	4328.5	14.29%	28.05%	20%
Sesame	3462.8	14.29%	22.44%	20%
Wheat	729.1	14.29%	4.72%	10%
Sunflower	253.9	14.29%	1.65%	10%
Sorghum	32.1	14.29%	0.21%	10%
Sugarcane	6082.9	14.29%	39.42%	20%
Groundnuts	541.4	14.29%	3.51%	10%

Note: US$ = United States Dollar.

calculation); and cropping pattern 3 gives 20% of the cultivated area to each of the three crops with the highest annual gross margin and gives 10% of the cultivated area to each of the other four crops.

Although Ethiopia has not published any data (i.e. area, location, and cropping pattern) on its agricultural development plans involving the Blue Nile Basin, there has been some discussions on the extent of possible agricultural development in Ethiopia (Kalpakian, 2015). The information available to us on the Ethiopian agricultural development plans was not enough to analyze their impacts on the WEF nexus of the Blue Nile Basin. Therefore, agricultural development in Ethiopia was not included in this study. However, the model could accommodate such analysis should the required data be available.

Available flow data (see Section 3.5) were used to create 27 hydrologic sequences or "traces" using the index-sequential method (Kendall and Dracup, 1991; Ouarda et al., 1997). The index-sequential method is a technique that applies synthetic series of inflow sequences, created based on historical record, to the future starting with all years in the record (Ouarda et al., 1997; Wheeler et al., 2016).

3.4. Economic evaluation of scenarios

Cost-benefit analysis was performed to determine the change in the annual economic gain for different scenarios compared with the baseline considering three components: irrigated agriculture, hydro-energy generation, and reservoir evaporation. The productivity approach (Majdalawi et al., 2016), which captures changes in production, was used to calculate the change in the benefits and costs of irrigated agriculture and hydro-energy generation. The change in the cost of reservoir evaporation was computed using the opportunity cost approach, which considers the value of the next-highest-valued alternative use of a resource (Jantzen, 2006).

In this study, the change in the economic gain from irrigated agriculture was associated with the addition of planned irrigation schemes. The annual gross margin, which is the annual profit per unit area, was calculated for each crop in the planned irrigation schemes (Table 3). Whereas the benefit from crop cultivation was assumed to be the revenue resulting from their yield, the cost of crop cultivation was limited to the cost of agricultural operations, the cost of agricultural inputs, and their interest. Eqs. 1 and 2 show the calculation of the annual gross margin of crops and the change in the annual economic gain from irrigated agriculture respectively.

$$GM_i = Y_i P_i - I_i - O_i - (I_i + O_i)\, r_{SDN} \tag{1}$$

$$GA_{SDN} = \sum_{i=1}^{n} GM_i A_i \tag{2}$$

where GM_i is the annual gross margin of the ith crop (US$/ha), Y_i is the annual yield of the ith crop (kg/ha), P_i is the Price of the ith crop (US$/kg), I_i is the annual cost of agricultural inputs of the ith crop (US$/ha), O_i is the annual cost of agricultural operations of the ith crop (US$/ha), r_{SDN} is the bank interest rate in Sudan, GA_{SDN} is the change in the annual economic gain of Sudan from irrigated agriculture in a certain scenario (US$), A_i is the cultivated area of the ith crop in planned irrigation schemes in a certain scenario (ha), and n is the number of cultivated crops.

The change in the economic gain from hydro-energy was linked with energy generation from the GERD, Roseires Dam, and Sennar Dam. Whereas the benefit of hydro-energy was assumed to be the revenue resulting from the generated energy units, the cost of hydro-energy was restricted to the operation cost of hydropower facilities which was assumed to be fixed (i.e. no variable cost). As shown by Eq. (3), the change in the annual economic gain of Sudan from hydro-energy (i.e. from Rosieres and Sennar dams) is the difference between the revenue from the generated energy units in a certain scenario and the revenue from the generated energy units in the baseline. The change in the economic gain of Ethiopia from hydro-energy, shown by Eq. (4), is the revenue from the generated energy units from the GERD in a certain scenario minus the operation cost of the GERD minus the interest of the operation cost.

$$GH_{SDN} = P^E_{SDN} E_{RS} - P^E_{SDN} E^{bl}_{RS} \tag{3}$$

$$GH_{ETH} = P^E_{ETH}\, E_{GERD} - OC_{GERD} - OC_{GERD}\, r_{ETH} \tag{4}$$

where GH_{SDN} is the change in the annual economic gain of Sudan from hydro-energy in a certain scenario (US$), P^E_{SDN} is the energy price in Sudan (US$/KWh), E_{RS} is the annual energy generated from Roseires and Sennar dams in a certain scenario (KWh), E^{bl}_{RS} is the annual energy generated from Roseires and Sennar dams in the baseline (KWh), GH_{ETH} is the change in the annual economic gain of Ethiopia from hydro-energy in a certain scenario (US$), P^E_{ETH} is the energy price in Ethiopia (US$/KWh), E_{GERD} is the annual energy generated from the GERD in a certain scenario (KWh), OC_{GERD} is the annual operation cost of the GERD (US$), and r_{ETH} is the bank interest rate in Ethiopia.

Finally, the value of irrigated agriculture, which is the only consumptive use considered in this study, was used to calculate the opportunity cost of evaporation from Roseires and Sennar reservoirs. Evaporation from the GERD Reservoir was not included in the economic evaluation because the alternative use (i.e. irrigating planned schemes in Sudan) would not be possible without the GERD (see Section 4.3.2). Eq. (5) shows the change in the annual economic loss of Sudan due to evaporation from Roseires and Sennar reservoirs.

$$LE_{SDN} = \left(EV_{SR} - EV^{bl}_{SR}\right)\left(\frac{GA_{SDN}}{IWR - IWR_{bl}}\right) \tag{5}$$

where LE_{SDN} is the change in the annual economic loss of Sudan due to reservoirs' evaporation in a certain scenario (US$), EV_{SR} is the annual evaporation from Roseires and Sennar reservoirs in a certain scenario (MCM), EV^{bl}_{SR} is the annual evaporation from Roseires and Sennar reservoirs in the baseline (MCM), GA_{SDN} is the change in the annual economic gain of Sudan from irrigated agriculture in a certain scenario (US$), IWR is the annual irrigation water demands in a certain scenario (MCM), IWR_{bl} is the annual Irrigation water demands in the baseline (MCM).

It worth mentioning that the investment cost of the GERD and the planned irrigation schemes was not considered since the economic evaluation is performed for the long-term (i.e. the investment cost already happened).

3.5. Data used

The performance of four daily long-term SRPs (i.e. 30 years or more) was evaluated in this study including the African Rainfall Climatology Version 2 (ARC 2.0; Novella and Thiaw, 2013), the Tropical Applications of Meteorology using Satellite and ground-based observations (TAMSAT; Tarnavsky et al., 2014), the Climate Hazards group InfraRed Precipitation with Station data version 2 (CHIRPS 2.0; Funk et al., 2014), and the Precipitation Estimation from Remotely Sensed

Information using Artificial Neural Networks-Climate Data Record (PERSIANN-CDR; Ashouri et al., 2015). ARC 2.0 has spatial coverage between 20°W and 55°E and between 40°S and 40°N, temporal coverage from 1983 to near present, and a spatial resolution of 0.1° × 0.1°. TAMSAT data set encompasses only the African continent for the period from 1983 to 2012 with a 0.0375° × 0.0375° spatial resolution (Maidment et al., 2014). CHIRPS 2.0 covers the globe from 50°S to 50°N over the period from 1981 to present and has a spatial resolution of 0.05° × 0.05° (Funk et al., 2014, 2015; Toté et al., 2015). PERSIANN-CDR data set covers the period from January 1983 to near present. It has 0.25° × 0.25° spatial resolution and covers the globe between 60°S and 60°N (Ashouri et al., 2015).

