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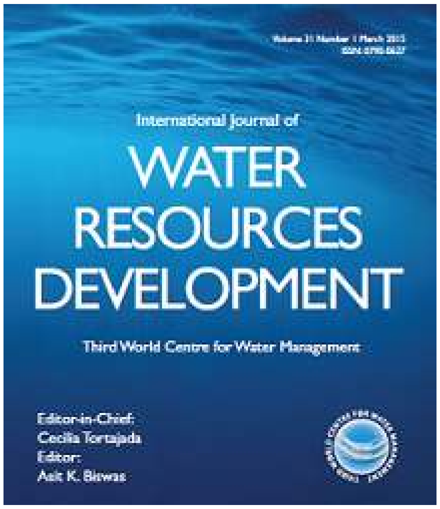

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Exploring management approaches for water and energy in the data-scarce Tekeze-Atbara Basin under hydrologic uncertainty

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Exploring management approaches for water and energy in the data-scarce Tekeze-Atbara Basin under hydrologic uncertainty

This study examines management approaches for hydropower generation and irrigation and domestic water supply for Tekeze-Atbara, a transboundary river between Ethiopia, Eritrea, and Sudan, under above- and below- normal hydrologic conditions considering current and future water demand scenarios. Satellite data are used to substitute unavailable or inaccessible ground meteorological and dam data. Based on three examined coordination scenarios, the analysis finds that coordinating the management of the Sudanese dams would bring significant benefits to water supply and energy generation. An optimisation analysis is necessary to reveal the full value of coordination of dams in Tekeze-Atbara Basin.

Keywords: Nile Basin; storage dams; satellite-based rainfall products; satellite-based reservoir monitoring; water-energy nexus; coordination

Introduction

Access to sustainable water, energy, and food sources has become a major concern in the modern-day especially under the ongoing rapid changes in the natural and human environments. The demands for water, energy, and food in the Eastern Nile Basin (ENB) countries (Figure 1) are speedily growing due to population growth, economic development, and urbanisation (NBI, 2012). From 1990 to 2017, the total population of the ENB countries increased from around 134 to 260 million (UN, 2017) and the Human Development Index of the individual countries grew at different rates except for South Sudan (UNDP, 2018). Moreover, around 80 million of the population of the ENB countries lived in urban areas in 2017 compared to approximately 38 million in 1990 with the expectation to reach about 217 million by 2050 (UN, 2018). On the other hand, climate change is expected to exhibit large-scale changes in the elements of the hydrologic cycle such as precipitation and runoff (IPCC, 2008; N. Stern, 2006). For

East Africa, several studies projected an increase in precipitation (Shongwe, Van Oldenborgh, Van Den Hurk, & Van Aalst, 2011), whereas others reported a decrease (Souverijns, Thiery, Demuzere, & Lipzig, 2016). Moreover, river flow has been projected to increase in large parts of East Africa coupled with more frequent successions of floods and a decrease in the severity of droughts (Cole, Elliott, & Strobl, 2014; Shongwe et al., 2011). In light of the above pressures and challenges, fulfilling the present and future water, energy, and food demands requires consistent plans and targets for water management (García-Vera, 2013), efficient and optimally-operated energy generation systems (Boadi & Owusu, 2017; Peng, Xu, & Liu, 2016), and enhanced agricultural practices (Amekawa, 2009; Møller, Drews, & Larsen, 2017; Pradhan, Sijapati, & Bajracharya, 2015). Further, understanding the interdependences of water, energy, and food systems is imperative for their sustainable management (Al-Saidi & Elagib, 2017; Liu et al., 2017). Several studies investigated the nexus of water, energy, and food in a variety of contexts and spatial and temporal scales and concluded the importance of their joint management (Bazilian et al., 2011; Chirisa & Bandauko, 2015; Engström et al., 2017; Kurian, 2017; Larsen & Drews, 2019; Lindström & Granit, 2012).

Tekeze-Atbara River, the last major tributary of the Nile River before it ends in the Mediterranean Sea, is geographically shared between Ethiopia, Eritrea, and Sudan (Sutcliffe & Parks, 1999). Numerous studies have been published for the Nile Basin on the management of water and energy resources under a variety of scenarios and climatic conditions. However, few focused on or tested water management strategies for Tekeze-Atbara Basin. A recent study by Digna, Mohamed, van der Zaag, Uhlenbrook, & Corzo (2017) reviewed 36 published and unpublished simulation and optimisation models that have been developed between 1958 and 2016 on management and planning of the Nile water resources (e.g. Arjoon, Mohamed, Goor, & Tilmant, 2014; Block & Strzepek, 2010; Goor, Halleux, Mohamed, & Tilmant, 2010; Guariso, Haynes, Whittington, & Younis, 1981; Guariso & Whittington, 1987; Jeuland, 2010; King & Block, 2014; Lee, Yoon, & Shah, 2012; Levy & Baecher, 1999; McCartney & Menker Girma, 2012; Satti, Zaitchik, & Siddiqui, 2015; Stedinger, Sule, & Loucks, 1984; Wheeler et al., 2016; Whittington, Waterbury, & Jeuland, 2014; Whittington, Wu, & Sadoff, 2005; Y. Zhang, Block, Hammond, & King, 2015). The study revealed that 10 of the 36 reviewed Nile models included Tekeze-Atbara in their modelling domains. Nevertheless, only one of the ten models, i.e. Abreha (2010), examined scenarios to quantify trade-offs between energy generation and water supply for Tekeze-Atbara Basin. A number of other studies have been recently published on modelling the water resources of the Nile Basin of which three were limited to the Blue Nile Basin (Basheer et al., 2018; Mekonnen, Duan, Rientjes, & Disse, 2018; Stamou & Rutschmann, 2018), one to the White Nile Basin (Basheer & Elagib, 2018b), one to Tekeze-Atbara Basin (Abera, Asfaw, Engida, & Melesse, 2018), three to the ENB (Digna et al., 2018; Mulat, Moges, & Moges, 2018; Wheeler et al., 2018), and one covered the whole Nile Basin (Jeuland, Wu, & Whittington, 2017). Apart from Abera et al. (2018), none of the recent studies focused on testing management scenarios for Tekeze-Atbara Basin. Abera et al. (2018) developed a monthly model for Tekeze-5 Dam (see Figure 1) to optimise its operation for hydropower production under Representative Concentration Pathway (RCP) 4.5 and 8.5 climate scenarios. They found that climate change would increase hydropower production from the dam by 25 to 30%. Previous studies that focused on Tekeze-Atbara Basin, as reviewed above, helped to improve the understandings on the management of water and energy in the Basin. Nevertheless, they relied on monthly models and consequently simplified some elements of the river system that vary from day to day and inherently influence water supply and hydropower generation (e.g. dam outlet capacities, dam operating rules, tailwater elevation) (World Bank, 1980). Moreover, they used deterministic hydrologic conditions to drive their model simulations.

In light of what has been mentioned above, this study explores the implication of three coordination scenarios for cascade dams in Tekeze-Atbara Basin for hydropower generation and irrigation and domestic water supply. Tekeze-Atbara River was selected herein because there is still little scientific understanding of it, as reviewed above, although it contributes roughly 15% of the annual flow of the Nile as measured at Aswan near the Sudanese-Egyptian border. Moreover, it suffers from metrological and hydrologic data-scarcity, which enables presenting alternative sources and innovative methods to obtain data. In this study, a daily river basin model is developed, calibrated, and validated for Tekeze-Atbara for the period 1984-2016 to include river flow, irrigation water demands, domestic water demands, and hydropower storage dams. The model simulates rainfall-runoff of sub-basins with limited/unavailable data, water allocation to hydropower and water supply, and irrigation water demands of future schemes. Due to the few operating rainfall stations in the study area, point-to-pixel evaluation is conducted for five long-term Satellite-based Rainfall Products (SRPs), and the best performing one is used as a boundary condition to the rainfall-runoff component of the model. Satellite imagery is used to derive the past reservoir water levels of Tekeze-5 Dam because no data about them were accessible for this study. The present analysis examines 36 scenarios which result from the combinations of three dam coordination levels (business as usual, coordination within Sudan, and sub-basin coordination), two water demand scenarios (current and future), and six starting water levels for Tekeze-5 Dam. Each of the scenarios is examined across 50 above-normal and 50 below-normal stochastic hydrologic sequences that are developed by bootstrapping from the historic flow record. The present analysis is not meant to quantify the costs and benefits of coordination in Tekeze-Atbara Basin, as the examined scenarios do not include the full expected future water demands, nor is an optimisation model used to modify the operation of the river system. However, the examined scenarios are hoped to inform the decision makers of the Tekeze-Atbara Basin and other basins on the importance of coordinated management of river systems especially under sustained above- or below-normal hydrologic conditions which are anticipated to occur before the middle of the 21st century (Hirabayashi, Kanae, Emori, Oki, & Kimoto, 2008; IPCC, 2008). The remaining part of this paper is composed of four main sections: the first gives an overview of Tekeze-Atabra Basin and its water-related infrastructures; the second deals with the methodology used for this study; the thrid analyses and discusses the results; the fourth draws conclusions based on the other three sections.

Study area

General features

The study area encompasses Tekeze-Atbara Basin. Figure 1 shows the extent and general characteristics of the study area. Tekeze-Atbara Basin is located in north-eastern Africa and is geographically shared between Ethiopia, Eritrea, and Sudan. The basin covers an area of around 231,000 km^2 of which approximately 51% is in Sudan, 39% is in Ethiopia, and 10% is in Eritrea. Tekeze-Atbara River starts in north-western Ethiopia at an altitude of above 4,500 m asl, where it is known as Tekeze River, and flows northwest through the rugged topography of Ethiopia while small tributaries join the mainstem from Ethiopia and Eritrea. The river enters Sudan at around 580 m asl where it is called Setit River. Around 70 km downstream the Ethiopian-Sudanese border, Upper Atbara, a main tributary that originates in Ethiopia, joins Setit River to form

Atbara River. After that, Atbara continues northwest through the relatively flat terrain of Sudan, gets joint by small streams, and merges with the Main Nile in Atbara Town at around 350 m asl. The Main Nile continues northwards through North Sudan and Egypt and ends in the Mediterranean Sea.

[Figure 1 near here]

The average annual flow of Tekeze-Atbara River is around 12,800 Mm3, which accounts for approximately 15% of the average yearly flow of the Nile measured at Aswan near the Sudanese-Egyptian border. On average, the current annual water abstraction and reservoir evaporation in Tekeze-Atbara Basin account for around 1,900 and 800 Mm3, respectively. High inter- and intra-annual variability characterises the flow of Tekeze-Atbara (Zaghloul, El-Moattassem, & Rady, 2007) with around 92% of the annual flow occurring from July to October (see Figure 2). Based on Köppen Geiger climate classification, the study area comprises temperate (Cwb), tropical (Aw), and arid (BSh and BWh) climates (H.E Beck et al., 2018).

[Figure 2 near here]

Dams and hydropower

Figures 1 and 3 show the locations of the three currently operating dams in the study area and Table 1 reports their main attributes. The construction of Khashm Elgirba Dam in Sudan, the oldest dam on Tekeze-Atbara River, was completed in 1964 to provide irrigation water to New Halfa Scheme through headworks located on the left side of the dam (World Bank, 1980). Both the dam and the irrigation scheme were built to resettle 50,000 Sudanese that have been displaced as a result of the construction of the Egyptian High Aswan Dam which has a reservoir that extends around 150 km inside Sudan (Salman, 2016). According to the Ministry of Water Resources, Irrigation, and

Electricity of Sudan, around 50% of the original storage capacity of Khashm Elgirba has been lost due to sedimentation from 1964 to 1985 whereas roughly 6% has been lost from 1986 to 2009. Khashm Elgirba Dam also serves in hydropower generation in two ways (Institute of Hydrology, 1978; Sudanese Hydro Generation Co Ltd, 2011): (1) downstream releases can be passed through two 5.3-MW Kaplan turbines; (2) water diversion to New Halfa Scheme and Town can be passed through three 2.4-MW pump-turbines when the reservoir water level is at least two meters higher than the water level in the diversion canal. The three pump-turbines are also used to pump water from the reservoir to the diversion canal when the reservoir water level drops below the canal water level (Institute of Hydrology, 1978).

