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Temporal analysis of water-energy nexus indicators for hydropower generation and water pumping in the Lower Blue Nile Basin

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Graphical abstract

Highlights

- A daily Blue Nile model is utilized to explore nine indicators for water-energy nexus
- Time series of hydropower generation and water pumping indicators are analyzed
- Both the water availability and dam operation influence the nexus indicators
- A shift in regime was found in 2013 for most of the indicators due to the heightening of the Roseires Dam
- Turbines of higher capacity in the Roseires Dam will allow better utilization of its hydropower potential

Abstract

This study performs a temporal analysis for nine water-energy nexus indicators for hydropower generation and irrigation water pumping in the Lower Blue Nile Basin. The nine indicators are water-energy productivity, firm daily energy generation, percentage of days at power generation capacity, variation in daily energy generation, annual energy generation, highest daily pumping energy, lowest daily pumping energy, variability in daily pumping energy, and annual pumping energy. The Blue Nile, a major tributary of the Nile, within Sudan is taken as an example to demonstrate application and interpretation of the temporal evolution of the nine nexus indicators. A daily calibrated and validated water allocation model for the Blue Nile is used to construct time series of the nine indicators from 1984 to 2016. Time series analysis is performed to detect significant trends and regime shifts in the nine indicators. The analysis reveals that the heightening of the Roseires Dam in 2013, one of the dams in the study region, resulted in significant shifts in annual energy generation, percentage of days at power generation capacity, variation in daily energy generation, water-energy productivity, and annual pumping energy. The significant shift (an increase in this case) that occurred in the percentage of days at power generation capacity indicates that turbines with higher capacity could be installed in the Roseires Dam to utilize its hydropower potential more efficiently. It is also shown that annual hydro-energy generation in the study region is dependent on water availability in the dry season (November to June). Temporal analysis of the nexus indicators demonstrates robustness to detection of significant human interventions in the hydrological system. Understanding the temporal dynamics of the water-energy nexus is key to efficient utilization of water and energy resources, especially in a basin like the Nile where considerable alterations to the headwaters are underway.

Keywords: Hydropower generation; irrigation water pumping; regime shift detection;
RiverWare; Blue Nile Basin; Sudan

1. Introduction

Water and energy are quintessential components for sustainable development and growth. The demands for them are escalating at high rates due to population growth, urbanization, and economic development. By the year 2050, global energy demands are expected to increase by 50% and water withdrawals are expected to grow by 50% and 18% in the developing and developed countries, respectively (Flammini et al., 2014). Moreover, water and energy systems contribute considerably to climate change, and they are also highly susceptible to nonstationarity in climate (Howells et al., 2013). The growing demands for water and energy against scarcity, supply crisis, and management failure of these resources have increased the concern about their intimate interlinks (Al-Saidi and Elagib, 2017). Water and energy resources are intrinsic to economic planning and developing resources-related policies (Gleick, 1994), especially in a world that is facing inequality in access to resources (Simpson and Jewitt, 2019). Integrated analysis of water and energy systems is central to electricity planning and comprehension of water constraints (Ackerman and Fisher, 2013). Highlighting the gap between the current and optimal utilization of water and energy resources can be achieved by illustrating the flows of the two resources and their cross-connections with other sectors (Liu et al., 2019).

Understanding the water-energy nexus, i.e. connections between water and energy, is essential. For instance, the impacts of changes in precipitation and temperature regimes on water and energy security are likely where the provision of reliable water and energy supplies are going hand-in-hand, e.g. where hydropower plants utilize water to power the electricity grid and the grid, in turn, powers the pumps that supply water (Romero-Lankao et al., 2018).

Based on an evaluation of the nexus of interventions on urban water and energy use, Engström et al. (2017) reveal that interventions yielding the greatest potential for reductions in energy use and greenhouse gas emissions are not necessarily the most water-conserving ones and vice versa. A nexus perspective is, therefore, a starting point for identifying synergies, trade-offs, and solutions that consider water use across different sectors and scales (Rasul et al., 2019). Understanding the relationship between water and energy resources can be improved by quantitative analyses of their nexus (Dai et al., 2018). In assessing this nexus, the ultimate goal is to inform “strategies, policy measures, planning, and institutional set-up or interventions” (Flammini et al., 2014).

Nexus narratives have been used to both support and oppose large-scale hydropower development and expansion of irrigation in transboundary river basins (Lebel and Lebel, 2018). Large river basins with their various human pressures, such as agricultural activities, hydropower development, and dam-impacted catchments, result in ecological risks and thus require accounting for the nexus approach in the planning for sustainable river management and development (Keskinen et al., 2016, 2015; Kibaroglu and Gürsoy, 2015; Nilsson et al., 2005). At least, 153 large river systems can be identified in Latin America, Africa, Asia, and Australasia where the impacts of economic activities (e.g., irrigation, hydropower generation) are too strong (Nilsson et al., 2005). Based on an analysis of the relationship between growth in population, dam development, and the nexus resources, Chen et al. (2016) and Shi et al. (2019) argue in favor of an abundant need for multi-purpose dam construction in the foreseeable future to deal with the socio-economic problems in developing and least developed countries. Nevertheless, they also state explicitly that human beings should at the same time “think more about how to better construct, operate, and maintain dams and reduce their negative impacts” (Chen et al., 2016). For instance, calculating the loss of water resources from multi-purpose dams through evaporation from the surface of reservoirs is

complicated by the mode of dam operation, which is in turn determined by economic criteria, upstream and downstream demands for water, and ecological requirements (Gleick, 1994). Adopting a nexus approach allows examining the different benefits and losses in the face of dam operation modes and elucidating the challenges to reaching win-win situations across a nexus in large river basins (Jalilov et al., 2016).