Time series of daily rainfall, measured using ground gauges, was acquired from the Sudan Meteorological Authority (SMA). The obtained data include records from four rainfall gauges, which are located in or near the study area, namely Ed Damazin, Sennar, Wad Medani, and Khartoum, covering the period from January 1999 to March 2007. Fig. 5 shows the locations of the rainfall gauges in and around the study area and highlights the gauges utilized in this study. SMA performs data quality checks on the subject gauges (i.e., gaps, outliers, homogeneity); hence further checks were not conducted on the same.

Shuttle Radar Topography Mission (SRTM; Jarvis et al., 2008) Digital Elevation Model (DEM), which has a spatial resolution of three arc second, was used to delineate the five sub-basins between the GERD and Sennar Dam (see Fig. 2). Average monthly evapotranspiration of each of the five sub-basins was calculated based on the Moderate Resolution Imaging Spectroradiometer Global Evapotranspiration Project (MOD16; Mu et al., 2011) which provides global monthly evapotranspiration grids for the years from 2000 to 2014 (1 km × 1 km spatial resolution).

Daily flow data of the Blue Nile at El-diem gauge, which is located near the Ethiopia-Sudanese border, were obtained from the Ministry of Water Resources, Irrigation, and Electricity of Sudan (MoWRIES). The obtained flow data cover 1983 to 1996 and 2000 to 2012. Flow data for 1997, 1998, and 1999 were not acquired because of a gap in the record. Average monthly water demands of existing irrigation schemes were obtained from the MoWRIES. For Rosieres and Sennar dams, the MoWRIES provided the geometry and the monthly evaporation coefficients of the reservoirs (both measured in 2012 and 1985 for Roseires and Sennar respectively), turbine specifications, outlet capacities, and downstream rating curves. Similar data for the GERD were obtained from the Eastern Nile Technical Regional Office (ENTRO) of the Nile Basin Initiative (NBI). Percentages of transmission losses for the reach between the GERD and Roseires Dam (1% of the GERD outflow) and the reach between Roseires and Sennar dams (2% of Roseires dam outflow) were obtained from the MoWRIES. Average times of travel from the GERD to Roseires Reservoir and from Roseires Dam to Sennar Reservoir were acquired from the MoWRIES. Further, the operating policies of Roseires and Sennar dams, before and after the heightening of Roseires Dam, were also obtained from the MoWRIES.

Bank interest rates in Ethiopia (5%) and in Sudan (10%) were acquired from NBE (2016) and Hassan (2011), respectively. Energy price and hydro-energy generation cost in Ethiopia (US$ 0.10/KWh and US$ 0.04/KWh, respectively) were obtained from Jeuland et al. (2017) and Foster and Morella (2011), respectively. Energy price in Sudan (US$ 0.09/KWh) was obtained from Ranganathan and Briceño-Garmendia (2011). Data for the seven crops suggested for cultivation in the planned irrigation schemes were obtained from Kenana Engineering and Technical Services (KETS), an international company based in Khartoum, that provides consultation work on agriculture-related aspects in the national and regional markets. The crop data include agricultural inputs and their costs, agricultural operations and their costs, crop factors, crop prices, and crop yields.

Based on the description of soil types in the Lower Blue Nile Basin stated in MoIHES (1977) (i.e. clayey soil), the soil type of the nine planned irrigation schemes was assumed to be black clayey soil. The properties of this soil type were taken from the soil database of CropWat (FAO, 2015). Average monthly values for minimum temperature, maximum temperature, humidity, wind speed, and sunshine hours at the locations of planned irrigation schemes were obtained from the database of New_LocClim (FAO, 2014; Grieser et al., 2006).

The online supplementary data file, published with this paper, includes some key data used in this study.

4. Results and discussion

4.1. Performance of satellite-based rainfall products

The results of the eight selected performance metrics (RMSE, MBE, MABE, R^2, FB, POD, FAR, and ETS) are presented in Fig. 6. R^2 showed

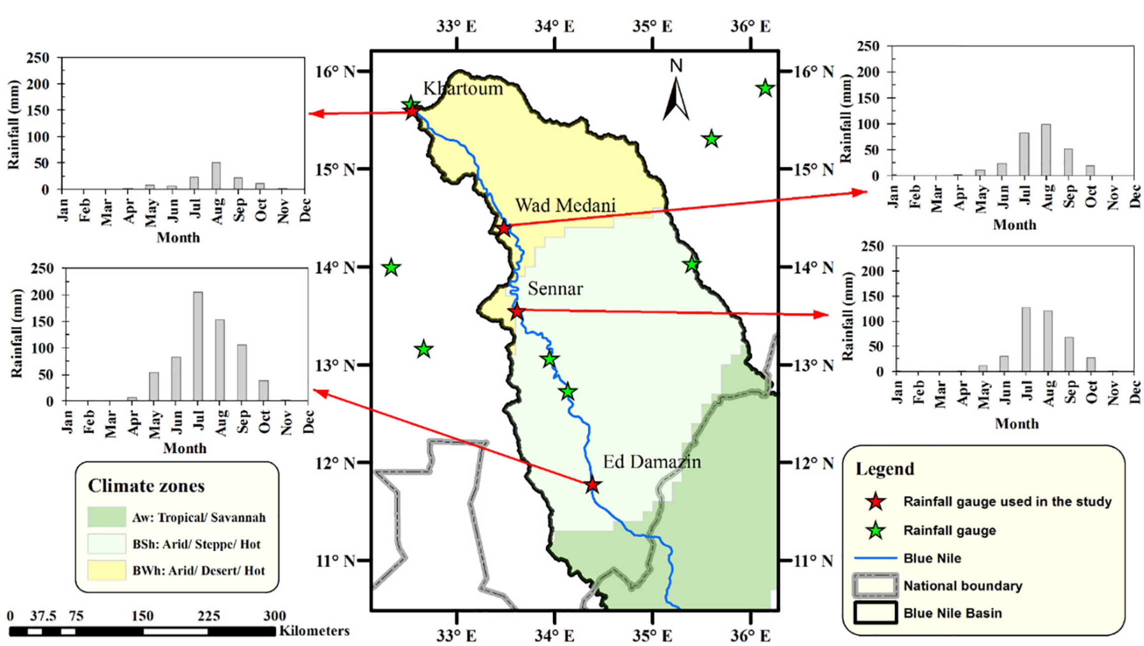


Fig. 5. Köppen-Geiger climatic zones of the study area, rainfall gauges in and around the study area, and the average monthly rainfall at the stations used in the study.