[Table 1 near here]

In 2009, Ethiopia completed the construction of Tekeze-5 Dam, the second tallest double curvature concrete arch dam in Africa, to generate hydropower through four 75-MW Frances turbines (Abera et al., 2018; Adera, 2015; Tekeze Inauguration Bulletin, 2009; Welde, 2016). In 2015, the construction of Upper Atbara and Setit Dam Complex (UASDC) was completed at a location right upstream the confluence of Upper Atbara and Setit Rivers (see Figure 1). The latter River is called Tekeze in Ethiopia as explained in the previous section. UASDC crosses both Upper Atbara and Setit Rivers to form a common reservoir (Sloff, Omer, Heynert, & Mohamed, 2015). The dam was built to generate hydropower through four 80-MW turbines, to provide irrigation water to a future irrigation scheme called Upper Atbara, and to supply Gedarif Town with domestic water through a pipeline that is currently under construction (Zoellner, Scheid, & Mukthar, 2017). The dam body includes two sets of outlets: (1) a powerhouse and a spillway that release water to Upper Atbara River and (2) a spillway that discharges into Setit River. Lastly several dams are planned for construction on the Ethiopian side of

Tekeze-Atbara River (Digna et al., 2018). However, they were not included in this study.

[Figure 3 near here]

Irrigation and domestic water users

Figures 1 and 3 illustrate existing water abstractions on Tekeze-Atbara in addition to planned abstractions in the basin part of Sudan. The information available to us on future irrigation and domestic water users in the Ethiopian and Eritrean parts of the basin were not enough to estimate their water demands and therefore were not considered. New Halfa, located in Sudan, is the only existing large-scale irrigation scheme that withdraws water from Tekeze-Atbara River. The scheme has an area of around 185,000 ha and was constructed during the 1960s to resettle the Sudanese population that has been displaced due to the construction of the High Aswan Dam as explained in the previous section. The scheme is located downstream Khashm Elgirba Dam on the west bank of the river. A diversion canal is used to supply New Halfa Scheme and Town with irrigation and domestic water, respectively, from Khashm Elgirba Reservoir. Furthermore, Upper Atbara Irrigation Scheme is planned to be constructed downstream Khashm Elgirba Dam on the east bank of the river. According to the Ministry of Water Resources, Irrigation, and Electricity of Sudan, the scheme is expected to have an area of around 300,000 ha and will likely be supplied with irrigation water through headworks on the right side of Khashm Elgirba Dam. Lastly, a pipeline is currently under construction to provide 450,000 residents of Gedarif Town with domestic water from the reservoir of UASDC (Zoellner et al., 2017).

Methodology

Model description

To examine management approaches for hydropower generation and irrigation and domestic water supply, a daily river basin model was developed, calibrated, and validated for Tekeze-Atbara for the period 1984 to 2016 to include hydropower dams, large-scale irrigation schemes, significant domestic water users, and major inflows and water losses. Figure 3 shows a schematic of the model developed for this study. The model simulates rainfall-runoff of sub-basins with limited/unavailable data (i.e., sub-basins 1 to 7), water allocation to hydropower and water supply, and irrigation water demands of future schemes. The baseline model includes five main elements: three dams (i.e., Tekeze-5 Dam, UASDC, and Khashm Elgirba Dam) and two water consumers (i.e., New Halfa Irrigation Scheme and Town). Furthermore, the baseline model includes eight inflow nodes (sub-basins 1 to 7 and Upper Atbara), evaporation losses from storage reservoirs, and transmission losses from river reaches. Upper Atbara Irrigation Scheme and Gedarif Town were included in future scenarios as explained in a following section. The data used in developing and driving the model and their sources are outlined in the following section.

Several methods were employed in modelling rainfall-runoff of sub-basins 1 to 7 including simple canopy interception, average monthly evapotranspiration, soil deficit and constant loss calculations for infiltration, and Snyder unit hydrograph (HEC, 2000). It is worth mentioning that all the parameters of the seven sub-basins were spatially lumped. FAO Penman-Monteith equation (G. Allen, Pereira, Raes, & Smith, 1998) was used to estimate the irrigation water demands of the planned Upper Atbara Scheme. It was assumed that Upper Atbara Scheme has a soil type similar to New Halfa Scheme (i.e., clayey soil; The World Bank, (1980)) due to their proximity. Figure S2 in the online supplementary data shows the estimated irrigation water demands of Upper Atbara Scheme. Fixed lag times and loss percentages were used to model channel travel time and losses, respectively. Furthermore, average monthly evaporation coefficients were applied to estimate evaporation losses from the storage reservoirs. The calibration and validation criteria of the model are presented in a following section.

In this study, several modelling tools were utilised to simulate the different processes. The Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS; HEC (2000)), CropWat (FAO, 2015), and RiverWare (Zagona, Fulp, Shane, Magee, & Morgan, 2001) were used to model rainfall-runoff, irrigation water demands, and water allocation to hydropower generation and water users, respectively. Figure S3 in the online supplemental data displays the linkages between the three modelling tools used in this study.

Data used

Daily data of river water levels at Kubor Station were obtained from the Ministry of Water Resources, Irrigation, and Electricity of Sudan (MoWRIE) for the period 1984 to 2007. The water levels were used together with the concurrent rating curves to create a river flow time series for the station. MoWRIE also provided river flow data for Bardana and Rumela stations for the period 2008 to 2016, river flow data for Hamadiet Station for 2013 to 2016, and reservoir water levels for UASDC for 2015 and 2016 (note that UASDC became operational in 2015). The inflow of Upper Atbara River for 1984 to 2014 was compiled from Kubor Station (1984-2007) and Rumela Station (2008 to 2014). Moreover, the observed flow at Hamadiet Station (2015-2016), the observed outflow from, and water levels of, UASDC (2015-2016), and evaporation losses from UASDC were used to estimate the inflow of Upper Atbara River for 2015 and 2016 using water balance. For Khashm Elgirba Dam and UASDC, the geometry and monthly evaporation coefficients of the reservoirs, the outlet capacities, the specifications of the hydropower turbines, the downstream discharge-water level relationships, and the operating rules were obtained from MoWRIE. Apart from the operating rules, similar data were attained for Tekeze-5 Dam from Wheeler et al. (2016) and the Eastern Nile Technical Regional Office (ENTRO) of the Nile Basin Initiative (NBI). The method used to derive the past reservoir water levels of Tekeze-5 Dam, explained in a following section, utilises Landsat satellite images of the United States Geological Survey (USGS). Furthermore, MoWRIE provided intermittent outflow data for Khashm Elgirba Dam from 1984 to 2014, current water demands of New Halfa Scheme and Town, future water demands of Gedarif Town, and the design cropping pattern and irrigation efficiency of Upper Atbara Scheme. Due to poor coverage of Tekeze-Atbara Basin with rainfall stations, five daily SRPs that cover the model period were evaluated, and the best-performing one was used as a boundary condition to model the inflow from sub-basins 1 to 7 (Figure 3). The evaluated SRPs are: Africa Rainfall Climatology Version 2.0 (ARC2; Novella & Thiaw (2013)), Climate Hazards group Infrared Precipitation with Stations version 2.0 (CHIRPS V2.0; Funk et al. (2014)), Multi-Source Weighted-Ensemble Precipitation version 2.0 (MSWEP 2.0; Hylke E Beck, Dijk, Levizzani, Schellekens, & Miralles (2017)), Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks–Climate Data Record (PERSIANN-CDR; Ashouri et al. (2015)), and Tropical Applications of Meteorology Using Satellite Data and Ground-Based Observations version 2.0 (TAMSAT-2; Tarnavsky et al. (2014)). Daily rainfall data from seven ground stations for the period 1984 to 2007 were used to evaluate the performance of the SRPs (Figure 1 shows the stations). The ground rainfall data were obtained from the Sudan Meteorological Authority and ENTRO. More information about the evaluation method of the SRPs is provided in the next section of this paper. The seven sub-basins (see Figure 3) were delineated based on the 90-m resolution topographic data of the Shuttle Radar Topography Mission (SRTM; Jarvis, Reuter, Nelson, & Guevara (2008)). The global monthly evapotranspiration data of the Moderate Resolution Imaging Spectroradiometer Global Evapotranspiration Project (MOD16; Mu, Zhao, & Running (2011)), which covers the period 2000 to 2014, were used to estimate the average monthly evapotranspiration from the seven sub-basins. The climatic parameters required to estimate the irrigation water demands of Upper Atbara Scheme were acquired from New_LocClim (FAO, 2014; Grieser, Gommes, & Bernardi (2006)), a database developed by the Food and Agriculture Organization of the United Nations.

Key data utilised in this study are provided in the online supplementary file (namely water abstractions, dam operating rules, and reservoir geometry and evaporation coefficients).

Evaluation of Satellite-based Rainfall Products

Point-to-pixel evaluation was conducted to assess the daily performance of the five selected SRPs (i.e., ARC2, CHIRPS V2.0, MSWEP 2.0, PERSIANN-CDR, and TAMSAT-2) through the period 1984 to 2007. This method compares satellite-estimated rainfall at locations of ground rainfall stations with the concurrent rainfall records of the stations. This method is suitable for regions with sparse rainfall stations (Basheer & Elagib, 2018a), and therefore was selected for this study. R programming language (R Core Team, 2015) was used to download the SRPs and to carry out the evaluation. To measure the disparity between the satellite estimates and the ground observations, three metrics were used: the Root Mean Square Error (RMSE; Equation 1), the Mean Bias Error (MBE; Equation 2), and the coefficient of determination (R^2; Equation 3). Whereas RMSE shows the magnitude of the average error and can take any value from zero (indicates no error) to +∞ (signals a high error), MBE describes the direction of error bias and varies between -∞ and +∞ (both indicate a high error), with no error at zero. R^2 measures how well the estimated values correlate with the observed values and varies from zero (total disagreement) to one (perfect correlation). To assess the detection skills of the SRPs, four categorical metrics were selected, which are based on dichotomous evaluation of each time step within the assessment period (rainy/non-rainy). The selected categorical metrics are the Probability Of Detection (POD), the False Alarm Ratio (FAR), and the Equitable Threat Score (ETS). In order to calculate the three selected categorical metrics, a threshold of 0.1 mm/day was used to classify each time step within the evaluation period into the following: a hit, h, when rainfall was both observed at the station and estimated by the Satellite-based Rainfall Product (SRP); a miss, m, when rainfall was observed at the station but not estimated by the SRP; a false alarm, f, when rainfall was estimated by the SRP but not observed at the station; or a null, n, when rainfall was neither observed at the station nor estimated by the SRP. Equations 4, 5, and 6 were used to calculate POD, FAR, and ETS, respectively. POD gives the fraction of observations that were successfully detected and ranges from zero, indicating no observation was detected, to one, indicating all observations were detected. On the other hand, FAR measures the fraction of estimations that were not observed. It ranges from zero, which indicates that all estimations were observed, to one, which indicates that all estimations were not observed. Lastly, ETS gives the portion of observations and estimations that were correctly detected, adjusted for the number of hits (He; Equation 7) that would be expected by random chance. It varies from -1/3, which is the worst value, to one, which is the perfect value.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(E_i - O_i)^2} \qquad (1)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(E_i - O_i) \qquad (2)$$

$$R^2 = \frac{\left(n\left(\sum_{i=1}^{n} O_i E_i\right) - \left(\sum_{i=1}^{n} O_i\right)\left(\sum_{i=1}^{n} E_i\right)\right)^2}{\left(n\left(\sum_{i=1}^{n} O_i^2\right) - \left(\sum_{i=1}^{n} O_i\right)^2\right)\left(n\left(\sum_{i=1}^{n} E_i^2\right) - \left(\sum_{i=1}^{n} E_i\right)^2\right)} \qquad (3)$$

$$POD = \frac{H}{H + M} \qquad (4)$$

$$FAR = \frac{F}{H + F} \qquad (5)$$

$$ETS = \frac{H - H_e}{H + M + F - H_e} \qquad (6)$$

$$H_e = \frac{(H + M)(H + F)}{N} \qquad (7)$$

Where O_i is the ith observed value, E_i is the ith estimated value, n is the number of data pairs, H is the total number of hits, M is the total number of misses, F is the total number of false alarms, and N is the total number of nulls.