To carry out a rapid nexus appraisal and assess the performance in terms of resource use efficiency, indicators specific to each type of intervention can be quantified using specific tools (Flammini et al., 2014). Development and application of indicators for the nexus enable improved analysis, understanding, and addressing of the inextricable interlinkages between water supply and energy production in order to enhance cross-sectoral coherence and manage the nexus challenges effectively (Basheer and Elagib, 2018; Larsen and Drews, 2019; Rasul, 2014). In other words, designing and using nexus indices to summarize the effects of multiple complex resource processes can be useful in measuring progress toward policy objectives (Lawford et al., 2013). Nawab et al. (2019) developed a nexus strength indicator to present a unified accounting of multiple ecological resources usage of energy and water in the urban industrial system. Using indicators of water-energy nexus, Elagib et al. (2019) showed how hydrological phenomena, such as drought and flood, can determine the state of hydropower generation from dams in an urban environment. Analysis of nexus indicators can help minimize the water and energy consumption and maximize economic productivity (El Gafy et al., 2017). A review carried out by Dai et al. (2018) has found a few studies that include historical analyses of the variation of the water-energy nexus. Towards optimized outcomes and minimized risk related to the nexus, these analyses can provide useful information for understanding the nexus, building reasonable scenarios, and educating and guiding actions and policies by decision makers (Dai et al., 2018). Studying the historical water-energy nexus

indicators of storage dams through observed data and/or modeling provides a solid ground for setting solutions for hydro-energy generation and satisfying water demands (Si et al., 2019).

Emerging data generation and processing technologies can help manage the water and energy systems more efficiently and sustainably (Helmstedt et al., 2018; Lawford et al., 2013; Lawford, 2019). In order to inform more effective national policies and regulations, the importance of modeling in generating the nexus data is emphasized (Bazilian et al., 2011). Modeling could help decision-makers and stakeholders make informed decisions for satisfactory water-energy nexus management (Zhang and Vesselinov, 2016). For instance, modeling the nexus has attracted attention in recent years to enable identification of strategies of water and energy resources capture while minimizing negative impacts at national and/or sub-national levels (Pittock et al., 2016; Basheer et al., 2018; Basheer and Elagib, 2018; Stamou and Rutschmann, 2018; Si et al., 2019). In this regard, a quantitative stochastic analysis of competitive and cooperative relationships between energy and water systems has shown that renewable energy production can increase while both power generation costs and carbon dioxide emission can decrease under integrated management of hydropower and water supplies (Hu et al., 2018).

Motivated by the above backdrop, the present research aims at producing actionable information by (1) developing and applying some indicators of water-energy nexus using water allocation modeling and (2) performing temporal analysis of these indicators over several decades. This study demonstrates that temporal analysis of water-energy nexus indicators could help identify significant changes in the water and energy systems and venues for efficient resource use. The research is carried out for the Blue Nile in Sudan, which is characterized by multi-purpose storage dams for hydropower generation and irrigation water supply. The selection of the Blue Nile in Sudan with its two dams, the Roseires and the Sennar (Fig. 1), is justifiable by the high reliance of the rapidly growing populations of the

downstream countries, Sudan and Egypt, on the Nile water and the expected challenges for consistent provisioning of water resources that climate change is projected to present due to more variable flows (Conway, 2017). This river plays a paramount role in the economy of Sudan by providing water to irrigate vast croplands over several schemes, producing hydropower and reducing flood damage (Goor et al., 2010; Omer et al., 2015). The Blue Nile Basin is considered by Al-Saidi and Hefny (2018) as a “resource basin” for which the nexus approach can highlight key neglected issues on interlinked resources. What makes this study also important is a result found by Endo et al. (2017), who reviewed 37 projects dealing with nexus research. They found that only 7% of the projects in Africa had a focus on water–energy interconnections.

2. Study area

Fig. 1 shows the location and main characteristics of the study area. Herein, the Blue Nile Basin within Sudan is taken as a case study to demonstrate the application of water-energy nexus indicators and measures on hydropower generation and water pumping. The Blue Nile is one of the main tributaries of the Nile River and has a drainage area of around 310,000 km². It is geographically shared between Ethiopia and Sudan with around 64% and 36% of the basin area in each of the two countries, respectively. It originates in Ethiopia from around 4000 m asl, flows through the Ethiopian Plateau while other tributaries join the mainstem, and enters Sudan at around 500 m asl (Sutcliffe and Parks, 1999). The Blue Nile continues its journey in Sudan and meets the White Nile – a main branch of the Nile River – at the Capital of Sudan, i.e., Khartoum, at around 375 m asl. Two major tributaries join the Blue Nile in Sudan, namely the Dinder and the Rahad rivers. The two streams start in Ethiopia and contribute together around 4.6% of the total inflow of the Blue Nile on average. Downstream Khartoum, the flows of the Blue Nile and the White Nile combine to form the

Main Nile, which merges with the Atbara River and cruises northwards through the desert landscapes of Northern Sudan and Egypt before ending in the Mediterranean Sea.

The Blue Nile contributes around 60% of the flow of the Nile measured at Aswan near the Sudanese-Egyptian border (NBI, 2012; Sutcliffe and Parks, 1999). Furthermore, the flow of the Blue Nile has high inter- and intra-annual variabilities. As Fig. 2 shows, the total annual flow of the river, which is measured at the outlet of the basin, ranges approximately between 30,000 and 71,000 Mm³ with a mean of around 53,000 Mm³. The two extremes occurred in 1984 and 1988, which were directly related to very low and very high rainfalls, respectively (Conway and Hulme, 1993; Davies and Walsh, 1997; Sutcliffe et al., 1989).