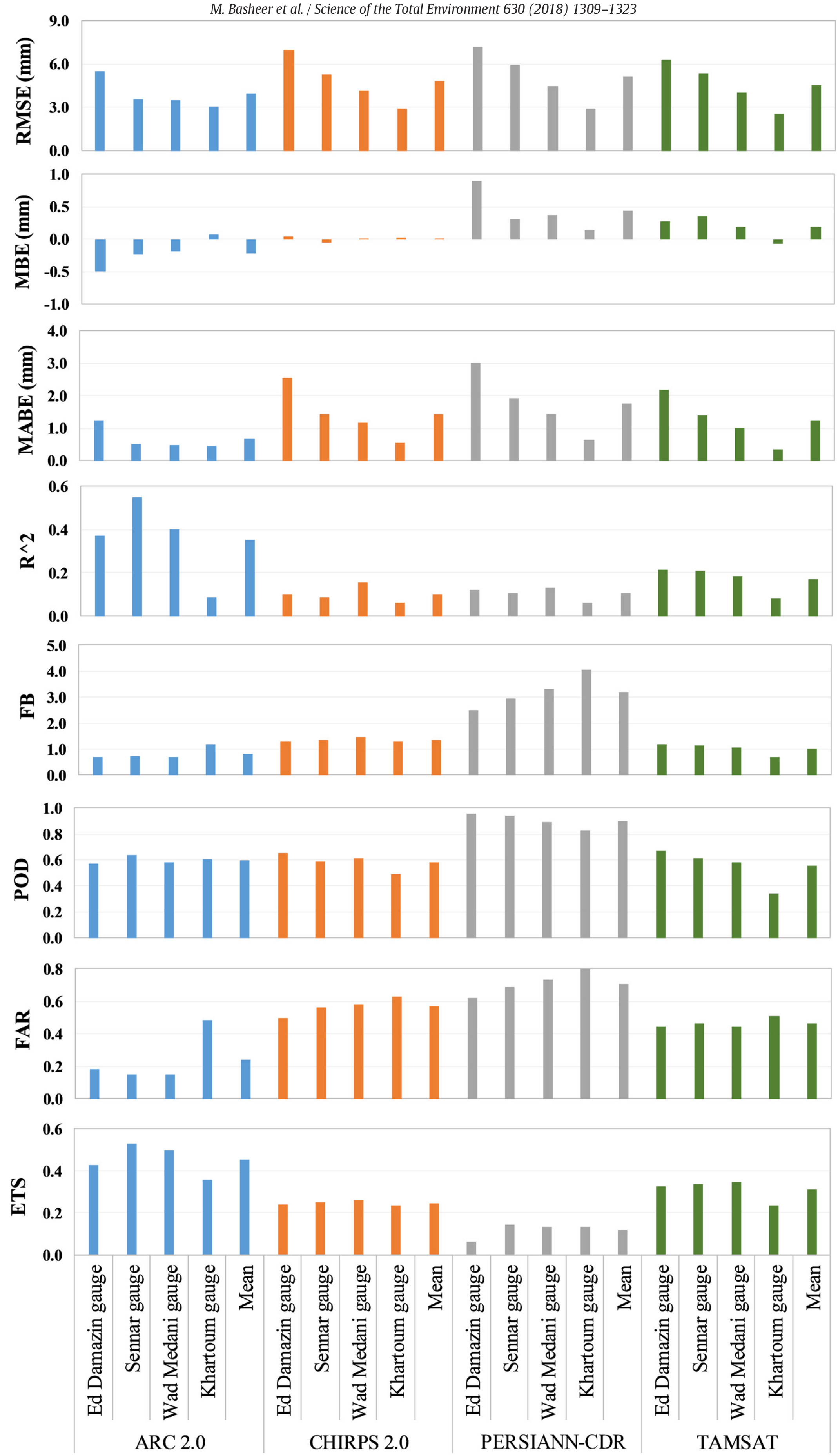


Fig. 6. Performance metrics of the evaluated satellite-based rainfall products (SRPs) at four rainfall gauges.

weak correlation between the estimated and observed rainfall coupled with high correlation significance. It was found that the highest R^2 value (0.55) is a characteristic of ARC 2.0 at Sennar gauge. For the four gauges, the results of RMSE and MABE showed that ARC 2.0 has the best performance. In contrast, the results of MBE revealed that CHIRPS 2.0 has the best performance. In consonance with RMSE, MBE, and MABE, it was found that TAMSAT has the second-best performance and PERSIANN-CDR has the worst performance.

Regarding the categorical metrics, PERSIANN-CDR detected 95%, 94%, 89%, and 82% of the rainy days at Ed Damazin, Sennar, Wad Medani, and Khartoum gauges, respectively, which shows the best performance in terms of POD among the evaluated SRPs. However, ARC 2.0 and TAMSAT showed the best and the second-best performances, respectively, based on ETS, FAR, and FB.

Overall, Fig. 6 revealed that ARC 2.0 has the best performance compared with the other evaluated SRPs. Therefore, ARC 2.0 was used as an input to model the seasonal inflows from Sub-basins 1–5.

4.2. Model performance

Fig. 7 illustrates the model calibration and validation at Roseires and Sennar dams. It can be observed that the model accurately predicts the volume and timing of outflow from Roseires and Sennar dams. As shown in Table 4, based on the recommendations of Stern et al. (2016), the model showed excellent performance at Roseires and Sennar dams in both the calibration and validation periods. The high R^2 values (with high correlation significance) signalize excellent agreement between the observed and simulated outflows. The values of the calibration parameters are presented in the online supplementary data file published with this paper.

4.3. Dam operation in different cooperation states

This section presents the analysis we conducted to translate the three suggested cooperation states (see Section 3.3) into detailed operating policies for the GERD, Rosieres Dam, and Sennar Dam.

4.3.1. Grand Ethiopian Renaissance Dam (GERD)

To determine an operating policy for the GERD that maximizes the benefits of Ethiopia from energy, several policies, based on target power, were tested subject to the 27 hydrologic traces (see Section 3.3). For each of the tested target power policies, the outflow from the GERD at each timestep was determined so as to achieve the power target of that particular policy. However, higher priority was given to keeping the reservoir at a water level between the FSL and the Minimum Operating Level (MOL), which in turn resulted in divergence from the power target at some timesteps. The policy that provided the highest 100% assured annual energy generation (i.e. the highest energy generation with 100% probability of exceedance based on the 27 hydrologic traces) was selected as the policy that maximizes the benefits of Ethiopia from energy generation. Fig. 8 demonstrates the probability of exceedance of the GERD annual energy generation with different policies. The evidence from Fig. 8 shows that operating the GERD with a regular target power of 1490 MW results in the highest guaranteed annual energy generation of approximately 13,000 GWh. Therefore, in the unilateral action and the coordination states, the GERD was

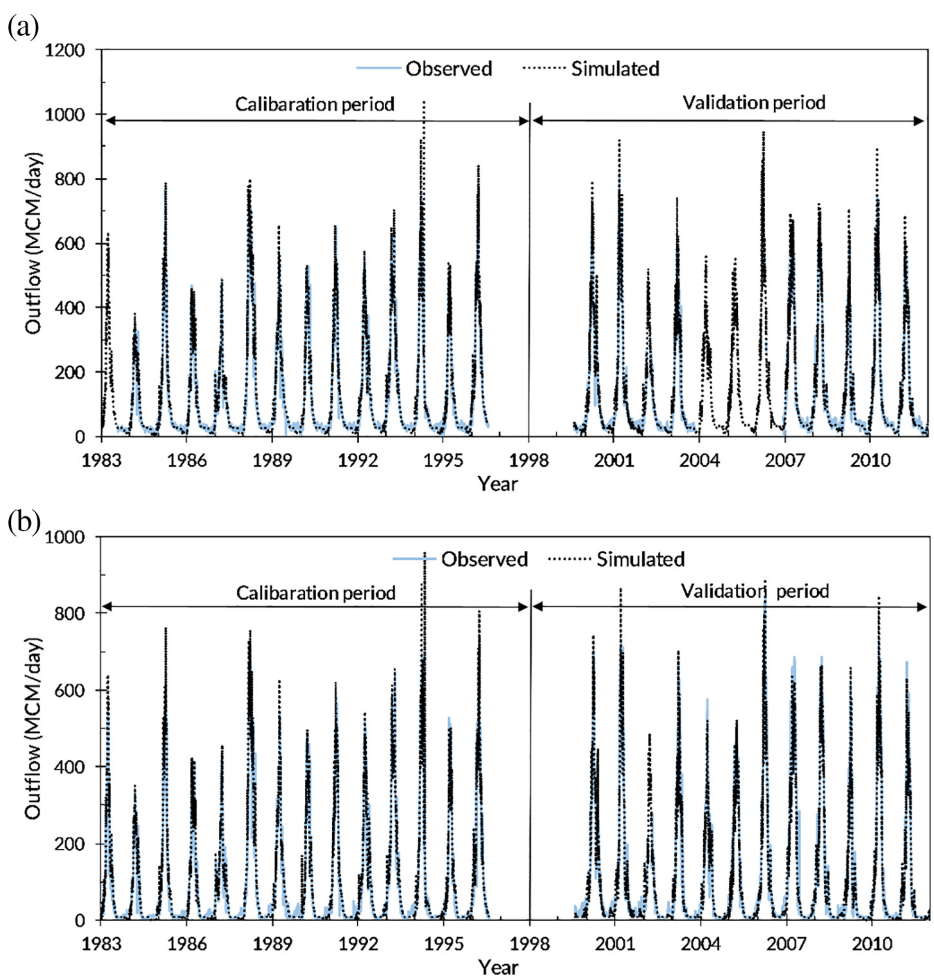


Fig. 7. Observed and simulated outflow from: (a) Roseires Dam (b) Sennar Dam.