Based on the above procedure, ARC2 was selected as the overall best performing SRP in the study area and was used as an input to model rainfall-runoff of sub-basins 1 to 7. The supplementary data to this article provides and discusses the results of the performance evaluation of ARC2, CHIRPS V2.0, MSWEP 2.0, PERSIANN-CDR, and TAMSAT-2.

Satellite-based reservoir water level estimation

For this study, no ground data were accessible on the filling approach or the steady operation of Tekeze-5 Dam. Therefore, Landsat satellite images were used together with the elevation-area table of Tekeze-5 Reservoir to derive a time series of the reservoir water level from the filling commencement until the end of 2016. To achieve that, the following steps were taken:

- Landsat images were downloaded for the period from January 2007 to December 2016. The images were filtered based on cloud cover, sun azimuth, and clarity over the area of Tekeze-5 Reservoir. Accordingly, 71 images were selected for use through the period January 2007 to December 2016.
- For the 71 images, the reservoir water surface was classified, and the reservoir area was calculated.
- The elevation-area table of Tekeze-5 Reservoir was used to determine the water levels that correspond with the 71 area values which were derived in the previous step. To this end, the reservoir water level was known at 71 timesteps.
- Linear interpolation between the 71 values of reservoir water level was performed to create a daily water level time series for Tekeze-5 Reservoir.

Figure 4 shows the surface area of Tekeze-5 Reservoir once every year from the start of the filling until 2016. The figure also displays the time series of the reservoir water level that was derived based on the steps mentioned above. Figure 4 illustrates that Tekeze-5 Reservoir was 54% full by the end of 2009, a result that agrees with information reported by Tekeze Inauguration Bulletin (2009) that the filling was 52% complete by the end of 2009. The evidence from Figure 4 shows that the filling of Tekeze-5 Reservoir started in August 2007 and the reservoir reached the Full Supply Level (FSL) in September 2011. In this study, the satellite-estimated water levels of Tekeze-5 were used as a target to model the operation of the dam throughout the filling period (i.e., from August 2007 to September 2011). From October 2011 onwards, it was assumed that Tekeze-5 Dam is operated to target a fixed power level while maintaining the reservoir at a water level higher than the Minimum Operating Level (MOL) and lower than FSL. This assumption was because the primary purpose of the dam is energy production. Several power targets were tested for the period October 2011 to December 2016, and one was selected based on the correspondence between the modelled and the satellite-estimated water levels in that period. Accordingly, a 300-MW power target was selected (see Figure S4 in the online supplemental data). Therefore, the following operating policy was adopted for Tekeze-5 Dam: targeting a constant power rate of 300 MW while maintaining the reservoir water level between the MOL and the FSL.

[Figure 4 near here]

Model calibration and validation

The model was calibrated and validated at Khashm Elgirba Dam utilising intermittent outflow data that were available for this study. Whereas the calibration period extends from 1984 to 1999, the validation period covers 2000 to 2016. The physical parameters of sub-basins 1 to 7 in addition to the travel times and loss percentages of river reaches constitute the parameters used to calibrate the model. For basins 1 to 7, the calibration parameters are 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 (HEC, 2000). The model performance was assessed based on quantitative comparison of the observed and simulated outflows from Khashm Elgirba Dam using six statistical metrics: Nash-Sutcliffe coefficient of Efficiency (NSE; Equation 8), R^2 (Equation 3), MBE (Equation 2), RMSE (Equation 1), POD (Equation 4), and FAR (Equation 5). NSE can take any value from one to $-\infty$ with one indicating perfect prediction ability, zero indicating that the prediction of the model is as good as the mean observed data, and negative values showing that the mean observed data is better than the model prediction.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(E_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O_i})^2} \qquad (8)$$

Where O_i is the i^{th} observed value, E_i is the i^{th} estimated value, n is the number of data pairs, and $\overline{O_i}$ is the mean of observed values.

The flow of Tekeze-Atbara River is characterised by high intra-annual variability with around 92% of the annual flow occurring from July to October (see Figure 2.a). For this reason, the model performance was assessed in two different periods in the year: July to October and November to June. Whereas NSE was used to measure the perdition ability of the model in relation to the mean observed data, R^2 was used to show the fraction of variation in the observed data that could be explained by the model. MBE and RMSE were used to indicate the magnitude and direction of error in the model estimations; POD and FAR were used to assess the skill of the model in detecting flow events. To calculate POD and FAR, a threshold of 0.5 Mm3/day was used to classify each calibration or validation time step into a hit, h, when flow was both observed and estimated, a miss, m, when flow was observed but not estimated, a false alarm, f, when flow was estimated but not observed, or a null, n, when flow was neither observed nor estimated.

Scenarios analysed

This study aims to explore management approaches for water and energy in Tekeze-Atbara Basin under prolonged above- and below-normal hydrologic conditions. For this purpose, 36 scenarios were examined (see Figure S5 in the online supplemental data). The scenarios result from the combinations of three dam coordination levels, two demand scenarios, and six starting water levels of Tekeze-5 Dam. Each of the scenarios was subject to 50 above-normal and 50 below-normal hydrologic sequences that have a

20-year length. The combinations of the scenarios and the hydrologic sequences result in a total of 3600 simulations.

Three dam coordination scenarios were examined in this study: business as usual, coordination within Sudan, and sub-basin coordination. Tables S1 to S3 in the online supplemental data report the operating rules of Khashm Elgirba Dam, UASDC, and Tekeze-5 Dam in the three coordination scenarios. In the business as usual scenario, it was assumed that the operation of the three dams would continue as of their current operation. Currently, the primary purpose of Tekeze-5 Dam and UASDC is hydropower generation whereas Khashm Elgirba Dam is operated for water supply and energy generation. Moreover, measures are taken in the operation of UASDC and Khashm Elgirba Dam to control reservoir sedimentation by flushing and seasonal fluctuation of water levels (World Bank, 1980). In the scenario of coordination within Sudan, the original operating rules of Tekeze-5 and Khashm Elgirba dams were sustained, and the operation of UASDC was amended by allowing it to make extra water releases to meet the downstream water supply deficits. In the sub-basin coordination scenario, Khashm Elgirba Dam and UASDC were operated like in the case of coordination within Sudan while Tekeze-5 Dam was set to make extra water releases to cover the downstream water supply deficits when the other two dams are unable to satisfy the water demands. The rationale behind the selection of the three scenarios is exploring three levels of coordination: (1) unilateral operation of dams which may result in water supply shortages, (2) in-country coordination to reduce water supply shortages, and (3) sub-basin coordination to further lower water supply deficits. We acknowledge that the selected dam operation scenarios are not optimal nor do they reflect the exact path to coordination for Tekeze-Atbara Basin. However, the present analysis would shed light on the potential benefits and costs of coordination within a highly understudied basin and would pave the way for further examinations. It is important to mention that the operating rules of Tekeze-5 Dam, UASDC, and Khashm Elgirba Dam in the three scenarios are based on the current operation of the three dams, thus do not vary across dry and wet years. In this study, two demand scenarios were examined: a current demand scenario with only New Halfa Scheme and Town included as water consumers; a future demand scenario with New Halfa Irrigation Scheme and Town, Upper Atbara Irrigation Scheme, and Gedarif Town incorporated in the system. Although Ethiopia has agricultural development plans involving Tekeze-Atbara Basin, their data were inaccessible for this study. Moreover, little information is published about them as revealed by a review of the literature. In order to develop demand scenarios that include the Ethiopian part of the basin, one needs to know the areas, locations, and cropping patterns of planned irrigation schemes. While we acknowledge not considering the future water demands of Ethiopia as a limitation, we believe that the analysed scenarios would be an addition to the literature and a starting point for future studies. Because Tekeze-5 is a multi-year storage dam, six scenarios for the initial water level of the dam were examined: 1,096 m asl (i.e., MOL), 1,100 m asl, 1,110 m asl, 1,120 m asl, 1,130 m asl, and 1,140 m asl (i.e., FSL).

In this study, 50 above-normal and 50 below-normal hydrologic sequences with a 20-year length were stochastically generated based on the historic flow record. A 20-year extent was chosen to exemplify prolonged above- or below-normal conditions. To create the hydrologic sequences, the Standardized Streamflow Index (SSFI; Modarres (2007)) was calculated for the total annual flow for 1984 to 2016 (Figure 2.b). Positive and Negative SSFI values were used to classify the years into above- and below-normal years, respectively. SSFI was selected due to the normality in the distribution of the historic annual river flow data explained by a low skewness coefficient of 0.58. After the years were classified, 50 above-normal (below-normal) hydrologic sequences with a 20-year length were created by repeating the following process 50 times: the bootstrap method (Efron, 1992) was used to resample from the historic above-normal (below-normal) years 20 times with replacement. This method was used due to its simplicity and the absence of clear serial correlation or dependence in the historic above- or below-normal years (Ebtehaj, Moradkhani, & Gupta, 2010; Noguchi, Gel, & Duguay, 2011). Figure S6 in the supplementary data shows the hydrologic sequences generated in this study.

Results and discussion

Model performance

Figure 5 shows the observed and simulated outflow from Khashm Elgirba Dam in the calibration and validation periods. The evidence from Figure 5.a shows that the model corresponds well with the hydrologic cycle in both the calibration and validation periods. The scatter plots (Figures 5.b and 5.c) show a fair distribution of points around the one-to-one line confirmed by the slope values of the regression lines which are around 0.8 and 0.9 in the calibration and validation periods, respectively. This characteristic suggests no systematic error in the estimates of the model.

[Figure 5 near here]

Table 2 reports the values of the performance metrics for the calibration and validation periods. For July to October, the values of NSE and R^2 indicate good to very good performances in the calibration and validation periods based on the recommendations of M. Stern, Flint, Minear, Flint, & Wright (2016) for performance ranking of models. The values of MBE for July to October reveal overall overestimation by the model. The high RMSE values of July to October, compared to MBE, are due to the tendency of the metric to magnify the error amounts. This attribute of RMSE has been highlighted by Elagib, Alvi, & Mansell (1999) among several others. POD and FAR values for July to October show that the model detected a high fraction of the observed flow days and falsely estimated flow in a small number of days. This good detection capability from July to October is because it is easier for the model to capture flow events in the flood season than in the dry season. The values of MBE and RMSE show less perdition error from November to June than from July to October. For November to June, the model correctly detected more flow events in the validation period than in the calibration as shown by POD, falsely identified fewer flow events in the validation period than in the calibration period as explained by FAR, and had less estimation error in the calibration period than in the validation period as revealed by MBE and RMSE. The values of NSE and R^2 for November to June suggest that low portion of the variation in the observed flow can be explained by the variation in the modelled flow. This is partly due to the high falsely detected flow days as shown by FAR. Overall, the model showed better performance in the validation period than in the calibration period using all metrics except RMSE and MBE.

[Table 2 near here]

Water supply and hydropower generation in Sudan

This section presents the water supply shortages and hydropower generation in Sudan with the two demand scenarios, the three dam operation scenarios, and the above- and below-normal hydrologic conditions. It was found that the initial reservoir water level of Tekeze-5 has minor impacts on water supply shortages and hydropower generation in Sudan. This was due to the operating policy of Tekeze-5 Dam which is based on a constant power target (see Tables S1 to S3 in the online supplemental data). Therefore, the results presented herein are only for an intermediate initial water level of the Dam (i.e., 1120 m asl).