As Fig. 1 presents, the study area contains several dams and irrigation schemes that are currently in operation: the Roseires and the Sennar dams; the Gezira and Managil, the Gunied, the Suki, the North West Sennar, and the Rahad 1 irrigation schemes. Table 1 shows the main characteristics of the Roseires and the Sennar dams. Infrastructure development in the study area started as early as 1925 with the construction of the Sennar Dam and the commencement of the Gezira Scheme (MoIHES, 1977). The primary purpose of the Sennar Dam is to supply the Gezira Scheme with irrigation water by gravity. The Gunied Sugar Scheme was constructed in 1962. A pumping station, located on the Blue Nile reach upstream Khartoum, extracts the irrigation water of the Gunied Scheme from the Blue Nile. Infrastructure development in the study area progressed in 1966 with the completion of the first stage of the Roseires Dam and the Managil extension of the Gezira Scheme (MoIHES, 1977). The heightening of the Roseires Dam (i.e., the second stage) was completed in 2013 to add 10 m of elevation (DIU, 2016). The purpose of the Roseires Dam is to supply the Gezira and the Managil schemes with irrigation water and to generate hydropower (MoIHES, 1977). The Roseires Dam supplies the two schemes through water releases to the Sennar Dam, which diverts the irrigation water. Three irrigation schemes were established in the study area

during the 1970s: the Suki was completed in 1971; the North West Sennar was completed in 1972; the Rahad 1 was completed in 1977 (MoIHES, 1977). The three schemes abstract their irrigation water from the Sennar Reservoir via pumping stations, with the Rahad 1 Scheme receiving part of its irrigation water from the Rahad River (MoIHES, 1977).

3. Methodology

This section starts with formulation and discussion of the water-energy nexus indicators. Then, a description is provided on the river basin model of the Lower Blue Nile, which has been used to develop time series for some of the indicators. Third, the methods used for temporal analysis of the time series of the water-energy nexus indicators are shown. Lastly, the data sources of the Lower Blue Nile model are presented.

3. 1. Water-energy nexus indicators

Fig. 3 demonstrates the water-energy nexus components considered herein which are: hydro-energy generation from storage dams, energy required for pumping water from rivers and storage reservoirs, reservoir evaporation, and water availability. The figure also shows some indicators for the interlinkages of the four nexus components. The following parts of this section describe the interlinkages and indicators.

3. 1. 1. Hydro-energy generation and reservoir evaporation

Hydro-energy generation is a process that converts the velocity or potential energies of water into mechanical energy and then electricity using turbines and electromagnetic generators. Whether the velocity or potential energy of water is converted into electricity or not depends on the type of hydropower plant. Storage dams increase the potential energy of water by increasing the difference in water level between upstream and downstream the dam and then converts the potential energy into electricity by releasing water through hydropower

turbines. On the other hand, run-of-river plants primarily convert the velocity energy of water into electricity. In this study, we only considered hydro-energy generation from storage dams. Several studies classically viewed hydro-energy generation from storage dams as a non- or a semi non-consumptive water user (Perry, 2011; Sadoff and Grey, 2002). However, raising the potential energy of water through reservoir storage increases the water surface and, consequently, increases water losses to the atmosphere through evaporation. Based on this fact, several recent studies analyzed the water footprint of hydropower generation by accounting for reservoir evaporation losses (Bakken et al., 2017; Basheer and Elagib, 2018; Larsen and Drews, 2019). In this study, the Water-Energy Productivity (WEP), a water-energy nexus indicator for hydropower generation developed by Basheer and Elagib (2018), was explored and applied. They defined WEP as the amount of hydro-energy generated per each unit of water lost to evaporation. The WEP is calculated on annual basis by dividing the total annual energy generation by the total annual evaporation losses of a hydro-energy generation system, as shown by Equation 1 (Basheer and Elagib, 2018).

$$WEP_A = \frac{\sum_{i=1}^Y HE_i}{\sum_{i=1}^Y EV_i} \quad (1)$$

where WEP_A is the annual Water-Energy Productivity (GWh/Mm³), HE_i is hydro-energy generation in the i^{th} day of the year (GWh), EV_i is reservoir evaporation in the i^{th} day of the year (Mm³), and Y is the number of days in the year.

3. 1. 2. Hydro-energy generation and water availability

Water availability and hydro-energy generation from storage dams are inherently related since the abundance or scarcity of water determines how much of it could be stored or passed through the hydropower turbines (Hamududu and Killingtveit, 2012; Van Vliet et al., 2016). Subject to the purpose(s) and the operating policy of the storage dam, high river flow enables sustaining high reservoir water levels, increasing the potential energy of water,

passing high amounts of water through the hydropower turbines, and elevating hydro-energy generation. In the case of multipurpose storage dams that generate hydro-energy and supply water, the location of water abstraction, i.e., upstream or downstream the dam, is another factor that affects hydro-energy generation. Water abstraction downstream of a dam increases hydro-energy production because it enables energy generation before water abstraction. On the other hand, water abstraction upstream of a dam reduces hydro-energy generation. In this study, several indicators and statistical measures were explored and analyzed to understand the interlinkages of hydro-energy generation and river flow. Those indicators are annual hydro-energy generation (Equation 2), firm daily energy generation (Equation 3), variability in daily energy generation (Equation 4), and percentage of days at energy capacity (Equation 5).

$$HE_A = \sum_{i=1}^Y HE_i \quad (2)$$

$$FDE = \min \{HE_1, HE_2, HE_3, \dots, HE_Y\} \quad (3)$$

$$CV_{HE} = \frac{\sqrt{\frac{\sum_{i=1}^Y (HE_i - \overline{HE})^2}{Y-1}}}{\overline{HE}} \quad (4)$$

$$PDEC = \frac{\sum_{i=1}^Y \begin{cases} 1 & \text{if } HE_i = HE_c \\ 0 & \text{if } \text{otherwise} \end{cases}}{Y} \times 100 \quad (5)$$

where HE_A is the annual hydro-energy generation (GWh), HE_i is hydro-energy generation in the i^{th} day of the year (GWh), Y is the number of days in the year, FDE is the firm daily energy in a certain year (GWh/day), CV_{HE} is the coefficient of variation of daily energy generation in a certain year, $\overline{HE}$ is the mean daily energy generation in a certain year (GWh/day), $PDEC$ is the percentage of days at energy capacity (%), and HE_c is the daily energy generation capacity (GWh/day).