Table 4
Model performance in the calibration and validation periods.

Performance metric	Calibration				Validation			
	Sennar dam		Roseires dam		Sennar dam		Roseires dam	
	Metric value	Ranking	Metric value	Ranking	Metric value	Ranking	Metric value	Ranking
R^2	0.95	Excellent	0.96	Excellent	0.97	Excellent	0.97	Excellent
NSE	0.95	Excellent	0.96	Excellent	0.96	Excellent	0.97	Excellent
MEP	9.55	Excellent	0.52	Excellent	−3.45	Excellent	0.31	Excellent

Note: R^2 = coefficient of determination; NSE = Nash-Sutcliffe coefficient of efficiency; MEP = Mean Error Percentage.

operated at this power generation rate whenever possible. In the collaboration state, the GERD was operated as follows: the highest priority was given to keeping the reservoir at a water level between the FSL and the MOL, the second-highest priority was given to meeting the daily downstream water demands, and the lowest priority was given to targeting a steady power level of 1490 MW.

4.3.2. Rosieres and Sennar dams

Table 5 presents various assignments of the MOL and FSL for Roseires and Sennar dams, and reports the effects on Sudan including the risk of daily supply shortages (i.e. percentage of days with supply shortage; Wheeler et al., 2016), the maximum annual supply shortage (i.e. the maximum resulting from the 27 hydrologic traces), and the 100% assured annual energy generation (i.e. the highest energy generation with 100% probability of exceedance based on the 27 hydrologic traces). This assumes existing irrigation schemes (i.e. no new agricultural development) and with the GERD operated to provide the highest 100% assured annual energy generation (i.e. 1490 MW target power; see Section 4.3.1). The evidence from Table 5 shows that supply shortages, which results from operating the GERD to target 1490 MW while complying with its MOL and FSL, could be eliminated by raising the MOL of Roseires and Sennar dams to 489 m asl and 421.7 m asl respectively, allowing these to drop only to meet irrigation needs. Even though, operating at these levels results in an increase of 213 MCM in the maximum annual evaporation losses (i.e. the maximum resulting from the 27 hydrologic traces) from Roseires and Sennar reservoirs compared with the baseline (i.e. with neither the GERD nor agricultural development), it also increases the 100% assured annual energy generation from Roseires and Sennar dams by around 780 GWh. Hence, in the unilateral action state, Roseires and Sennar dams were operated at a constant water level (i.e. FSL equals MOL) of 489 m asl and 421.7 m asl respectively and allowing these to drop only to meet irrigation needs. Note that in the unilateral action state, Roseires Dam was not operated at the highest possible FSL (i.e. 490 m asl) to allow for unexpected releases from the GERD (see Section 3.3). Whereas the operation of Sennar Dam in the coordination and collaboration states was similar to its operation in the unilateral action state, Roseires Dam was operated at a constant level of 490 m asl assuming information sharing between Ethiopia and Sudan (see Section 3.3).

Interestingly, Table 5 reveals that Sudan has a risk of daily supply shortage of around 0.03% in the baseline (i.e. with neither the GERD nor agricultural development). This minimal risk can be attributed to the deficiency in irrigation water during the annual filling period of Roseires and Sennar reservoirs especially after the heightening of Roseires Dam (the supplementary file shows the original operating policy of the two dams). Although this rather small risk seems to be negligible, it signals that Sudan can take no further agricultural development without having the GERD online.

4.4. Water-Energy-Food nexus in different cooperation states

This section presents the WEF nexus of the Blue Nile Basin in scenarios that maximize the economic gain of the basin across different cooperation states (i.e. unilateral action, coordination, and collaboration) using different cropping patterns in planned irrigation schemes (i.e. cropping patterns 1, 2, and 3).

4.4.1. Unilateral action

The results revealed that, using the cropping patterns 1 or 3, Sudan can implement all the nine planned irrigation schemes in the study area with zero risk of daily supply shortage, and concurrently generate, from Rosieres and Sennar and dams, a 100% assured annual energy of 2570 GWh per year and 2510 GWh per year when using cropping patterns 1 and 3 respectively. Moreover, using cropping pattern 2, it was found that Sudan can implement eight of the nine planned irrigation schemes in the study area with a zero risk of daily supply shortage, and generate a 100% assured annual energy of 2380 GWh per year from Roseires and Sennar dams. A maximum annual evaporation loss (i.e. the maximum resulting from the 27 hydrologic traces) from Rosieres and Sennar reservoirs of 1736 MCM was recorded with

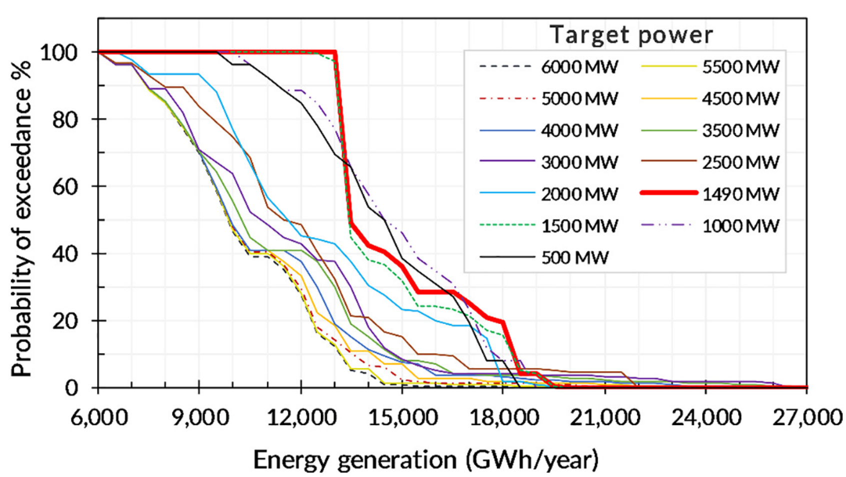


Fig. 8. Probability of exceedance of annual energy generation of the Grand Ethiopian Renaissance Dam with different policies of power targets.

Table 5
Rosieres and Sennar Dams' operation with no agricultural development and with the GERD operated to target 1490 MW while complying with its MOL and FSL.

Operating setting					Maximum annual evaporation losses (MCM)	Risk of daily supply shortage (%)	Maximum annual supply shortage (MCM)	100% assured annual energy generation (GWh)
Roseires dam		Sennar dam		GERD				
MOL (m asl)	FSL (m asl)	MOL (m asl)	FSL (m asl)	Target power (MW)				
469	490	417.2	421.7	No dam	1523	0.03	89	1790
469	489	417.2	421.7	1490	1531	8.78	1354	2180
474	489	418.1	421.7	1490	1571	8.04	1222	2230
479	489	419.0	421.7	1490	1609	6.16	904	2300
484	489	419.9	421.7	1490	1666	3.10	529	2410
489	489	421.7	421.7	1490	1736	0.00	0	2570

Note: GERD = Grand Ethiopian Renaissance Dam; MOL = Minimum Operating Level; FSL = Full Supply Level.

implementing the maximum possible planned irrigation schemes using any of the three cropping patterns. On the other hand, as presented in Section 4.3.1, the unilateral action state enables Ethiopia to generate a 100% assured annual energy of 13,000 GWh per year.