Figures 6.a to 6.d illustrate the probability of exceedance of the annual water supply shortages of Sudan with the current and future water demand scenarios under above and below-normal hydrologic conditions. Figure 6.a reveals that business as usual operation of dams with the current water demands under below-normal hydrologic conditions results in water supply shortages in Sudan that range from 19 to 1,425 Mm3/year. Under the same circumstances, shifting from business as usual to coordination within Sudan reduces the probability of exceedance for the water supply shortages that range between 0 and 175 Mm3/year. Moreover, it was found that shifting from coordination within Sudan to sub-basin coordination of dams has low impacts on Sudan's water supply shortages (i.e., slightly reduces the probability of exceedance for the shortages that lie between 610 and 690 Mm3/year; see Figure 6.a). Along the same lines, Figure 6.b shows that business as usual operation of dams under above-normal hydrologic conditions and with the current water demands produces supply shortages in Sudan that range from 0 to 182 Mm3/year with around 10% probability of exceeding 60 Mm3/year. Shifting to coordination within Sudan reduces the maximum annual supply shortages to 8 Mm3 with only 0.3% probability of having water shortages (Figure 6.b). The evidence from Figure 6.b suggests no difference between supply shortages in the coordination within Sudan and the sub-basin coordination scenarios. On the other hand, a water supply shortage range of 21 to 2,160 Mm3/year was found with the future water demand scenario under below-normal hydrologic conditions and business as usual operation of dams (see Figure 6.c). Shifting to coordination within Sudan or sub-basin coordination lessens this range to 0 to 2,070 Mm3/year with a 70% probability of occurrence of water supply shortages compared to a 100% in the case of business as usual. Furthermore, Figure 6.d illustrates that business as usual operation of dams under above-normal hydrologic conditions and with the future water demand scenario results in low annual supply shortages that range from 0 to 290 Mm3 with around 10% probability of exceeding 77 Mm3/year. Moreover, coordinating the operation of dams within Sudan or across the basin results in nearly similar shortages with around 3.5% probability occurrence. As Figures 6.a and 6.c show, under below-normal hydrologic conditions, shifting from coordination within Sudan to sub-basin coordination produces minor benefits in terms of reduction in water supply shortages. This result can be explained by the limited storage in Tekeze-5 Reservoir which occurred due to water scarcity in below-normal conditions. Further, Figures 6.b and 6.d also suggest no difference between water supply shortages in the coordination within Sudan and the sub-basin coordination scenarios. This is because the water supply shortages were nearly eliminated in the scenario of coordination within Sudan. The latter finding signals that sub-basin coordination would positively impact water supply in the basin in above-normal conditions should Ethiopia implements its irrigation plans.

Regarding hydropower generation in Sudan, the following was noted (see Figures 6.e to 6.h): an insignificant difference in annual energy generation across the three dam operation scenarios; a profound diffrence in daily energy generation across the three dam operation scenarios; a slightly higher annual energy generation with the current demand scenario than with the future demands scenario; a considerably higher annual energy generation under above-normal hydrologic conditions than under below-normal hydrologic conditions. It was found that the annual energy generation of Sudan under below-normal hydrologic conditions (Figures 6.e and 6.g) ranges from 100,000 to 1,220,000 MWh with a coefficient of variation of around 0.24. However, this range increases under above-normal hydrologic conditions (Figures 6.f and 6.h) to between 865,000 to 1,500,000 MWh with a coefficient of variation of approximately 0.07.

[Figure 6 near here]

To sum up, shifting from business as usual to coordinated operation of dams within Sudan decreases the water supply shortages considerably in above- and below-normal hydrologic conditions and with both water demand scenarios. The three dam operation scenarios have insignificant impacts on the annual energy generation of Sudan and considerable impacts on the daily distribution of energy generation. The annual energy generation increases significantly in above-normal hydrologic conditions compared to below-normal hydrologic conditions with less variability in energy generation in the former than the latter.

Hydropower generation in Ethiopia

Figure 7 demonstrates the total annual energy generation of Ethiopia from Tekeze-5 Dam under the two demand scenarios, the above and below-normal hydrologic conditions, and the two operation settings of Tekeze-5 Dam. The results presented in Figure 7 are based on a 1120 m asl initial water level for Tekeze-5 as little difference was found in the results of the six initial reservoir water levels. The evidence from Figure 7 shows that the demand and dam operation scenarios have insignificant impacts on annual and daily energy generation from Tekeze-5 Dam. It was found that energy generation from the dam ranges between 110,000 and 2,370,000 MWh/year in below-normal hydrologic conditions. In above-normal hydrologic conditions, the results show a minimum annual energy generation of around 1,170,000 MWh and a maximum of around 2,370,000 MWh. This increase in the minimum is due to water abundance in above-normal conditions compared to below-normal conditions. It is worth mentioning that 2,370,000 MWh is the maximum possible amount of energy that could be generated from the dam annually. Figure 7 demonstrates less variability in annual energy generation in above-normal conditions than in below-normal conditions. This variability decrease can be confirmed with a coefficient of variation of 0.06 and 0.4 in the above- and below-normal hydrologic conditions, respectively.

[Figure 7 near here]

Conclusions

Coordinated management of water and energy systems is more urgent now than ever especially in arid regions with seasonal, dammed, transboundary rivers. While understanding the uniqueness of each river is key to the sustainable management of water and energy resources (H. Zhang & Li, 2018), the unavailability/inaccessibility of ground hydrologic and/or meteorological data has for long hindered the optimal management of the two resources. This study explores in-country and transboundary management strategies for water supply and hydropower generation under prolonged above- and below-normal hydrologic conditions for Tekeze-Atbara, a transboundary river between Ethiopia, Eritrea, and Sudan, that suffers a scarcity of ground data (unavailability and inaccessibility). To achieve that, a daily river basin model is developed for Tekeze-Atbara for the period 1984 to 2016 to include hydropower dams, large-scale irrigation schemes, significant domestic water users, and major inflows and water losses. To overcome the data scarcity issue of the study region, satellite-based rainfall and evapotranspiration data are used as inputs to the model. Moreover, satellite imagery is used to estimate reservoir water levels where no data are available. In this study, 36 scenarios are examined across 50 above-normal and 50 below-normal hydrologic conditions that are generated using the bootstrap method. The scenarios result from combinations of dam operating settings, water demand scenarios, and initial system conditions.

Based on certain scenario assumptions, the results revealed that coordinating the operation of the Sudanese dams in the study area would have positive impacts on irrigation and domestic water supply under both above- and below-normal conditions. Even though this in-country coordination would have insignificant impacts on annual hydro-energy generation in Sudan, it implies changes in daily energy generation which require adjusting the energy mix on the country level. On the other hand, the assumed sub-basin coordination of dam operation resulted in slight improvements in water supply and hydropower generation in the basin compared to coordination within Sudan only. Nevertheless, sub-basin coordination is anticipated to have significant positive impacts in above-normal hydrologic conditions with future irrigation in Ethiopia added to the system. It is important to note that any positive outcomes of coordination would support trust-building between riparian countries which often happens in small steps over a long period (Huisman, Jong, & Wieriks, 2000; Uitto & Duda, 2002). Mutual trust is instrumental to international cooperation (Raadgever, Mostert, Kranz, Interwies, & Timmerman, 2008) especially in a hydro-politically complex basin like the Nile.

This study has some limitations that can be addressed by future research. Landsat satellite images were used to estimate the historic water levels of Tekeze-5 Reservoir. Landsat has a 30 m spatial resolution, a 21-day temporal resolution, and a varying cloud cover and sun azimuth. Future studies could use other sources of satellite imagery that have better characteristics and apply cloud and shadow removal techniques (Helmer & Ruefenacht, 2005; Lin, Tsai, Lai, & Chen, 2013; Tseng, Tseng, & Chien, 2008) to enable estimating reservoir water levels more accurately and at finer time intervals. The daily model developed for this study uses monthly evaporation coefficients to estimate reservoir evaporation and therefore assumes a constant daily evaporation rate for each month. This assumption is used in reality to operate the three dams in Tekeze-Atbara Basin and most dams in the Nile Basin. Notwithstanding this limitation, the daily model developed herein certainly adds value over a monthly model as it simulates several daily processes that inherently impact water supply and hydropower generation (e.g. tailwater level, dam release capacity, dam operating rules) (World Bank, 1980). In this study, the above- and below-normal hydrologic sequences were generated based on the historic river flow record. This approach, however, overlooks the non-stationarity in the climate system which has been revealed by several studies on East Africa as a temperature rise (Nadir Ahmed Elagib, 2010; Nadir Ahmed Elagib & Mansell, 2000; IPCC, 2008) or a change in precipitation (Shongwe et al., 2011; Souverijns et al., 2016) and river flow (Cole et al., 2014; Gebremicael, Mohamed, Zaag, & Hagos, 2017; Gizaw, Biftu, Gan, Moges, & Koivusalo, 2017). Whereas the increase in temperature would increase evaporation and/or transpiration from reservoirs and irrigatted lands, the increase (decrease) in precipitation and river flow would increase (decrease) hydropower generation (Cole et al., 2014) and enhance (negatively affect) water supply. A 20-year length was chosen for the hydrologic sequences to exemplify prolonged conditions. Further research could test hydrologic sequences with different lengths and generate sequences based on climatic projections. Furthermore, the future demand scenario considered herein did not include the agricultural development plans of Ethiopia because little data were available to us about them. Digna et al. (2018) reported a potential irrigation area in Ethiopia of around 45,000 ha that is yet to be exploited. Irrigation water abstractions in Ethiopia would certainly impact water supply and hydropower generation in the basin. While the findings of this study show that raising the level of coordination would produce benefits to water supply, an optimisation model is necessary to quantify the full value of coordination. Such an optimisation model should consider future dams and water users in Ethiopia in addition to the economic, social, and environmental impacts of the water infrastructures in the basin. Lastly, the extent of this study was limited to the Tekeze-Atbara Basin to explore possible management approaches for water and energy in the basin. However, it is essential to conduct a similar analysis for the whole Nile Basin to shed light on possible cooperative management approaches on a larger scale.

Last of all, meeting the current and future demands for water and energy necessitates coordinating the management of river basins. Sustainable and efficient management of water and energy systems should consider all the relevant social, economic, and environmental aspects on the local, national, and regional levels. Research on innovative management approaches for water and energy resources is highly needed, especially in data-scarce regions.

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Table 1. Main characteristics of dams located in the study area.

Characteristic	**KED**	**UASDC**	**Tekeze-5**
Full supply level (m asl)	474	521	1,140
Minimum Operating Level (m asl)	463	509	1,096
Total storage volume (MCM)	628 (in 1990)	3,687 (in 2015)	9,293 (in 2016)
Surface Area at FSL (km^2)	100	302	156.9
Surface area at MOL (km^2)	8	128	88.5
Installed power capacity (MW)	16	320	300
Purpose	Seasonal storage for hydropower generation and water supply	Seasonal storage for hydropower generation and water supply	Multi-year storage for hydropower generation

Note: KED = Khashm Elgirba Dam; UASDC = Upper Atbara and Setit Dam Complex; FSL = Full Supply Level; MOL = Minimum Operating Level.

Data sources: The Ministry of Water Resources, Irrigation, and Electricity of Sudan and the Eastern Nile Technical Regional Office.

Table 2. Model performance metrics in the calibration and validation periods.

Months	**Performance metric**	**Calibration**	**Validation**
July to October	NSE	0.71	0.84
	R^2	0.72	0.74
	MBE (Mm3/day)	1.96	21.28
	RMSE (Mm3/day)	52.39	61.35
	POD	0.92	0.95
	FAR	0.14	0.02
November to June	NSE	0.18	0.37
	R^2	0.22	0.35
	MBE (Mm3/day)	-0.38	6.30
	RMSE (Mm3/day)	6.66	12.12
	POD	0.52	0.83
	FAR	0.66	0.31

Note: NSE = Nash-Sutcliffe coefficient of efficiency; R^2 = coefficient of determination; MBE = Mean Bias Error; RMSE = Root Mean Square Error; POD = Probability Of Detection; FAR = False Alarm Ratio.