Annual hydro-energy generation (HE_A) is the summation of hydro-energy generation in individual days in the year. The FDE is the amount of hydro-energy generation that can be guaranteed on a daily basis throughout the year. Furthermore, the coefficient of variation of daily energy generation (CV_{HE}) measures the dispersion in daily energy generation. Lastly, the percentage of days at energy capacity (PDEC) ranges from 0 to 100%.

3. 1. 3. Pumping energy and water availability

Pumping stations are widely used to extract and transfer water from rivers and reservoirs to higher elevations for treatment, distribution, or use. The amount of input energy required for water pumping depends primarily on three factors (Moreno et al., 2009, 2007; Tarjuelo et al., 2015). These factors are: (1) the elevation difference between the water abstraction and delivery points, (2) the amount of pumped water, and (3) the efficiencies of the pump and the motor. For pumping stations situated on river streams, the elevation of the water abstraction point increases with the river flow and vice versa depending on the river rating curve at the pumping location. Pumping from a storage reservoir to a higher elevation implies that the elevation of the water abstraction point equals the reservoir water level, which varies depending on the operating policy of the reservoir. The higher the elevation of the water abstraction point, the lower the pumping energy. The second factor that influences the pumping energy, i.e., the amount of pumped water, relies on the availability of sufficient water and the right to water abstraction. Generally, the amount of pumped water decreases when the river flow or reservoir storage water is less. Lastly, the overall efficiency of the pumping station also determines the amount of pumping energy. This efficiency depends on the elevation difference between the water abstraction and delivery points as well as the amount of pumped water. In the present study, four indicators were used to understand the interlinkages between water availability, i.e. river flow and reservoir storage, and water pumping. These indicators are annual pumping energy (Equation 6), lowest daily pumping

energy (Equation 7), highest daily pumping energy (Equation 8), and variability in pumping energy (Equation 9).

$$PE_A = \sum_{i=1}^Y PE_i \quad (6)$$

$$LDE = \min \{PE_1, PE_2, PE_3, \dots, PE_Y\} \quad (7)$$

$$HDE = \max \{PE_1, PE_2, PE_3, \dots, PE_Y\} \quad (8)$$

$$CV_{PE} = \frac{\sqrt{\frac{\sum_{i=1}^Y (PE_i - \overline{PE})^2}{Y-1}}}{\overline{PE}} \quad (9)$$

Where PE_A is the annual pumping energy (GWh), PE_i is the pumping energy in the i^{th} day of the year (GWh), Y is the number of days in the year, LDE is the lowest daily pumping energy in a certain year (GWh/day), HDE is the highest daily pumping energy in a certain year (GWh/day), CV_{PE} is the coefficient of variation of daily pumping energy in a certain year, and $\overline{PE}$ is the mean daily pumping energy in a certain year (GWh/day).

3. 2. Lower Blue Nile Basin modeling

3. 2. 1. Model structure

This study utilized and modified a previously developed water balance model for the Blue Nile Basin by Basheer et al. (2018) to quantify hydropower generation, irrigation water supply, and evaporation losses in the basin. The original model has a daily time step and covers the Blue Nile from the Ethiopian-Sudanese border to Sennar Dam from 1984 to 2012. For this study, the model was first extended to cover the Blue Nile Basin from the Ethiopian-Sudanese border to Khartoum and the period from 1984 to 2016, and then was recalibrated and validated. The modified model was used to construct daily time series of hydropower generation, pumping energy, and reservoir evaporation and then to calculate the nexus indicators discussed in Section 3.1.

302 The following part of this section describes the modified model that was employed in
303 this study. Fig. 4 shows a schematic of the model. The model includes eight inflow points,
304 two hydropower dams, five irrigation schemes, four pumping stations, evaporation losses
305 from the storage reservoirs, and channel losses. Daily river flow data for El-Diem Gage, El-
306 Hawata Gage, El-Gewisi Gage, and Sub-basins 1 to 5 were used together with the system
307 operating rules to drive the model. It is worth mentioning that the inflow from sub-basins 1 to
308 5 was derived by Basheer et al. (2018) using a hydrological model driven by the African
309 Rainfall Climatology Version 2 satellite rainfall data (Novella and Thiaw, 2013). As Fig.4
310 shows, the Lower Blue Nile model starts from El-Diem Gage, which is located near the
311 Ethiopian-Sudanese border. The outflow from El-Diem Gage and the inflow from sub-basins
312 1 and 2 enter the Roseires Reservoir. After that, the outflow from the Roseires Reservoir
313 joins the inflow from sub-basins 3 and 4 before entering the Sennar Reservoir. Three
314 pumping stations abstract irrigation water directly from the Sennar reservoir to supply the
315 North West Sennar, the Suki, and the Rahad 1 schemes. Whereas the majority of the
316 irrigation water of the Rahad 1 Scheme comes from the Rahad River, the pumping station on
317 the Blue Nile is operated only when the inflow of the Rahad River drops below the irrigation
318 demand of the Rahad 1 Scheme. The inflow from sub-basin 5 enters the Sennar Reservoir.
319 Headworks located on the left side of the Sennar Dam divert the irrigation water of the Gezira
320 and the Managil by gravity. The outflow from the Sennar Dam joins the inflow from the
321 Dinder and the Rahad rivers, which originates in the Ethiopian Highlands. Flow data of the
322 Dinder and the Rahad rivers at El-Gewisi and El-Hawata gages were used to simulate the
323 flow of the two rivers, respectively. The combined flows of the Blue Nile, the Dinder River,
324 and the Rahad River continue downstream before the Gunied Scheme abstracts its irrigation
325 water using a pumping station. The remaining flow passes through El-Kamleen Gage, where
326 the water level is derived using a rating curve, then combines with part of the return flow of