4.4.2. Coordination

Like the unilateral action state, with no risk of daily supply shortage, Sudan can implement all the nine planned irrigation schemes using cropping patterns 1 or 3, and eight of the planned irrigation schemes using cropping pattern 2. Moreover, the results showed that with implementing the maximum possible planned irrigation schemes using cropping patterns 1, 2, or 3, Sudan (i.e. Rosieres and Sennar dams) can generate a 100% assured annual energy of 2570 GWh, 2400 GWh, and 2530 GWh respectively. Although the operating level of Roseires Dam in the coordination state (i.e. 490 m asl) is higher than in the unilateral action state (i.e. 489 m asl), the 100% assured annual energy generation of Sudan was found the same in both states (i.e. 2570 GWh) when cropping pattern 1 is used. That can be attributed to the low installed capacity of Roseires Dam (i.e. 280 MW) which was fully used in the unilateral action state with cropping pattern 1. It was found that 1788 MCM evaporates annually from Roseires and Sennar reservoirs when Sudan implements the maximum possible planned irrigation schemes using any of the three cropping patterns. Lastly, the 100% assured annual energy generation of Ethiopia from the GERD in the coordination state remained the same as in the unilateral state (i.e. 13,000 GWh).

4.4.3. Collaboration

Collaboration enabled Sudan to implement all the nine planned irrigation schemes in the study area using any of the three cropping patterns and without any risk of daily supply shortage. Moreover, the results showed that with implementing the maximum possible planned irrigation schemes using cropping patterns 1, 2, or 3, the 100% assured annual energy generation of Sudan would amount to 2570 GWh, 2250 GWh, and 2530 GWh respectively with a maximum annual evaporation loss from Roseires and Sennar reservoirs similar to the maximum annual evaporation loss in the coordination state (i.e. 1788 MCM). However, the 100% assured annual energy generation of Ethiopia from the GERD decreased to around 12,500 GWh compared to 13,000 GWh in the unilateral action and coordination states.

4.5. Economic gain in different cooperation states

Table 6 presents the Highest Minimum Annual Increase in the Economic Gain (HMAIEG) of Ethiopia, Sudan, and the Blue Nile Basin from WEF in the study area in different cooperation states (i.e. the highest resulting from different agricultural development plans, the minimum resulting from various hydrologic traces, and the increase compared with the baseline). It was found that Ethiopia has the same HMAIEG in both the unilateral action and the coordination states. However, the HMAIEG of Ethiopia showed around 4% decrease in the collaboration state compared with its value in the unilateral action and the coordination states. Moreover, the results revealed a slight decrease in the net HMAIEG of Sudan in the coordination state compared with its value in the unilateral action state (around 0.4% decrease). That can be attributed to the low increase in the economic gain due to the increase in energy generation (1.8 million US$ per year) compared to the economic loss from the increase in evaporation (15.3 million US$ per year). The low installed capacity of Roseires Dam (280 MW) was the reason behind the low increase in the economic gain of Sudan from energy generation. In the collaboration state, the net HMAIEG of Sudan showed an increase of around 21% and 21.5% compared with its value in the unilateral action and the coordination states respectively. Lastly, the net HMAIEG of the basin showed a decrease of around 0.3% and an increase of around 16.5% in the coordination and the collaboration states respectively compared with the net HMAIEG in the unilateral state.

4.6. Impact on Egypt in different cooperation states

Reduction in the annual outflow from Sennar Dam is apparent because of agricultural development in the Study area. A major concern of Egypt, which is located downstream of Sudan (see Fig. 1), is how the outflow from Sennar Dam would change in various infrastructure development settings and cooperation conditions between Ethiopia and Sudan. Fig. 9 demonstrates the probability of exceedance of the outflow from Sennar Dam in different scenarios. The results showed that in the baseline with neither the GERD nor planned irrigation schemes implemented (BL – NAD – No GERD), the annual outflow from Sennar Dam ranges between a minimum of 19,117 MCM and a maximum of 55,159

Table 6
Highest Minimum Annual Increase in the Economic Gain (HMAIEG) from water, energy, and food in the study area in different cooperation states.

Cooperation state	Ethiopia (million US$)		Sudan (million US$)				The Blue Nile Basin (million US$)
	From energy	Net	From energy	From food	From evaporation	Net	
Unilateral action	754.0	754.0	53.1	3608.7	−62.8	3599.0	4353.0
Coordination	754.0	754.0	54.9	3608.7	−78.1	3585.5	4339.5
Collaboration	725.0	725.0	41.4	4393.6	−81.8	4353.2	5078.2

Note: negative values indicate economic loss; US$ = United States Dollar.

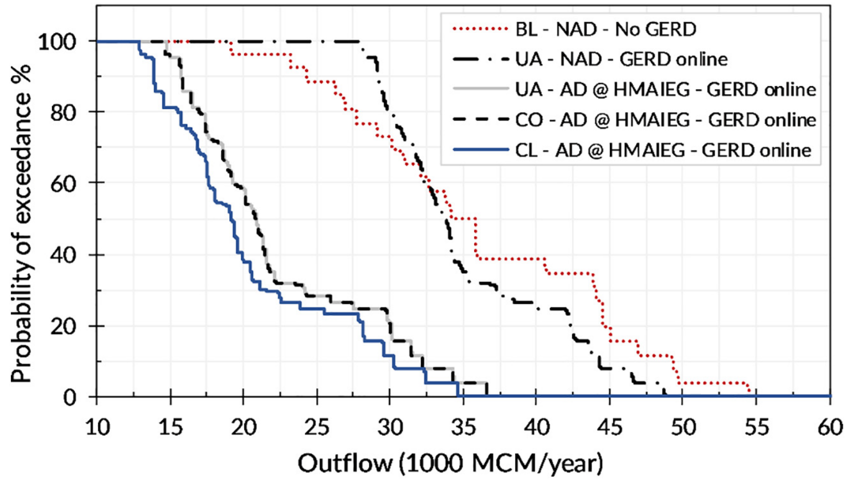


Fig. 9. Probability of exceedance of annual outflow from Sennar dam with different scenarios. Note: BL = Baseline; NAD = No Agricultural Development; GERD = Grand Ethiopian Renaissance Dam; UA = Unilateral Action state; AD @ HMAIEG = Agricultural development at the Highest Minimum Annual Increase in the Economic Gain; CO = Coordination state; CL = Collaboration state.

MCM with an average of around 35,829 MCM. Compared with the baseline (i.e. BL – NAD – No GERD), operating the system in the unilateral action state with the GERD online and with no planned irrigation scheme implemented (i.e. UA – NAD – GERD online) increased the minimum annual outflow from Sennar Dam to 28,089 MCM, decreased the maximum annual outflow from Sennar Dam to 51,456 MCM, and reduced the average annual outflow from Sennar Dam to around 33,751 MCM. Moreover, operating the system in the unilateral action or the coordination states to attain the HMAIEG from WEF with the GERD online (i.e. UA – AD @ HMAIEG – GERD online or CO – AD @ HMAIEG – GERD online) resulted in approximately similar annual outflow from Sennar Dam. The two scenarios showed a decrease in the minimum, the maximum, and the average annual outflow from Sennar Dam of around 4470 MCM, 16,000 MCM, and 14,860 MCM respectively compared with the baseline. Lastly, operating the system in the collaboration state to achieve the HMAIEG from WEF with the GERD online (i.e. CL – AD @ HMAIEG – GERD online) caused a decrease in the minimum, the maximum, and the average annual outflow from Sennar Dam of around 6190 MCM, 17,950 MCM, and 16,690 MCM respectively compared with the baseline.