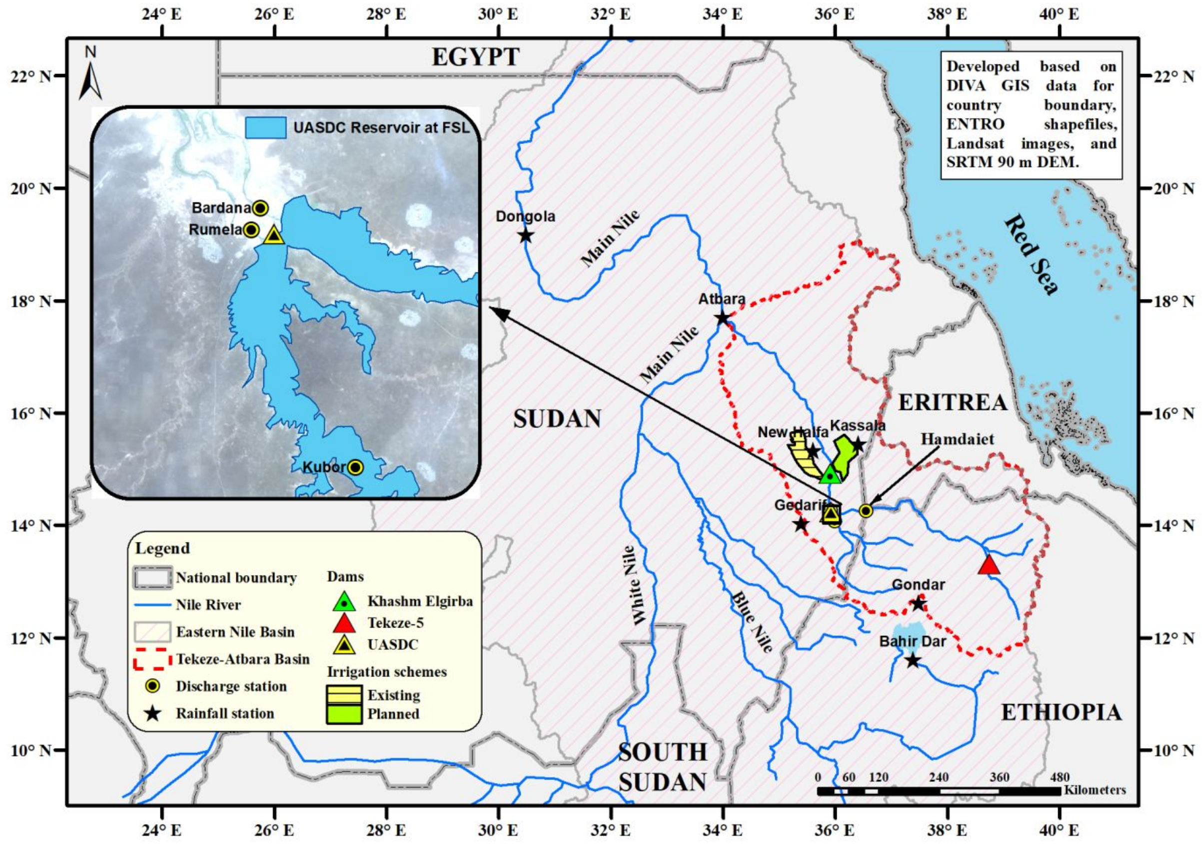

Figure 1. Topography, dams, irrigation schemes, and rainfall and discharge stations in the study area.

Note: UASDC = Upper Atbara and Setit Dam Complex; GIS=Geographic Information System; ENTRO = Eastern Nile Technical Regional Office; SRTM=Shuttle Radar Topography Mission; DEM=Digital Elevation Model; FSL = Full Supply Level.

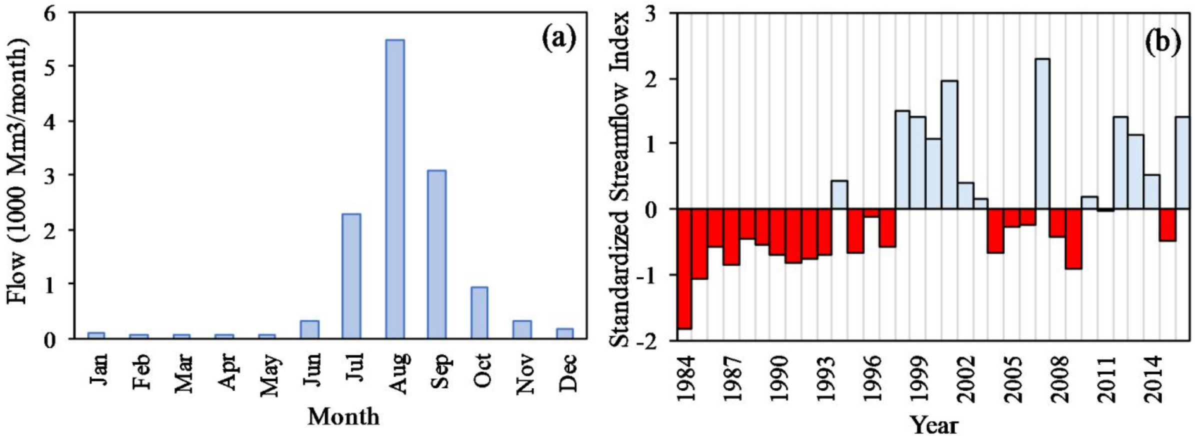

Figure 2. Tekeze-Atbara flow volume over the period 1984 to 2016: (a) average monthly (b) annual Standardized Streamflow Index (SSFI; Modarres (2007)).

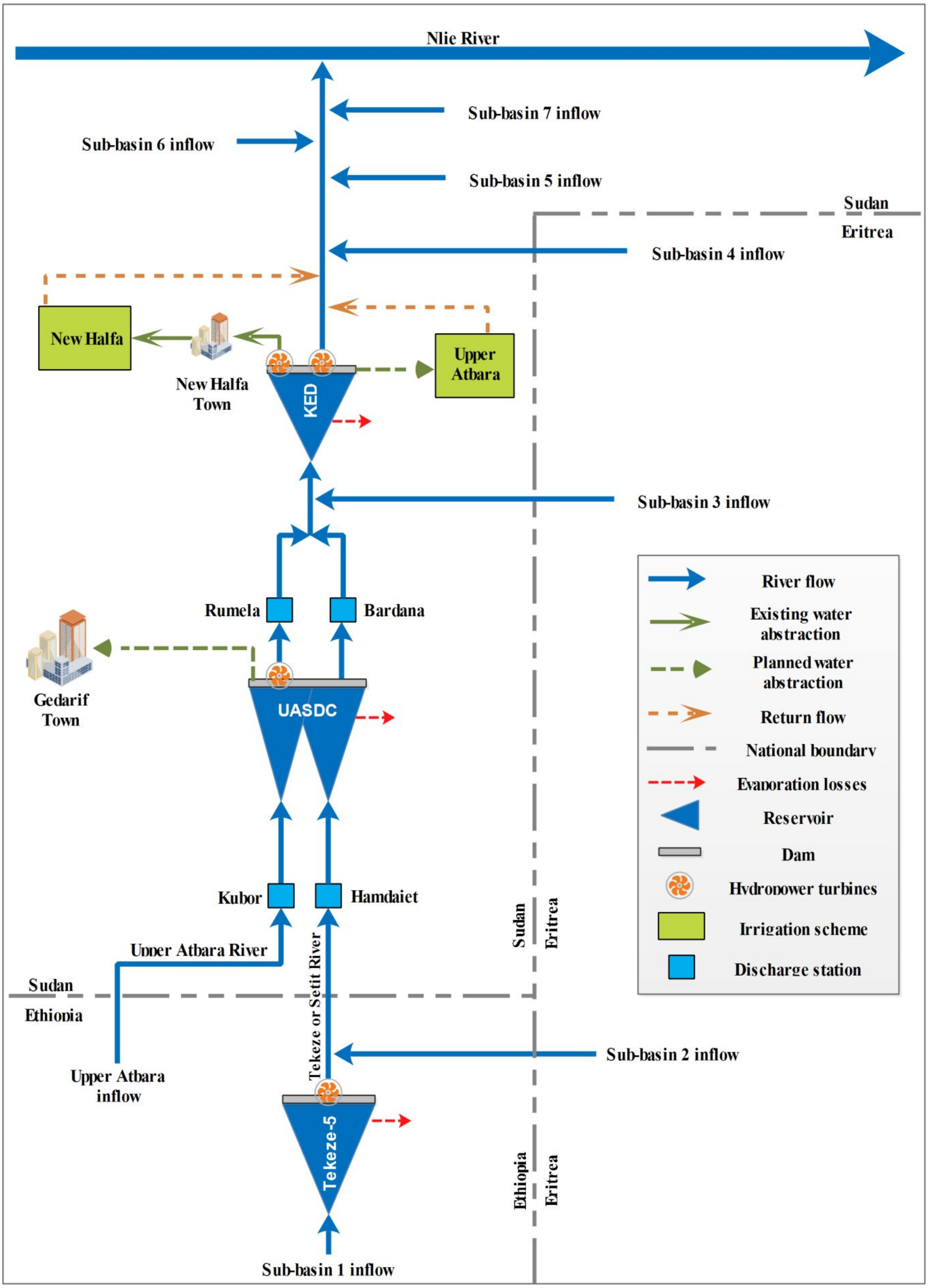

Figure 3. Schematic of the model developed for the study area.

Note: UASDC = Upper Atbara and Setit Dam Complex; KED = Khashm Elgirba Dam

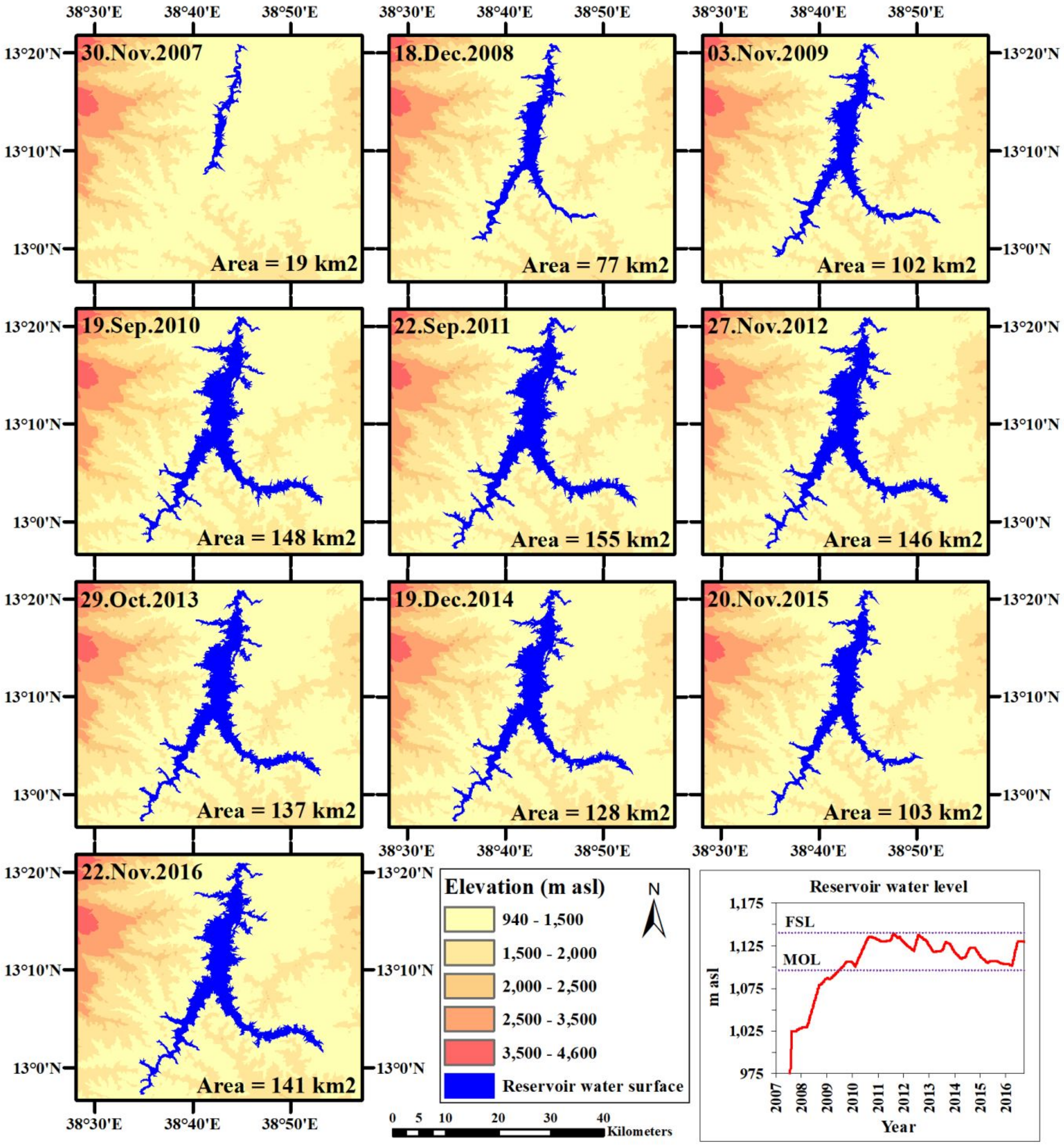

Figure 4. Reservoir surface area of Tekeze-5. The sub-figure in the bottom right corner shows a time series of the reservoir water level from the commencement of the filling until the end of 2016. The displayed data are based on Landsat satellite images.