the Gezira and the Managil before passing through the Khartoum Gage. The model also simulates hydropower generation, pumping energy, evaporation losses from reservoirs, and transmission losses from river reaches. Average monthly evaporation coefficients were used to simulate the evaporation losses from the Roseires and the Sennar reservoirs. A constant loss percentage and a constant lag time were populated for each river reach. Similarly, a constant percentage from irrigation water abstraction was used to estimate the return flows of the Rahad 1 and the Gezira and the Managil Schemes. For the four pumping stations, an average pumping efficiency was used in calculating the pumping energy for each station. The intake water levels of the pumping stations of the Rahad 1, the Suki, and the North West Sennar vary with the Sennar Reservoir water level. The water level at El-Kamleen Gage was connected to the intake water level of the Gunied pumping station.

3. 2. 2. Modeling framework

To simulate water allocation and the associated hydrologic and hydraulic processes, a model was developed using RiverWare. Moreover, RiverWare was used to calculate the indicators and measures of the water-energy nexus. RiverWare is a generalized river basin modeling software that can simulate the water balance for several kinds of objects (e.g. storage dams, river reaches, and diversion structures) using a variety of approaches and temporal resolutions (Zagona et al., 2001). RiverWare is empowered with a policy language that enables adding prioritized system operating rules using logical statements. This particular attribute provides flexibility in modeling complex river systems. RiverWare has been recently used to model several complex river systems worldwide including the Nile (Basheer et al., 2019, 2018; Basheer and Elagib, 2018; Wheeler et al., 2018, 2016) and Colorado (United States of America and United Mexican States, 2012).

3. 2. 3. Model calibration, validation, and performance

The daily Lower Blue Nile Basin model was calibrated in the period 1984 to 2000 and validated from 2001 to 2016. The calibration of the model was performed by adjusting the lag times of river reaches, channel loss percentages, and the return flow parameters of the Rahad 1 and the Gezira and the Managil schemes. To assess the performance of the model, a comparison of the simulated and the available observed daily outflow from the Roseires Dam, outflow from the Sennar Dam, and flow at the Khartoum Gage was carried out. The recommendations of Stern et al. (2016), who provided performance rankings for daily models, were used to rate the performance of the Lower Blue Nile Basin model. Three model performance indicators were used, namely the coefficient of determination (R^2), the Nash-Sutcliffe coefficient of efficiency (NSE), and the Mean Error Percentage (MEP),.

Fig. 5 shows the outflow from the Roseires and the Sennar dams and the flow at the Khartoum Gage in the calibration and validation periods. Moreover, Table 2 shows the performance metrics (based on daily modeled and observed data) and the rankings of the model at the Roseires Dam, the Sennar Dam, and the Khartoum Gage. It is evident from Fig. 5 that the model could accurately capture the annual flow cycle at the three calibration and validation locations. Based on the recommendations of Stern et al. (2016) for daily models ranking, the model showed mostly excellent performances at the three locations in both the calibration and the validation periods (see Table 2). The exception is the performance at the Khartoum Gage in the validation period using MEP, which showed a very good performance. The high R^2 values indicate that the model could explain a large portion of the observed values. All Pearson correlation coefficient (R) values are significant at $p < 0.00001$.

Time series analysis

The Standardized Streamflow Index (SSFI; Modarres, 2007) was used in this study to analyze the temporal evolution of the annual river flow in terms of above (wet case) and below (drought case) the long-term average flow amount. SSFI was found suitable for this analysis due to the nearly normal distribution of the annual river flow explained by a low skewness coefficient of around -0.097 . To analyze the time series of the water-energy nexus indicators and measures, two statistical tests were performed. First, the shift in regime was detected by determining the change point(s) or year(s) in the time series with a statistically significant change in mean at the probability level, p , according to the Student's t -test (Rodionov, 2004). The technique used herein uses the sequential algorithm, which requires less input data compared to other methods. Moreover, it has the ability to detect the regime shift earlier and subsequently monitor changes in its magnitude over time. For the current analysis, a cut-off length of 10 years and a significant level, p , of 0.05, were chosen. The results of this analysis were then explained in the context of recognized hydrological phenomena in the basin, such as drought and flood, or human-induced changes in the river hydrology such as flow regulations. Next, the non-parametric Kendall-tau test with two-tailed (Kanji, 2006) was used to determine the significant trend direction over the regime (change) periods, i.e. before and/or after the change point. This analysis reveals whether there was a decreasing or increasing trend in the given flow time series.

3. 3. Data used

The historic river flow records of the stream gages shown in Figs. 1 and 4 were acquired from the Ministry of Water Resources, Irrigation, and Electricity of Sudan (MoWRIES). The MoWRIES also provided the following data for the Sennar and the Roseires dams: the geometry of the reservoirs (i.e., the elevation-volume and elevation-area

tables), the outlet capacities, the average monthly evaporation rates, and the turbines characteristics. An average pumping efficiency for the pumping stations in addition to the elevations of the discharge basins were obtained from MoIHES (1977). The water demands of the five irrigation schemes located in the study area were obtained from MoWRIES. The current operating policies for the Sennar and the Roseires dams in addition to the inflow from sub-basins 1 to 5 were obtained from Basheer et al. (2018). Table 3 outlines the operating rules of the Roseires and the Sennar dams before and after the heightening of the Roseires Dam. Key data are provided in the supplementary material.