5. Conclusions

Raising cooperation in transboundary river basins from unilateral action to some higher cooperation level is likely to increase the overall economic gain from WEF. However, the distribution of benefits and costs among riparian countries is unique for each transboundary river basin. In this study, the Blue Nile Basin, a transboundary river basin between Ethiopia and Sudan, was used to illustrate the impacts of cooperation between riparian countries on the long-term economic gain from WEF. To achieve that, a daily model was developed for the Blue Nile Basin between the GERD and Sennar Dam to simulate the hydrological process, irrigation water requirements, and water allocation. Satellite-based rainfall data were used as a boundary condition to model the hydrological processes. The model was used to calculate the economic gain for Ethiopia and Sudan independently, and for the Blue Nile Basin in 120 scenarios. Those scenarios result from the combinations of cooperation states: unilateral action, coordination, and collaboration; and infrastructure development settings that include the GERD and planned irrigation schemes.

The results revealed that operating the GERD in any cooperation state eliminates the current risk of daily supply shortage of the Sudanese part of the Blue Nile Basin and substantially increases hydro-energy generation from Roseires and Sennar dams, but only with modifying the operation of the latter dams. The GERD not only eliminates the current daily supply shortage, but also enables Sudan to expand its irrigated agriculture. The extent of expansion in irrigated agriculture, hydro-energy generation from the GERD, and hydro-energy generation from Roseires and Sennar dams depend on the cooperation level between Ethiopia and Sudan. It was found that the economic gain of Sudan and the Blue Nile Basin slightly decreases with raising the cooperation level from unilateral action to coordination and considerably increases with raising the cooperation level to collaboration. On the other hand, it was found that the economic gain of Ethiopia remains the same in both the unilateral action and the coordination states, but decreases in the collaboration state. The results showed that operating the GERD in the unilateral action state with no agricultural development in Sudan reduces the variability in the annual outflow from Sennar Dam (i.e. increases the minimum and decreases the maximum) with a slight change in the average. However, the maximum, the minimum, and the average annual outflow from Sennar Dam significantly decrease in scenarios that maximize the economic gain of the Blue Nile Basin from WEF. The results showed that maximizing the economic gain of the Blue Nile Basin results in Sudan exceeding its water share according to the 1959 agreement for the full utilization of the Nile water which was signed between Sudan and Egypt. However, an assessment of the overall net economic gain of Ethiopia, Sudan, and Egypt is essential to judge these scenarios.

This study has some limitations related to data and approach. The study was designed to illustrate the impacts of cooperation between riparian countries on the WEF nexus. For this reason, it was limited to the Blue Nile Basin and it was neither possible to examine cooperation scenarios that include Ethiopia, Sudan, and Egypt nor to quantify and evaluate the impacts of the analyzed scenarios on the WEF nexus of Egypt. Furthermore, the impacts related to recession agriculture, floods, sedimentation, fishery, river morphology, and ecosystem services were beyond the scope of this study. Due to the unavailability of future projections for the costs and prices of the economic evaluation components, the costs of agricultural inputs, agricultural operations, and hydropower facilities' operation in addition to the prices of crops and energy were taken as per the time the study has been conducted and were applied to the long-term scenarios. The index-sequential method was used to create 27 hydrologic sequences or "traces" based on the historical flow record. This method accommodates the impact of climate variability on the flow of the Blue Nile. However, it does not consider the non-stationarity in climate which has been reported by several studies in terms of rising temperatures (Elagib and Mansell, 2000; Elshamy et al., 2009; Elagib, 2010) and a likely decrease in rainfall and river flow (Elshamy et al., 2009; UNEP, 2013). The rising temperatures would increase the irrigation water requirements, increase reservoirs' evaporation, increase the economic loss due to evaporation, and decrease the economic gain from hydro-energy and/or food. The decreasing rainfall would increase the dependency on irrigation, increase the need for irrigation water abstractions, and decrease the economic gain from hydro-energy and/or food. The decreasing river flow would also decrease the economic gain from hydro-energy and food. Further research should be undertaken to tackle the aforementioned limitations and uncertainties.

Last of all, the growing potential for conflict over water in the Nile Basin, along with the increasing demand for WEF necessitate reaching a higher level of cooperation between the riparian countries to maximize the benefits and minimize the costs associated with the three resources. The evidence from this study shows that a higher level of cooperation between Ethiopia and Sudan can be reached through sharing benefits between the two countries. That can be realized by developing and implementing integrated management strategies of WEF that reach beyond political boundaries, sectors, and institutions.

Acknowledgements

The authors would like to express their gratitude to the Center for Advanced Decision Support for Water and Environment System (CADSWES) for assistance with RiverWare. Also, many thanks are due to the Eastern Nile Technical Regional Office (ENTRO), Kenana Engineering and Technical Services (KETS), and the Ministry of Water Resources, Irrigation, and Electricity of Sudan (MoWRIES) for being a great support for the study. Special thanks are due to the National Oceanic and Atmospheric Administration (NOAA), the University of Reading, the U.S. Geological Survey (USGS), and the Climate Hazards Group of the University of California for making the satellite-based rainfall products easily accessible. Moreover, the first author would like to thank the Deutscher Akademischer Austauschdienst (DAAD) for providing the personal fund number 91589562 from which this study benefited.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.02.249.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. FAO Irrigation and Drainage Paper. Crop Evapotranspiration, Rome.

Al-Saidi, M., Elagib, N., 2017. Towards understanding the integrative approach of the water, energy and food nexus. Sci. Total Environ. 574:1131–1139. https://doi.org/10.1016/j.scitotenv.2016.09.046.

Arjoon, D., Mohamed, Y., Goor, Q., Tilmant, A., 2014. Hydro-economic risk assessment in the eastern Nile River basin. Water Resour. Econ. 8:16–31. https://doi.org/10.1016/j.wre.2014.10.004.

Ashouri, H., Hsu, K., Sorooshian, S., Braithwaite, D., Knapp, K., Cecil, D., Nelson, B., Prat, O., 2015. PERSIANN-CDR: daily precipitation climate data record from multisatellite observations for hydrological and climate studies. Bull. Am. Meteorol. Soc. 96:69–83. https://doi.org/10.1175/BAMS-D-13-00068.1.

Awulachew, S., McCartney, M., Steenhuis, T., Ahmed, A., 2008. A Review of Hydrology, Sediment and Water Resource Use in the Blue Nile Basin (No. IWMI Working Paper 131). Colombo.

Basheer, M., Elagib, N.A., 2017. Sensitivity of Water-Energy Nexus to dam operation: a water-energy productivity concept. Sci. Total Environ. 616–617:918–926. https://doi.org/10.1016/j.scitotenv.2017.10.228.

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Komor, P., Steduto, P., Mueller, A., Tol, R., Yumkella, K., 2011. Considering the energy, water and food nexus: towards an integrated modelling approach. Energ Policy 39:7896–7906. https://doi.org/10.1016/j.enpol.2011.09.039.

Bhattacharyya, S., Bugatti, N., Bauer, H., 2015. A Bottom-up Approach to the Nexus of Energy, Food and Water Security in the Economic Community of West African States (ECOWAS) Region.

Block, P., Strzepek, K., 2010. Economic analysis of large-scale upstream river basin development on the Blue Nile in Ethiopia considering transient conditions, climate variability, and climate change. J. Water Resour. Plan. Manag. 136:156–166. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000022.

Chai, T., Draxler, R., 2014. Root mean square error (RMSE) or mean absolute error (MAE)?—arguments against avoiding RMSE in the literature. Geosci. Model Dev. 7: 1247–1250. https://doi.org/10.5194/gmd-7-1247-2014.

Conway, D., 1997. A water balance model of the Upper Blue Nile in Ethiopia. Hydrol. Sci. J. 42:265–286. https://doi.org/10.1080/02626669709492024.