Note: MOL = Minimum Operating Level; FSL = Full Supply Level

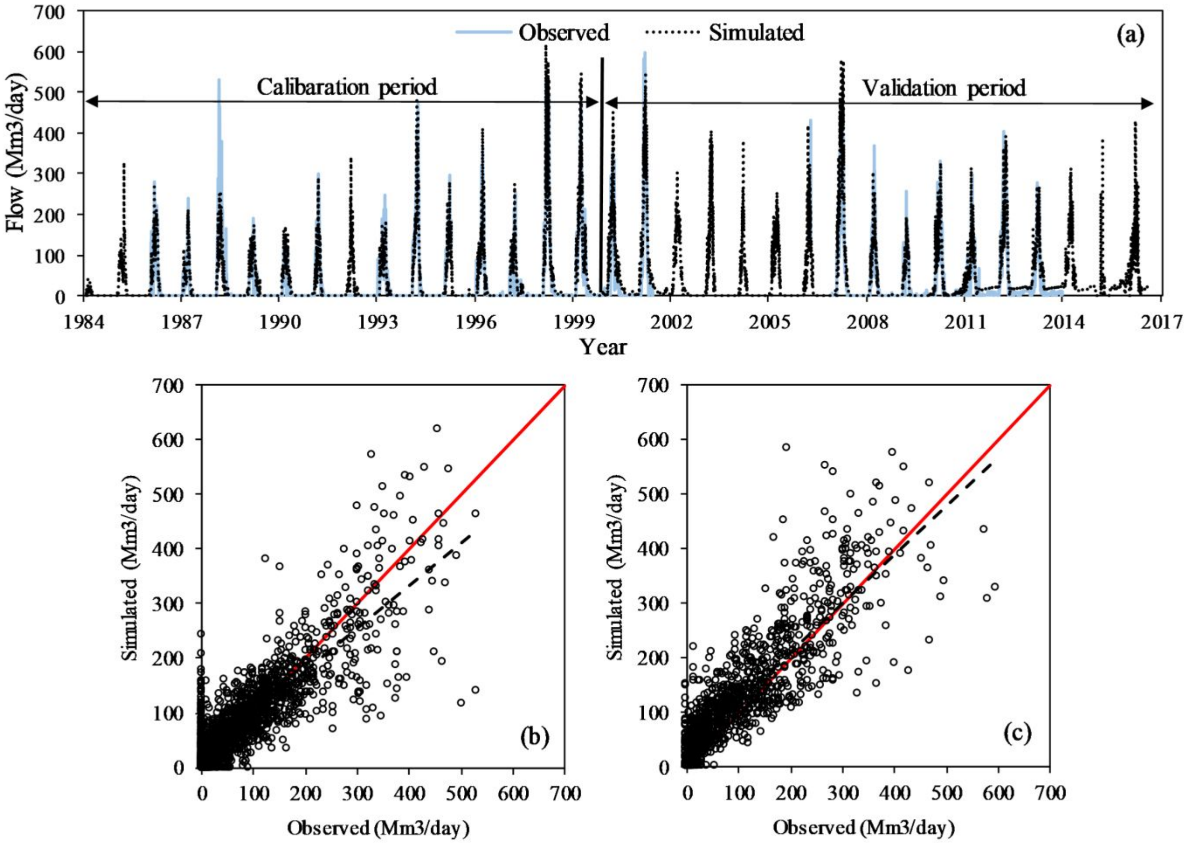

Figure 5. Daily observed and simulated outflow from Khashm Elgirba Dam: (a) time series of the calibration and validation periods (b) scatterplot of the calibration period (c) scatterplot of the validation period. In figures b and c, the continuous and dashed lines represent the 1:1 and regression lines, respectively.

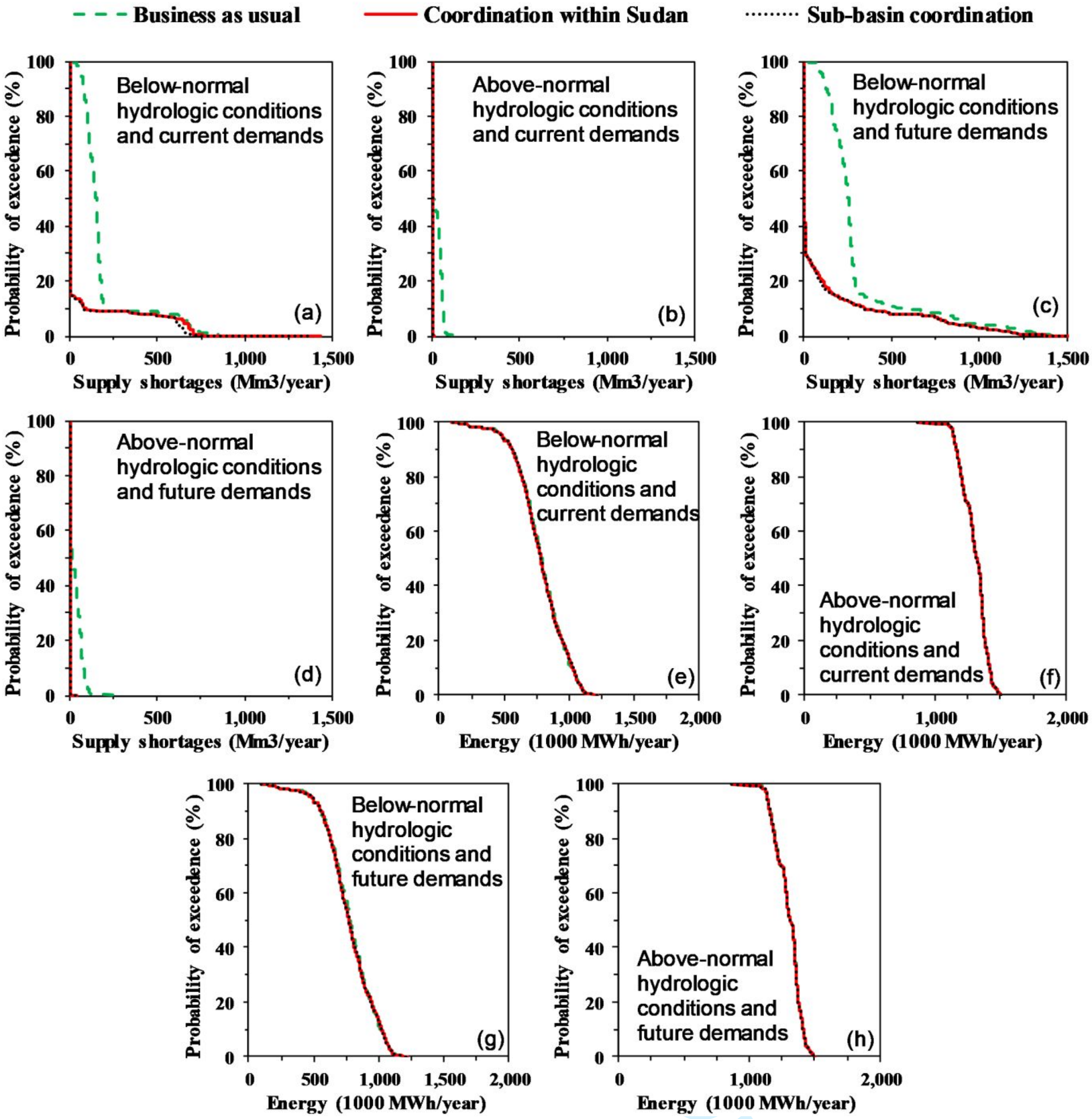

Figure 6. Sudan's annual water supply shortages and energy generation with different dam operation scenarios and Tekeze-5 Dam starting at 1120 m asl: (a), (b), (c), and (d) probability of exceedance of water supply shortages and (e), (f), (g), and (h) probability of exceedance of energy generation.

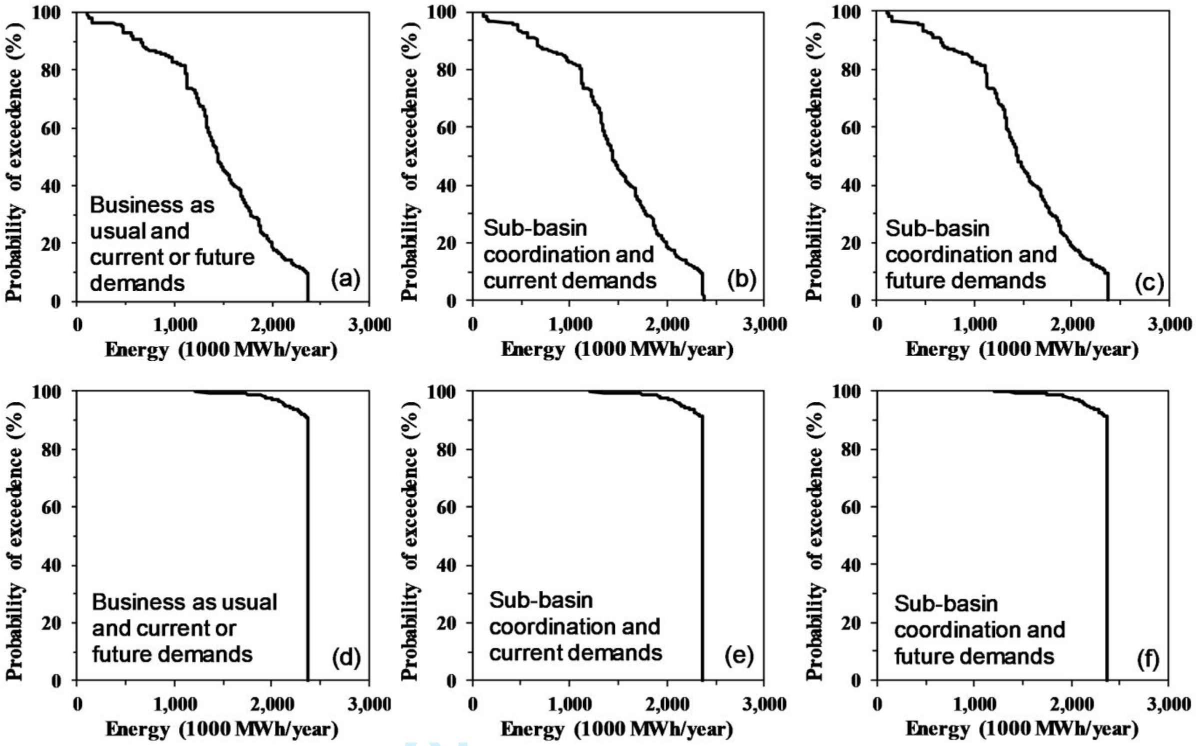

Figure 7. Probability of exceedance of Tekeze-5 Dam annual energy generation with Tekeze-5 Dam starting at 1120 m asl: (a), (b), and (c) below-normal hydrologic conditions and (d), (e), and (f) above-normal hydrologic conditions.