4. Results

4. 1. Inter-annual variability of river flow

Fig. 6 shows a time series of the SSFI of the Blue Nile flow at El-Diem Gage on an annual time scale. The figure clearly shows a decrease of successive below-average SSFIs over the study period following the persistent droughts of the 1980s, early 1990s, and early 2000s. These negative flow anomalies were primarily attributed to synchronized meteorological droughts reported in Sudan (Elagib and Elhag, 2011; Zhang et al., 2012) through analysis of 1964-2009 flow and rainfall data refuted consistent increasing or increasing trends in rainfall and flow extremes of recent years (Taye and Willems, 2012). It is noteworthy, however, that large-scale anomalies have been found to contribute to the flow anomalies of the Blue Nile (Abtew et al., 2009; Taye and Willems, 2012; Zaroug et al., 2014). The positive anomalies shown in Fig. 6 increase in frequency despite the dispersed negative anomalies of the early 20th century. Intensive land use and land cover change, as well as increasing rainfall extremes in the Upper Blue Nile in Ethiopia, could be suggested to have caused the recent positive flow anomalies (Degefu and Bewket, 2014; Tekleab et al.,

2013; Woldesenbet et al., 2017; Worku et al., 2018). Table 4 indicates a significant regime shift in the raw flow data in the year 2006 when the mean escalated from 47,330 to 55,938 Mm^3/year . Accordingly, a positive trend occurred from 1984-2005 but not significant at $p = 0.05$; the significance level was found to be 0.085.

4. 2. Water-energy productivity

Fig. 7 depicts a time series of the combined WEP of the Roseires and the Sennar dams. The WEP shows high year-to-year variability during the decade 2002-2012 and a drop thereafter to its lowest value, which almost remained since 2013. As shown in Table 4, the year 2013 represented the year of change in regime in the WEP time series; however, no significant trend was found during this period. Before 2013, the ranges of hydro-energy generation and the reservoir evaporation were 1450-1980 GWh/year and 540-895 Mm^3/year , respectively. Thereafter, these ranges became approximately 2275-2410 GWh/year and 1250-1330 Mm^3/year , respectively. Although both the hydro-energy generation and the reservoir evaporation increased, the WEP dropped due to a higher rate of increase in evaporation compared to that in hydro-energy generation.

4. 3. Nexus indicators of hydro-energy generation

In Fig. 8a, the time series of both the annual energy and the number of days at installed capacity are increasing; however, two changes in regime, i.e. in 1996 and 2013, were detected for the former but only one in 2013 for the latter as indicated in Table 4. The annual energy shows an increased mean from 1,612 to 1,784 GWh and an increasing trend over the period 1984-1995 (Table 4); then, the mean increased once again to 2,353 GWh, but the trend was not significant during this regime. The regime shift in annual energy in 1996 can be explained by an increase in energy generation due to an increase in river flow during the dry season (November to June). From 1984 to 1995, the mean Blue Nile flow in the dry season

was around 7,300 Mm³ compared to approximately 10,080 Mm³ from 1996 to 2012. Accordingly, the mean energy generation in the dry season grew from around 754 GWh before 1996 to over 915 GWh from 1996 to 2012. In 2013, the percentage of days of the year recording installed energy capacity increased significantly from ~39 to ~61% with a significant increasing trend during 1984-2012. During 1984-2016, the firm energy exhibited an increasing trend over several cycles but without a regime shift. Fig. 8b and Table 4 show increasing variability of the daily energy over time which escalated too high after 2012 to display a change in regime.

4. 4. Nexus indicators of pumping energy

As regards the pumping energy indicators, a prominent remark to make is the non-existence of significant trend in any one of them despite the occurrence of regime shifts. It can be noticed in Fig. 9a that the annual pumping energy had a regime shift in 2012 when the mean dropped from 3.84 to 3.30 GWh/year. The highest daily pumping energy has maintained somewhat a constant level (Fig. 9b). On the other hand, the lowest daily pumping energy reveals significant regime shift in 2014 characterized by a decline in the mean for the period of 2014 onwards in comparison with the mean for the period 1984-2013. Here, a rise occurred in the former indicator while a drop was detected in the time series of the latter indicator. Over the study period, two changes occurred in the time series of the coefficient of variability of the daily pumping energy, one detected in 2003 while the other in 2014 (Table 4). The former seems to correspond to a prolonged drought (below-average flow) period that extended from 2002 to 2005, as shown in Fig. 6.

5. Discussion

It is important to decipher the reason behind the striking change in regime in 2013 for most of the indicators discussed above. The Roseires Dam was heightened by the hydrologic