Diem, J., Hartter, J., Ryan, S., Palace, M., 2014. Validation of satellite rainfall products for western Uganda. J. Hydrometeorol. 15:2030–2038. https://doi.org/10.1175/JHM-D-13-0193.1.

DIU (Dams Implementation Unit of Sudan), 2016. Roseires Heightening Project [WWW Document]. Minist. Water Resour. Electr, Sudan URL. http://www.roseiresdam.gov.sd/en/raising_project.htm, Accessed date: 11 September 2016.

Ebert, E., Janowiak, J., Kidd, C., 2007. Comparison of near-real-time precipitation estimates from satellite observations and numerical models. Bull. Am. Meteorol. Soc. 88:47–64. https://doi.org/10.1175/BAMS-88-1-47.

Elagib, N.A., 2010. Trends in intra-and inter-annual temperature variabilities across Sudan. Ambio 39:413–429. https://doi.org/10.1007/s13280-010-0042-3.

Elagib, N.A., Mansell, M.G., 2000. Recent trends and anomalies in mean seasonal and annual temperatures over Sudan. J. Arid Environ. 45:263–288. https://doi.org/10.1006/jare.2000.0639.

Elshamy, M., Seierstad, I., Sorteberg, A., 2009. Impacts of climate change on Blue Nile flows using bias-corrected GCM scenarios. Hydrol. Earth Syst. Sci. 13:551–565. https://doi.org/10.5194/hess-13-551-2009.

ENTRO (Eastern Nile Technical Regional Office), 2009. One - System Inventory Annexe: Blue Nile Sub Basin (Addis Ababa).

FAO (Food and Agriculture Organization of the United Nations), 2014. New_LocClim. [WWW Document]. URL. http://www.fao.org/nr/climpag/pub/en3_051002_en.asp, Accessed date: 14 June 2017.

FAO (Food and Agriculture Organization of the United Nations), 2015. CropWat. [WWW Document]. URL. http://www.fao.org/nr/water/infores_databases_cropwat.html, Accessed date: 30 November 2016.

Foster, V., Morella, E., 2011. Ethiopia's Infrastructure A Continental Perspective (No. 5595). Policy Research, Washington, D.C https://doi.org/10.1596/1813-9450-5595.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Rowland, J., Romero, B., Husak, G., Michaelsen, J., Verdin, A., 2014. A quasi-global precipitation time series for drought monitoring. U.S. Geol. Surv. DataSer. 832:4. https://doi.org/10.3133/ds832.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci. Data 2. https://doi.org/10.1038/sdata.2015.66.

Grieser, J., Gommes, R., Bernardi, M., 2006. New LocClim - the local climate estimator of FAO. Geophys. Res. Abstr. 8, 8305.

Hassan, S., 2011. Central Bank of Sudan Policies for the Year 2011 [WWW Document]. Cent. Bank Sudan URL. http://www.cbos.gov.sd/en/node/3325, Accessed date: 11 June 2017.

HEC (Hydrologic Engineering Center), 2000. Hydrologic Modeling System HEC-HMS Technical Reference Manual (Washington).

HEC (Hydrologic Engineering Center), 2008. Hydrologic Modeling System HEC-HMS Applications Guide (Washington, D.C).

HEC (Hydrologic Engineering Center), 2015. Hydrologic Modeling System User's Manual (Washington, D.C).

Hoff, H., 2011. Understanding the Nexus. Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute, Stockholm.

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., Gielen, D., Rogner, H., Fischer, G., van Velthuizen, H., Wiberg, D., Young, C., Roehrl, R., Mueller, A., Steduto, P., Ramma, I., 2013. Integrated analysis of climate change, land-use, energy and water strategies. Nat. Clim. Chang. 3:621–626. https://doi.org/10.1038/nclimate1789.

IPoE, 2013. International Panel of Experts on the Grand Ethiopian Renaissance Dam Project (GERDP): Final Report (Addis Ababa).

IWMI (International Water Management Institute), 2012. The Nile River Basin Water, Agriculture, Governance and Livelihoods. 1st ed. Routledge, Oxon.

Jalilov, S., Varis, O., Keskinen, M., 2015. Sharing benefits in transboundary rivers: an experimental case study of central Asian water-energy-agriculture nexus. Water 7: 4778–4805. https://doi.org/10.3390/w7094778.

Jalilov, S., Keskinen, M., Varis, O., Amer, S., Ward, F., 2016. Managing the water-energy-food nexus: gains and losses from new water development in Amu Darya River basin. J. Hydrol. 539:648–661. https://doi.org/10.1016/j.jhydrol.2016.05.071.

Jantzen, J., 2006. The Economic Value of Natural and Environmental Resources. Institute for Applied Environmental Economics, Voorschoten.

Jarvis, A., Reuter, H., Nelson, A., Guevara, E., 2008. Hole-filled SRTM for the Globe Version 4 [WWW Document]. CGIAR-CSI SRTM 90m Database. URL. http://srtm.csi.cgiar.org accessed 12.30.16.

Jeuland, M., Wu, X., Whittington, D., 2017. Infrastructure development and the economics of cooperation in the Eastern Nile. Water Int. (0):1–21 https://doi.org/10.1080/02508060.2017.1278577.

Kalpakian, J., 2015. Ethiopia and the Blue Nile: development plans and their implications downstream. Air Sp. Power J. - Africa Francoph. 6, 40–57.

Karnib, A., 2017. Water-energy-food nexus: a coupled simulation and optimization framework. J. Geosci. Environ. Prot. 5:84–98. https://doi.org/10.4236/gep.2017.54008.

Keith, B., Ford, D., Horton, R., 2017. Considerations in managing the fill rate of the Grand Ethiopian Renaissance Dam Reservoir using a system dynamics approach. J. Def. Model. Simul. Appl. Methodol. Technol. 14. https://doi.org/10.1177/1548512916680780.

Kendall, D., Dracup, J., 1991. A comparison of index-sequential and AR(1) generated hydrologic sequences. J. Hydrol. 122:335–352. https://doi.org/10.1016/0022-1694(91)90187-M.