List of figure captions and notes

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Exploring management approaches for water and energy in the data-scarce Tekeze-Atbara Basin under hydrologic uncertainty

Supplementary data

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Exploring management approaches for water and energy in the data-scarce Tekeze-Atbara Basin under hydrologic uncertainty

Performance of satellite-based rainfall products

In the present study, the performance of five daily long-term SRPs (i.e., ARC2, CHIRPS v2.0, MSWEP 2.0, PERSIANN-CDR, and TAMSAT-2) was evaluated using daily rainfall data (1984 to 2007) from ground stations that are in or near the study area (Figure 1 in the main body of the paper shows the locations of the stations). Even though several studies assessed the performance of SRPs in Africa and the Nile Basin (Basheer et al., 2018; Basheer & Elagib, 2018b, 2018a; Diem, Hartter, Ryan, & Palace, 2014; T Dinku et al., 2007; Gebremicael, Mohamed, Zaag, & Hagos, 2017; Habib, Elsaadani, & Haile, 2012; Serrat-Capdevila, Merino, Valdes, & Durcik, 2016), none compared the performance of long-term SRPs in Tekeze-Atbara Basin. Figure S1 presents the results of the six metrics (i.e., RMSE, MBE, R^2, POD, FAR, and ETS) that were used to assess the performance of the SRPs. PERSIANN-CDR showed the best performance at all stations in terms of RMSE which varies from 0.04 mm at Dongola to 8.96 mm at Bahir Dar. The second-best performance was achieved by MSWEP 2.0 at Dongola, Kassla, New Halfa, and Gedarif, CHERPS v2.0 at Atbara and Bahir Dar, and ARC2 at Gondar. Moreover, the worst performance based on RMSE is a feature of TAMSAT-2 at Bahir Dar and Atbara and CHIRPS v2.0 at Gondar, Gedarif, New Halfa, Kassla, and Dongola. Generally, RMSE values suggest worse performance towards the upstream. This characteristic is because the five SRPs use InfraRed (IR) imagery as a primary input. Rainfall estimation based on IR imagery is known to poorly capture local heavy precipitation events that result from warm clouds (Maidment et al., 2017; Novella & Thiaw, 2013). Such events occur in the mountainous upstream part Tekeze-Atbara Basin (Tufa Dinku, Ceccato, & Connor, 2011). MBE showed mixed performances among the products with ARC2 outperforming at Dongola, Kassla, and Gondar, CHIRPS v2.0 at Atbara, New Halfa, and Gedarif, and TAMSAT-2 at Bahir Dar. Regarding R^2, ARC2 showed the best performance at all stations except Bahir Dar where PERSIANN-CDR performed the best. TAMSAT-2 showed the lowest R^2 values at all stations. It is worth noting that all Pearson correlation coefficient (R) values of ARC2 are statistically significant at $p < 0.0001$.

With regards to the categorical metrics, PERSIANN-CDR showed the best detection capability of rainy days explained by the highest POD values at all stations except Gondar at which ARC2 showed the best performance. The latter product exhibited the second-best performance at the other six stations, and TAMSAT-2 revealed the worst performance at all stations. Regarding FAR and ETS, ARC2 presented the best performance at all stations explained by the lowest FAR and the highest ETS values. In contrast, TAMSAT-2 showed the worst performance at all stations based on FAR and ETS. It can be noticed that the high POD values of PERSIANN-CDR were coupled with relatively high FAR values. This behaviour could be due to the likelihood of having more false alarms with the increase in detection skill.

Overall, ARC2 showed either the best or the second-best performance at most of the stations and with most of the performance metrics. Moreover, ARC2 showed better performance in the flat terrain of Sudan than in the Ethiopian highlands using all performance metrics except POD.

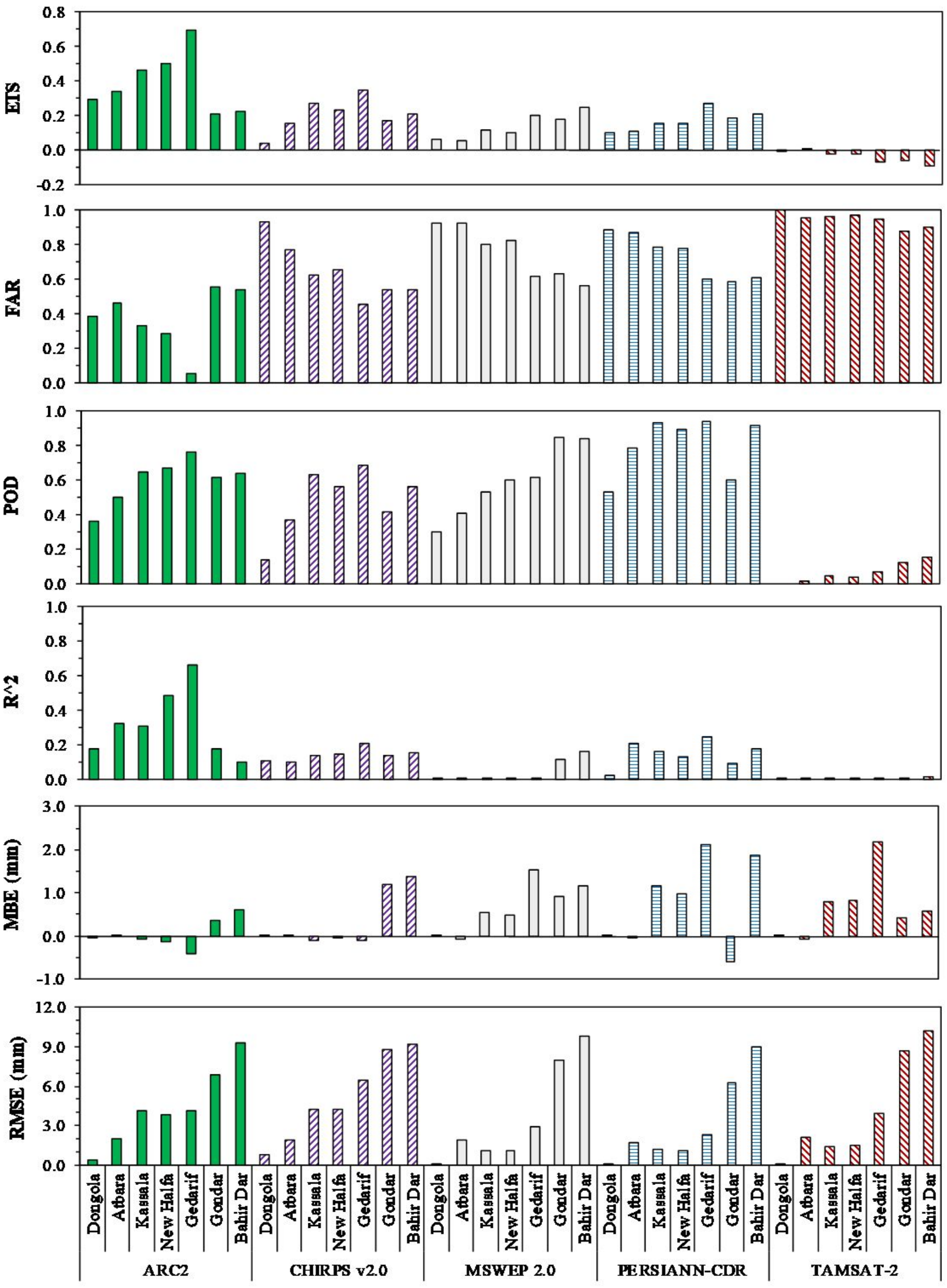

Figure S1. Performance metrics of the evaluated Satellite-based Rainfall Products at seven rainfall stations.

Note: RMSE = Root Mean Square Error; MBE = Mean Bias Error; R^2 = Coefficient of determination; POD = Probability Of Detection; FAR = False Alarm Ration; ETS = Equitable Threat Score; ARC2 = Africa Rainfall Climatology Version 2.0; CHIRPS v2.0 = Climate Hazards group Infrared Precipitation with Stations version 2.0; MSWEP 2.0 = Multi-Source Weighted-Ensemble Precipitation version 2.0; PERSIANN-CDR = Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks–Climate Data Record; TAMSAT-2 = Tropical Applications of Meteorology Using Satellite Data and Ground-Based Observations version 2.0