year 2012/2013, causing noticeable hydrological alterations (Alrajoula et al., 2016). The dam was initially constructed with a Full Supply Level (FSL) of 480 m asl with the possibility to be raised to 490 m asl (MoIHPS, 1966; Roseires Dam Heightening Unit, 2005). The Roseires was heightened to meet the increasing demands for electricity and irrigation water and to compensate for the storage capacity that had been lost to sedimentation (Ahmed and Ismail, 2008). Heightening the Roseires Dam raised the maximum storage capacity from about 1,700 to 5,909 Mm³ and the maximum reservoir surface area from roughly 260 to 565 km². To comprehend the implications of the heightening of the Roseires Dam for the nexus indicators discussed above, one must first understand the operating rules of the Sennar and the Roseires Dams. Both dams were constructed for seasonal storage, i.e. to store water in the flood season to be used in the dry season for irrigation water supply and hydropower generation. Four successive stages characterize the seasonal operation of the Roseires and the Sennar Dams: (1) impoundment, (2) stabilization at FSL, (3) draw-down, and (4) stabilization at Minimum Operating Level (MOL). The following information on the four operation stages was acquired from MoIHPS (1968) and Basheer et al. (2018). In the first stage, the water levels of the two reservoirs are raised from MOL to FSL. Before the heightening of the Roseires Dam, the first stage used to start on a day from 1st to 26th of September and continue for 45 days for both dams. The start day of the first stage has been changed to between 11th of August and 11th of September for both dams, and the impoundment period has been amended for the Roseires Dam to 55 days. Before (after) the heightening of the Roseires Dam, the start day of the first stage used to be (is) determined based on the following criteria: 1st of September (11th of August) if the flow at El-Diem Gage is less than 350 Mm³/day (450 Mm³/day) by that day; a day between 1st of September (11th of August) and 26th of September (11th of September) when the flow at El-Diem Gage drops below 350 Mm³/day (450 Mm³/day); 26th of September (11th of September) if the flow at El-Diem Gage remains higher than 350

Mm³/day (450 Mm³/day) by that day. The second operation stage, i.e. stabilization at FSL, starts after the end of the first stage and continues until the river flow drops below the water demands. In the third stage, the water stored in the Roseires and the Sennar reservoirs is drawn down to provide the difference between the river flow and various water demands whenever possible. Lastly, the fourth stage starts at the end of May to maintain the water levels of the two reservoirs at MOL and continues until the start of the first stage. The purpose of the fourth stage is to minimize reservoir sedimentation during the peak flood period.

The 2013 regime change in annual energy generation (Table 4 and Fig. 8a) was due to the increase in energy generation from the Roseires Dam during the first, second, and third stages of the seasonal operation of the dam. This increase in energy generation was due to the increase in reservoir water levels and outflows. However, the rise in water levels increased the reservoir surface area, escalated reservoir evaporation, and reduced the WEP (Fig. 7). The increase in the number of days at energy capacity can be explained by the increase in reservoir water levels and water releases from the Roseires Dam after the heightening. Further investigation of this result shows that when the turbines of the Roseires Dam reach their power capacity (280 MW; Table 1), water releases are made through the other outlets of the dam, i.e. gated spillways and deep sluice gates. These observations indicate the power capacity of the turbines of the Roseires Dam could be raised to utilize the hydropower potential that the heightening has created. Furthermore, the Roseires heightening has increased the variability in daily energy generation and has stabilized the firm daily energy generation (Fig. 8b). As explained in Section 2, four schemes in the study area abstract their irrigation water via pumping. Three of them abstract directly from the Sennar Reservoir while one abstracts from the river channel upstream from Khartoum (see Fig. 4). The 2012 shift in annual pumping energy can be attributed to the modification made to the start of the first

stage of the seasonal operation of Sennar Dam that was introduced with the heightening of Roseires Dam. This modification results in earlier filling of the Sennar Reservoir, higher reservoir water levels, and less annual pumping energy. On the other hand, the shifts in the highest daily pumping energy, the lowest daily pumping energy, and the variability in pumping energy are due to an interplay of the inter-annual variability of river flow and dam operating rules. The present analysis of regime shift in water-energy nexus indicators shows the ability to detect significant human interventions in the hydrological system such as the heightening of the Roseires Dam in 2013.

6. Conclusions

In this study, the Blue Nile - a major tributary of the Nile - within Sudan was taken to demonstrate the usefulness of temporal analysis of the nine nexus indicators. A calibrated and validated daily water balance model of the study region has been utilized to construct time series for the nine water-energy nexus indicators from 1984 to 2016. Time series analysis has been performed to understand and interpret the temporal dynamics of the nine indicators in terms of regime shifts and trends.

The nine indicators of water-energy nexus that have been explored in this study for hydropower generation and water pumping can help understand the interplay of hydro-energy, pumping energy, reservoir evaporation, and water availability. Such an understanding could contribute towards efficient utilization of the water and energy resources (Liu et al., 2017)m especially under the ongoing campaigns to better operate existing water-related infrastructures rather than building new ones (Chen et al., 2016).

The analysis revealed significant regime shifts in annual energy generation, percentage of days at energy capacity, CV of daily energy generation, WEP, and annual pumping energy in 2012/2013. These shifts were due to the heightening of the Roseires Dam by 10 m. Even

though the heightening increased annual energy generation, it reduced the WEP due to a considerable increase in evaporation losses. It is noteworthy that the hydropower capacity of the Roseires turbines has not been increased following the heightening of the dam. The significant shift in the percentage of days at energy capacity in 2013 indicates that hydropower turbines of higher capacity could be installed in the Roseires Dam to utilize its hydropower potential fully. The regime shifts detected in 2012/2013 shows that the use of statistical regime shift analysis of hydrological time series is robust enough to detect human interferences in the hydrology of rivers such as dam construction. This robustness could prove useful in identifying not only interventions in a river system in terms of infrastructural development, but also changes in the operation of existing water infrastructures which are often inadequately documented. Such an analysis could help in highlighting the untapped efficiency gains in water and energy systems (e.g. possible increase of turbines capacity).

The nexus indicators of hydropower generation and water pumping that have been analyzed in this study are not claimed to be comprehensive; rather, they represent a valuable step toward addressing the water-energy nexus in similar cases of dammed river basins. The presented nexus indicators can also be tailored depending on the analyzed case and analysis purpose.

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801

Figure

Fig. 1 Main features of the Lower Blue Nile Basin.