Keskinen, M., Someth, P., Salmivaara, A., Kummu, M., 2015. Water-energy-food nexus in a transboundary river basin: the case of Tonle sap Lake, Mekong River Basin. Water 7: 5416–5436. https://doi.org/10.3390/w7105416.
Keskinen, M., Guillaume, J., Kattelus, M., Porkka, M., Räsänen, T., Varis, O., 2016. The water-energy-food nexus and the transboundary context: insights from large Asian rivers. Water 8. https://doi.org/10.3390/w8050193.
Kibaroglu, A., Gürsoy, S., 2015. Water–energy–food nexus in a transboundary context: the Euphrates–Tigris river basin as a case study. Water Int. 40:824–838. https://doi.org/10.1080/02508060.2015.1078577.
King, A., Block, P., 2014. An assessment of reservoir filling policies for the Grand Ethiopian Renaissance Dam. J. Water Clim. Chang. 5:233–243. https://doi.org/10.2166/wcc.2014.043.
Legates, D., McCabe Jr, G., 1999. Evaluating the use of "goodness of fit" measures in hydrologic and hydroclimatic model validation. Water Resour. Res. 35:233–241. https://doi.org/10.1029/1998WR900018.
Maidment, R., Grimes, D., Allan, R., Tarnavsky, E., Stringer, M., Hewison, T., Roebeling, R., Black, E., 2014. The 30 year TAMSAT African rainfall climatology and time series (TARCAT) data set. J. Geophys. Res. Atmos. 119:10619–10644. https://doi.org/10.1002/2014JD021927.
Majdalawi, M., Raedig, C., Al-Karablieh, E., Schlueter, S., Tabieh, M., 2016. Integration of different environmental valuation methods to estimate forest degradation in arid and semi-arid regions. Int. J. Sustain. Dev. World Ecol. 23:392–398. https://doi.org/10.1080/13504509.2015.1124934.
Melesse, A., Abtew, W., Setegn, S., Dessalegne, T., 2011. Nile River Basin Hydrology, Climate and Water Use. Springer, Dordrecht https://doi.org/10.1007/978-94-007-0689-7.
MIT (Massachusetts Institute of Technology), 2014. The Grand Ethiopian Renaissance Dam: An Opportunity for Collaboration and Shared Benefits in the Eastern Nile Basin, An Amicus Brief to the Riparian Nations of Ethiopia, Sudan and Egypt From the International. Non-partisan Eastern Nile Working Group, Boston.
Mohtar, R., Daher, B., 2012. Water, energy, and food: the ultimate nexus. Encycl. Agric. Food, Biol. Eng, Second ed.:pp. 1–5 https://doi.org/10.1081/E-EAFE2-120048376.
Mohtar, R., Daher, B., 2016. Water-Energy-Food Nexus Framework for facilitating multi-stakeholder dialogue. Water Int. 8060:1–7. https://doi.org/10.1080/02508060.2016.1149759.
MoIHES (Ministry of Irrigation and Hydro-electric Energy of Sudan), 1977. Blue Nile Waters Study Phase IA: Availability and Use of Blue Nile Water (Khartoum).
MoIHPS (Ministry of Irrigation and Hydro-electric Power of Sudan), 1966. Roseires Dam (Khartoum).
MoIHPS (Ministry of Irrigation and Hydro-electric Power of Sudan), 1968. Regulation Rules for the Working of the Reservoirs at Roseires and Sennar on the Blue Nile.
Mu, Q., Zhao, M., Running, S., 2011. Remote Sensing of Environment Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sens. Environ. 115: 1781–1800. https://doi.org/10.1016/j.rse.2011.02.019.
NBE (National Bank of Ethiopia), 2016. Annual Report 2015/16 (Addis Ababa).
NBI (Nile Basin Initiative), 2012. State of the River Nile Basin 2012 (Entebbe).
Novella, N., Thiaw, W., 2013. African rainfall climatology version 2 for famine early warning systems. J. Appl. Meteorol. Climatol. 52:588–606. https://doi.org/10.1175/JAMC-D-11-0238.1.
Ouarda, T., Labadie, J., Fontane, D., 1997. Indexed sequential hydrologic modeling for hydropower capacity estimation. J. Am. Water Resour. Assoc. 33, 1337–1349.
Pittock, J., Dumaresq, D., Bassi, A., 2016. Modeling the hydropower–food nexus in large river basins: a Mekong case study. Water 8. https://doi.org/10.3390/w8100425.
Plusquellec, H., 1990. The Gezira Irrigation Scheme in Sudan: Objectives, Design, and Performance (No. 120). Washington, D.C.
Ranganathan, R., Briceño-Garmendia, C., 2011. Sudan's Infrastructure A Continental Perspective (No. 5815), Policy Research. Washington, D.C. https://doi.org/10.1596/1813-9450-5815.
Ribbe, L., Ahmed, S., 2006. Transboundary water resources issues in the Nile River Basin. ManagementTechnology. Resource Management and Development, Wasser Berlin. Berlin, pp. 13–26.
Sadoff, C., Grey, D., 2005. Cooperation on international rivers. Water Int. 30:420–427. https://doi.org/10.1080/02508060508691886.
Salini Impregilo, 2016. Grand Ethiopian Renaissance Dam Project [WWW Document]. URL. http://www.salini-impregilo.com/en/projects/in-progress/dams-hydroelectric-plants-hydraulic-works/grand-ethiopian-renaissance-dam-project.html, Accessed date: 9 November 2016.
Salman, S., 2016. The Grand Ethiopian Renaissance Dam: the road to the declaration of principles and the Khartoum document. Water Int. 8060:1–16. https://doi.org/10.1080/02508060.2016.1170374.
Satti, S., Zaitchik, B., Siddiqui, S., 2015. The question of Sudan: a hydro-economic optimization model for the Sudanese Blue Nile. Hydrol. Earth Syst. Sci. 19:2275–2293. https://doi.org/10.5194/hess-19-2275-2015.
Stern, M., Flint, L., Minear, J., Flint, A., Wright, S., 2016. Characterizing changes in Streamflow and sediment supply in the Sacramento River Basin, California, using hydrological simulation program—FORTRAN (HSPF). Water 432:1–21. https://doi.org/10.3390/w8100432.
Strasser, L., Lipponen, A., Howells, M., Stec, S., Bréthaut, C., 2016. A methodology to assess the water energy food ecosystems nexus in Transboundary River Basins. Water 8. https://doi.org/10.3390/w8020059.
Sutcliffe, J., Parks, Y., 1999. The Hydrology of the Nile, IAHS Special Publication. The International Association of Hydrological Science, Wallingford.
Swanson, A., 2014. The Grand Ethiopian Renaissance Dam: Sustainable Development or Not? Virginia Tech, Center for Leadership in Global Sustainability (CLiGS), Arlington
Tarnavsky, E., Grimes, D., Maidment, R., Black, E., Allan, R., Stringer, M., Chadwick, R., Kayitakire, F., 2014. Extension of the TAMSAT satellite-based rainfall monitoring over Africa and from 1983 to present. J. Appl. Meteorol. Climatol. 53:2805–2822. https://doi.org/10.1175/JAMC-D-14-0016.1.
Toté, C., Patricio, D., Boogaard, H., van der Wijngaart, R., Tarnavsky, E., Funk, C., 2015. Evaluation of satellite rainfall estimates for drought and flood monitoring in Mozambique. Remote Sens. 7:1758–1776. https://doi.org/10.3390/rs70201758.
UN (United Nations), 1964. Treaty Series. United Nations, New York.
UN (United Nations), 2015a. World Population Prospects: Key Findings and Advance Tables (No. ESA/P/WP.241) (New York).
UN (United Nations), 2015b. The Millennium Development Goals Report. United Nations, New York.
UNDP (United Nations Development Programme), 2015. Human Development Report 2015: Work for Human Development (New York).
UNEP (United Nations Environment Programme), 2013. Adaptation to Climate-Change Induced Water Stress in the Nile Basin: A Vulnerability Assessment Report (Nairobi).
Wheeler, K., Basheer, M., Mekonnen, Z., Eltoum, S., Mersha, A., Abdo, G., Zagona, E., Hall, J., Dadson, S., 2016. Cooperative filling approaches for the Grand Ethiopian Renaissance Dam. Water Int. 8060:1–24. https://doi.org/10.1080/02508060.2016.1177698.
Zagona, E., Fulp, T., Shane, R., Magee, T., Morgan, H., 2001. Riverware: a generalized tool for complex reservoir system modeling. J. Am. Water Resour. Assoc. 37, 913–929.
Zagona, E., Rajagopalan, B., Setzer, S., 2008. Riverware decision support tools for planning sustainable river development with hydropower. High-Level International Forum on Water Resources and Hydropower, pp. 1–8 Beijing.
Zambrano-Bigiarini, M., Nauditt, A., Birkel, C., Verbist, K., Ribbe, L., 2017. Temporal and spatial evaluation of satellite-based rainfall estimates across the complex topographical and climatic gradients of Chile. Hydrol. Earth Syst. Sci. 21:1295–1320. https://doi.org/10.5194/hess-21-1295-2017.
Zhang, Y., Block, P., Hammond, M., King, A., 2015. Ethiopia's Grand Renaissance Dam: implications for downstream riparian countries. J. Water Resour. Plan. Manag. 141, 5015002. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000520.
Zhang, Y., Erkyihum, S., Block, P., 2016. Filling the GERD: evaluating hydroclimatic variability and impoundment strategies for Blue Nile riparian countries. Water Int. 8060:1–18. https://doi.org/10.1080/02508060.2016.1178467.