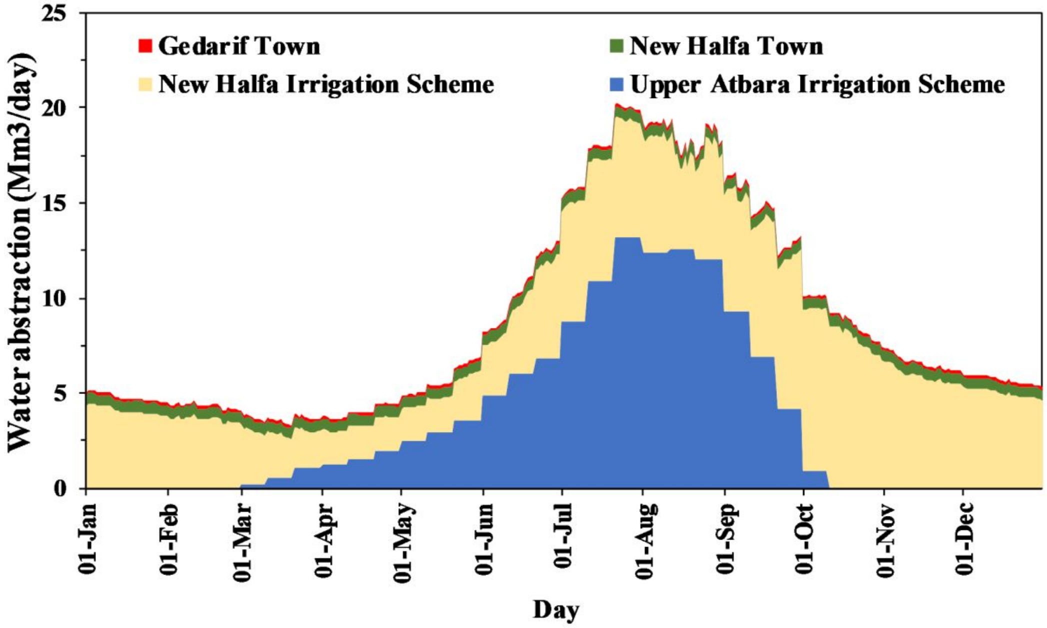

Figure S2 Water abstraction in the study area

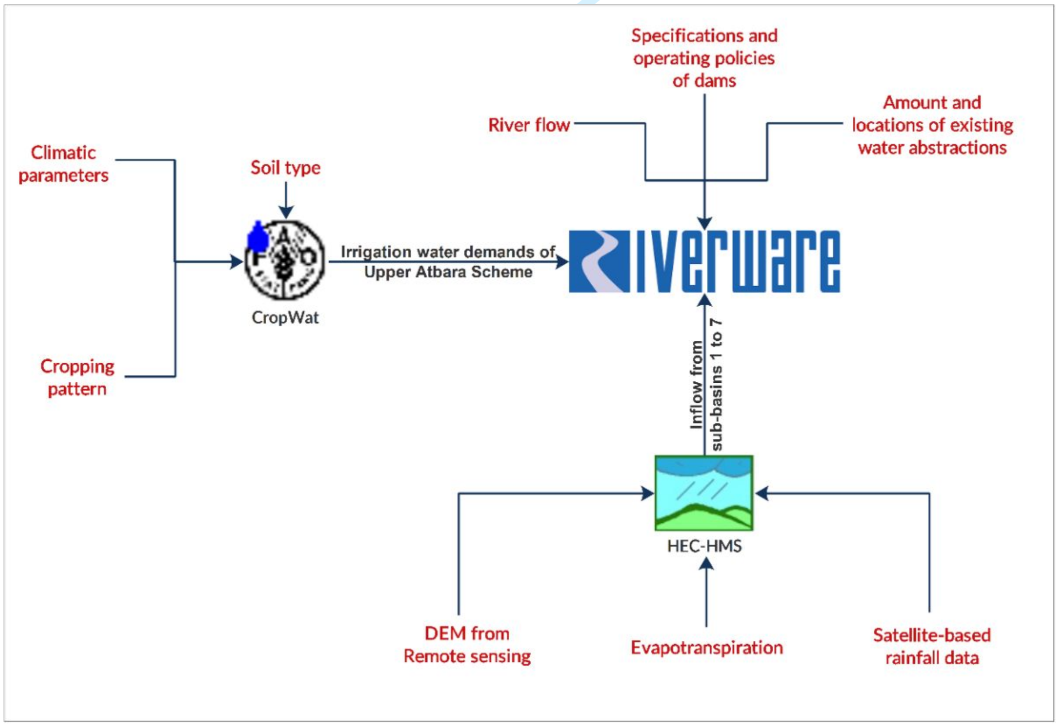

Figure S3 Modeling tools utilised in this study

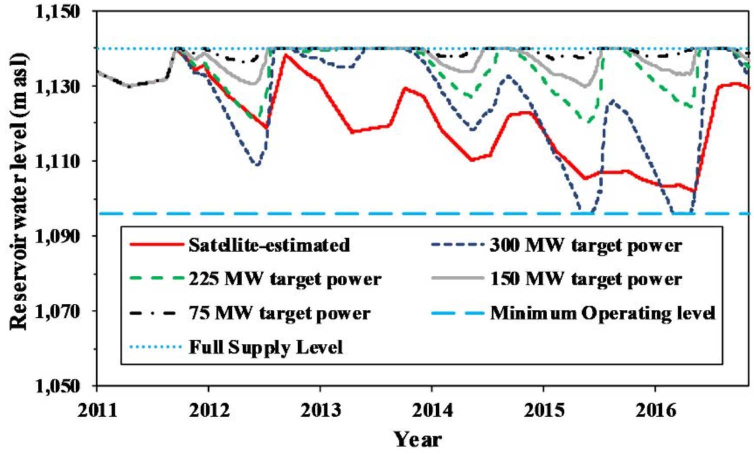

Figure S4 Satellite-estimated and modelled Tekeze-5 reservoir water levels with different power targets

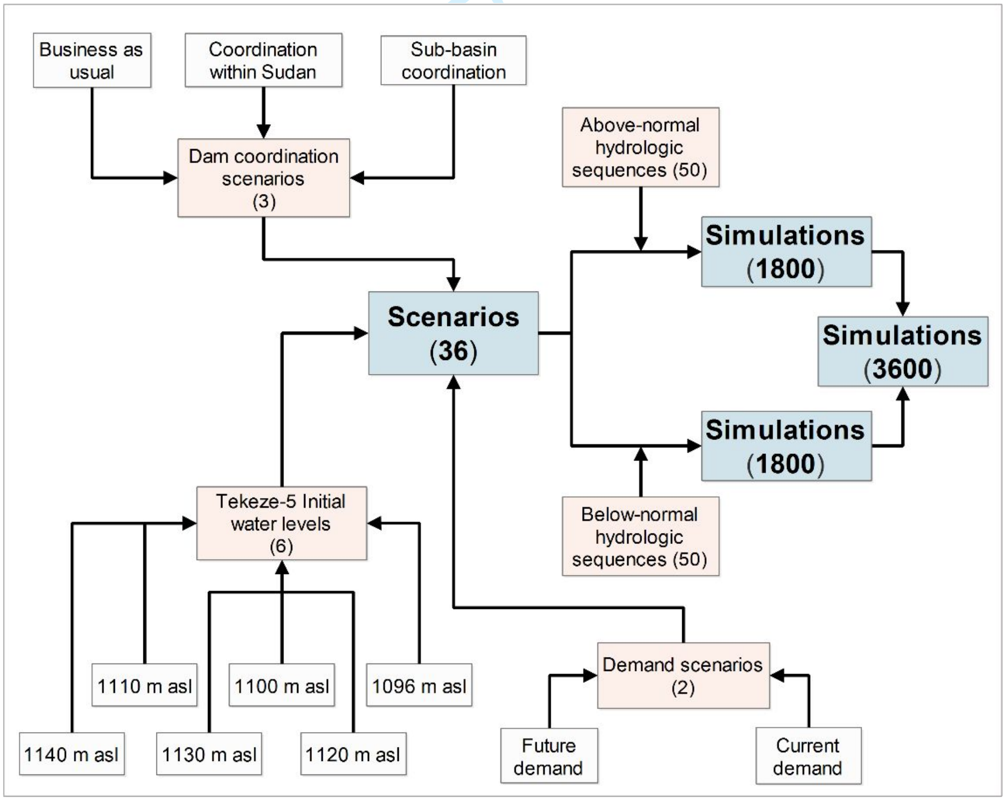

Figure S5 Scenarios developed for the study area

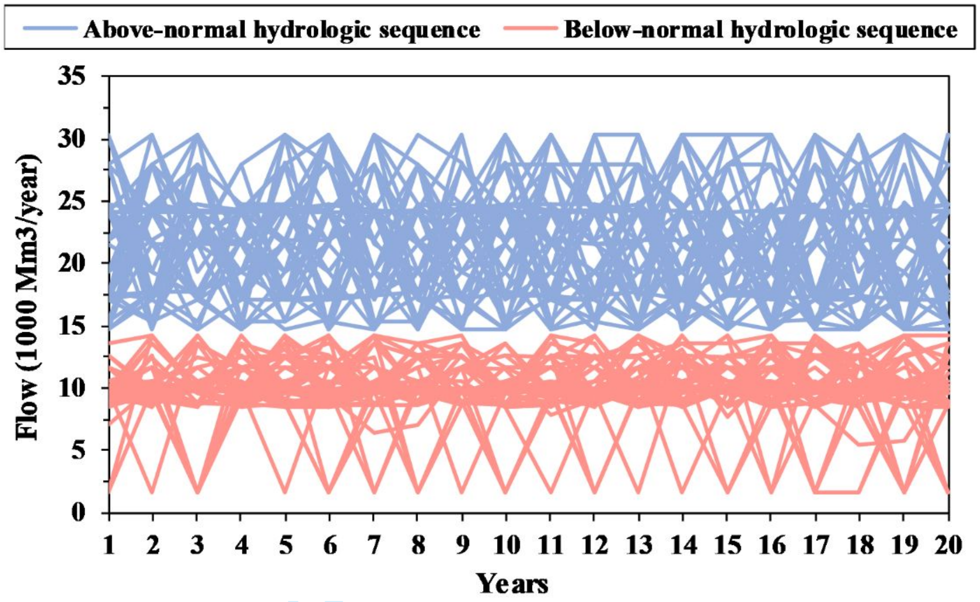

Figure S6 Hydrologic sequences generated for Tekeze-Atbara River

Table S1 Operating rules of dams located in the study area in the business as usual (i.e., current) scenario.

Priority	Khashm Elgirba Dam [a]	Upper Atbara and Setit Dam Complex [a]	Tekeze-5 Dam
1	The reservoir should be flushed in two to three days in mid-august	The reservoir should be flushed in two to three days in mid-august	The reservoir water level should remain higher than the minimum operating level
2	The reservoir water level should remain higher than the minimum operating level	The reservoir water level should remain higher than the minimum operating level	The reservoir water level should remain lower than the full supply level
3	The reservoir water level should remain lower than the full supply level	The reservoir water level should remain lower than the full supply level	Meet a power target [b]
4	Target certain water levels from June to mid-October	Meet the demand of Gedarif Town when the supply pipeline is constructed	
5	Meet the water demands of New Halfa Scheme and Town and Upper Atbara Scheme when constructed	Meet a power target	
6		Target certain water levels	

[a] Source: Ministry of Water Resources, Irrigation, and Electricity of Sudan
[b] Source: derived from Landsat 7 and 8 satellite images as explained in the paper

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Table S2 Operating rules of dams located in the study area in the coordination within Sudan scenario.

Priority	Khashm Elgirba Dam	Upper Atbara and Setit Dam Complex	Tekeze-5 Dam
1	The reservoir should be flushed in two to three days in mid-august	The reservoir should be flushed in two to three days in mid-august	The reservoir water level should remain higher than the minimum operating level
2	The reservoir water level should remain higher than the minimum operating level	The reservoir water level should remain higher than the minimum operating level	The reservoir water level should remain lower than the full supply level
3	The reservoir water level should remain lower than the full supply level	The reservoir water level should remain lower than the full supply level	Meet a power target [a]
4	Target certain water levels from June to mid-October	Meet the deficit in the downstream water supply and the demand of Gedarif Town when the supply pipeline is constructed	
5	Meet the water demands of New Halfa Scheme and Town and Upper Atbara Scheme when constructed	Meet a power target	
6		Target certain water levels	

[a] Source: derived from Landsat 7 and 8 satellite images as explained in the paper

Table S3 Operating rules of dams located in the study area in the sub-basin coordination scenario.

Priority	Khashm Elgirba Dam	Upper Atbara and Setit Dam Complex	Tekeze-5 Dam
1	The reservoir should be flushed in two to three days in mid-august	The reservoir should be flushed in two to three days in mid-august	The reservoir water level should remain higher than the minimum operating level
2	The reservoir water level should remain higher than the minimum operating level	The reservoir water level should remain higher than the minimum operating level	The reservoir water level should remain lower than the full supply level
3	The reservoir water level should remain lower than the full supply level	The reservoir water level should remain lower than the full supply level	Meet the deficit in the downstream water supply
4	Target certain water levels from June to mid-October	Meet the deficit in the downstream water supply and the demand of Gedarif Town when the supply pipeline is constructed	Meet a power target [a]
5	Meet the water demands of New Halfa Scheme and Town and Upper Atbara Scheme when constructed	Meet a power target	
6		Target certain water levels	

[a] Source: derived from Landsat 7 and 8 satellite images as explained in the paper

Table S4 Geometry of the reservoirs located in the study area.

Tekeze-5 in 2016			Khashm Elgirba in 1990			UASDC in 2015		
Elevation (masl)	**Storage (Mm3)**	**Surface area (km^2)**	**Elevation (masl)**	**Storage (Mm3)**	**Surface area (km^2)**	**Elevation (masl)**	**Storage (Mm3)**	**Surface area (km^2)**
1,000	69	5	464	27	11	495	157	24
1,010	134	8	465	43	19	500	365	52
1,020	245	14	466	55	25	505	730	89
1,030	423	22	467	67	32	508	1,048	116
1,040	678	30	468	95	41	510	1,311	139
1,050	1,023	40	469	131	52	515	2,165	206
1,060	1,474	51	470	176	63	520	3,358	278
1,070	2,036	62	471	238	72	525	5,007	398
1,080	2,707	73	472	315	81	530	7,280	511
1,090	3,480	82	473	403	90	Source: MoWRIE		
1,100	4,354	93	474	628	100			
1,130	7,810	140	Source: MoWRIE					
1,140	9,293	157						
1,150	10,958	176						
Source: ENTRO								

Note: ENTRO = Eastern Nile Technical Regional Office; MoWRIE = Ministry of Water Resources, Irrigation, and Electricity of Sudan

Table S5 Net evaporation coefficients of the reservoirs located in the study area.

Month	Tekeze-5 in 2016 (cm)	Khashm Elgirba in 1990 (cm)	UASDC in 1985 (cm)
January	13.4	17.9	16.7
February	14.4	18.4	16.4
March	9.9	20.9	21.3
April	8.0	25.6	23.8
May	7.9	26.3	23.7
June	0.2	27.8	20.3
July	-15.4	24.9	17.7
August	-18.3	22.7	16.3
September	-3.8	21.1	17.1
October	11.3	20.5	18.1
November	14.7	18.3	17.6
December	14.7	16.8	16.6
	Source: Wheeler et al. (2016)	Source: MoWRIE	Source: MoWRIE

Note: ENTRO = Eastern Nile Technical Regional Office; MoWRIE = Ministry of Water Resources, Irrigation, and Electricity of Sudan

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