Note: GIS = Geographic Information System; ENTRO = Eastern Nile Technical Regional Office; SRTM = Shuttle Radar Topography Mission; DEM = Digital Elevation Model

Fig. 2 Total flow of the Blue Nile at the outlet of the basin from 1984 to 2016: (a) exceedance probability of the annual flow (b) mean monthly flow.

Fig. 3 Water-energy nexus indicators and measures in the context of hydropower generation and water pumping

Fig. 4 Schematic of the model of the Lower Blue Nile Basin

Fig. 5 Observed and simulated outflow from: (a) the Roseires Dam, (b) the Sennar Dam, and (c) the Khartoum Gage

Fig. 6 Annual Standardized Streamflow Index (SSI) of the Blue Nile at El-Diem Gage

Fig. 7 Annual Water-Energy Productivity (WEP) of hydropower dams in the Lower Blue Nile Basin

Fig. 8 Hydropower generation in the Lower Blue Nile Basin: (a) annual energy and percentage of days at energy capacity; (b) variability and firm energy.

Note: CV = Coefficient of Variation

Fig. 9 Pumping energy in the Lower Blue Nile Basin: (a) annual energy; (b) highest energy, lowest energy, and variability.

Note: CV = Coefficient of Variation

Table 1 Main features of the Roseires and the Sennar Dams

Dam	FSL (m asl)	Storage at FSL (Mm ³)	MOL (m asl)	Storage at MOL (Mm ³)	Dam outlets	Installed power capacity (MW)
Sennar	421.7	640 (in 1985)	417.2	220 (in 1985)	72 gated spillways, 80 deep sluice gates and 2 turbine intakes	15
Roseires (after heightening)	490	5,909 (in 2012)	469	58.3 (in 2012)	5 deep sluice gates, 7 spillways, and 7 turbine intakes	280

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

Table 2 Daily performance of the model in the calibration and validation periods.

Location	Performance metric	Calibration	Validation		
		Metric value	Ranking	Metric value	Ranking
Rosieres Dam	R ²	0.97	Excellent	0.98	Excellent
	NSE	0.96	Excellent	0.98	Excellent
	MPE	0.88 (range: 100 to −1152)	Excellent	0.84	Excellent
Sennar Dam	R ²	0.95	Excellent	0.97	Excellent
	NSE	0.95	Excellent	0.96	Excellent
	MPE	−1.30 (range: 103 to −831)	Excellent	8.95	Excellent
Khartoum Gage	R ²	0.90	Excellent	0.94	Excellent
	NSE	0.90	Excellent	0.94	Excellent
	MPE	0.26 (range: 204 to -2705)	Excellent	−13.08	Very good

Note: R² = coefficient of determination; NSE = Nash-Sutcliffe coefficient of efficiency; MPE = Mean Percentage Error

Table 3 Outlines of the operating rules of the Roseires and the Sennar dams.

Priority	Before the heightening of the Roseires Dam		After the heightening of the Roseires Dam	
	Roseires	Sennar	Roseires	Sennar
1	Keeping the reservoir above the minimum operating level	Keeping the reservoir above the minimum operating level	Keeping the reservoir above the minimum operating level	Keeping the reservoir above the minimum operating level
2	Keeping the reservoir below the full supply level	Keeping the reservoir below the full supply level	Keeping the reservoir below the full supply level	Keeping the reservoir below the full supply level
3	Targeting certain water levels starting from a date between September 1st and September 26th. The starting is related to the flow at El-Diem Gage	Targeting certain water levels starting from a date between September 1st and September 26th. The starting is related to the flow at El-Diem Gage	Targeting certain water levels starting from a date between August 11th and September 11th. The starting is related to the flow at El-Diem Gage	Targeting certain water levels starting from a date between August 11th and September 11th. The starting is related to the flow at El-Diem Gage
4	Keeping the reservoir at the minimum operating level from June 1st to September 26th	Keeping the reservoir at the minimum operating level from June 1st to September 26th	Keeping the reservoir at the minimum operating level from June 1st to August 10th	Keeping the reservoir at the minimum operating level from June 1st to August 10th
5	Meeting part of the water demands of the Lower Blue Nile	Meeting part of the water demands of the Lower Blue Nile	Meeting part of the water demands of the Lower Blue Nile	Meeting part of the water demands of the Lower Blue Nile

Table 4 Regime shift and trend analyses of the water-energy indicators and measures.

Indicator or measure	Regime shift test				Kendall tau test		
	Change year	Mean before	Mean after	Significance level	Time span	Trend direction	Significance level, p
Flow at El-Diem Gage (Mm ³ /year)	2006	47330	55938	0.0187	1984-2005	+	NS
					2006-2016	–	NS
WEP (GWh/Mm ³)	2013	2.37	1.80	0.0001	1984-2012	–	NS
Annual hydro-energy (GWh)	1996	1612	1784	0.0007	1984-1995	+	0.0092
	2013	1784	2353	0.0001	1996-2012	–	NS
Days at energy capacity (%)	2013	39	61	0.0012	1984-2012	+	0.0201
Firm daily energy (GWh)	-	-	-	-	1984-2016	+	0.0006
CV of daily energy generation	2013	2.1	5.5	0.0024	1984-2012	+	0.0006
Annual pumping energy (GWh)	2012	3.84	3.30	0.0003	1984-2011	–	NS
Highest daily pumping energy (GWh)	-	-	-	-	-	–	NS
Lowest daily pumping energy (10 ⁻³ GWh)	2014	4.59	3.75	0.0003	1984-2013	–	NS
CV of daily pumping energy	2004	0.33	0.31	0.0017	1984-2003	–	NS
	2014	0.31	0.35	0.0452	2004-2013	+	NS

Note: WEP = water-energy productivity; CV = coefficient of variation; NS = Not significant at p = 0.05.