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Sensitivity of Water-Energy Nexus to dam operation: A Water-Energy Productivity concept

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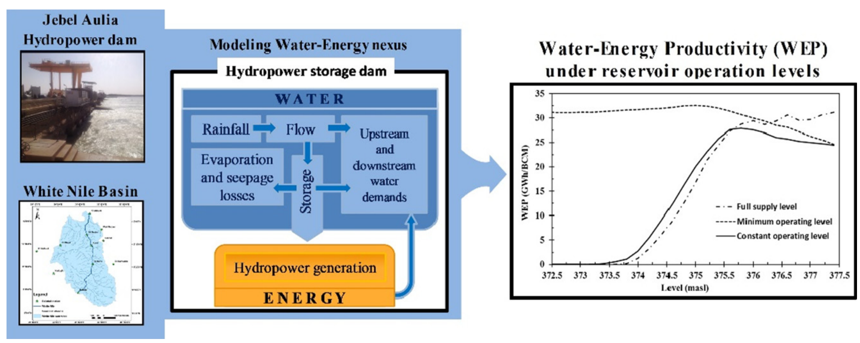
HIGHLIGHTS

- Sensitivity of Water-Energy Nexus (WEN) to dam operation policies is explored.
- Water-Energy Productivity (WEP) is proposed to measure Water-Energy Nexus of dams.
- A water allocation model is developed for the White Nile Basin (Sudan).
- 77 scenarios are examined for the White Nile Basin (Sudan) over 1980 to 2009.
- Basin-wide strategies are needed for efficient utilization of water and energy resources.

GRAPHICAL ABSTRACT



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ABSTRACT

Understanding and modelling the complex nature of interlinkages between water and energy are essential for efficient use of the two resources. Hydropower storage dams represent an interesting example of the water-energy interdependencies since they are often multipurpose. The concept of Water-Energy Productivity (WEP), defined as the amount of energy produced per unit of water lost in the process, is introduced in this study to illustrate the relationship between energy generation and water losses by examining the sensitivity of the Water-Energy Nexus (WEN) to changing dam operation policy. This concept is demonstrated by developing a water allocation model of the White Nile in Sudan, including Jebel Aulia Dam (JAD), using a general river and reservoir simulation software called RiverWare. A number of 77 operation scenarios of JAD are examined for 30 hydrologic years (1980–2009), considering reducing the Full Supply Level (FSL) gradually from its current value to the minimum possible value, increasing the Minimum Operating Level (MOL) gradually to the maximum possible level, and operating the dam at a Constant Operating Level (COL). The results show that raising the operating level does not necessarily increase the WEP. In comparison to the current policy, the analysis shows that a maximum WEP of 32.6 GWh/BCM (GWh/Billion Cubic Meters) would be reached by raising the MOL to 375 masl (meters above sea level), resulting in an increase in average annual energy generation to 164.6 GWh (+18.1%) at the expense of an annual water loss of 5.05 BCM (+12.7%). Even though this operation policy results in a more efficient water use compared to the original operation policy, a basin-wide assessment that includes all hydropower storage dams in the Nile basin should be conducted to decide on where and how much energy should be generated. The present analysis and future examination of the multi-dimensions of the WEN in the context of dam operation are imperative to improve the decision making in the quest for efficient resource use and management.

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Abbreviations: WEN, Water-Energy Nexus; WEP, Water-Energy Productivity; JAD, Jebel Aulia Dam; WN, White Nile; BCM, Billion Cubic Meters; masl, meters above sea level; MOL, Minimum Operating Level; FSL, Full Supply Level; COL, Constant Operating Level.

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1. Introduction

The current crises of global water and energy resources are anticipated to progressively amplify as a result of increasing population, growing developed and developing economies and future climate change (Chow et al., 2003; Sivakumar, 2011). Energy efficiency interventions can contribute considerably to reducing water use, lowering emissions, and meeting climate-related mitigation targets (Engström et al., 2017). Ernst and Preston (2017) state that "Adapting energy systems to climate change without considering water systems and vice versa creates unseen consequences that make achieving even modest adaptation objectives difficult". Therefore, the increasing demand for water and energy services in view of the limited resources has increased the need for further understanding of the multidimensional nature of interlinkages of the two resources (Hamiche et al., 2016). Due to the increasing energy demands and limited freshwater supplies, performing a quantitative assessment of this nexus facilitates the understanding of the relative dependencies of energy systems and fresh water (Siddiqi and Anadon, 2011).

Science and policy issues related to dams and water storage embody the idea of increasing interlinks of water, energy, and food resources (Al-Saidi and Elagib, 2017). To the best of our knowledge, the literature survey reveals very few studies explicitly addressing the grand nexus, i.e. interconnection and mutual impacts within water–energy–food systems, in the presence of a dam. A recent study carried out by Jalilov et al. (2016) for a planned building of a dam emphasizes the difficulty of reaching a win–win scenario across the water–energy–food security nexus in large (transboundary) river basins. The strong sub-nexus representing water-energy interactions or Water-Energy Nexus (WEN) can be exemplified by hydropower storage dams since they are often multipurpose (Lindström et al., 2012; Bullock and Hülsmann, 2017), as shown in Fig. 1. Even though storing water in reservoirs gives the potential for hydropower production, it increases water losses due to evaporation and seepage resulting from the water surface of the reservoir. Dam operation policy is thus hypothesized to have strong impacts on the dam-related WEN.

This study proposes the Water-Energy Productivity (WEP) as a measure for illustrating the sensitivity of the WEN to dam operation policy. Jebel Aulia Dam (JAD) on the White Nile (WN) basin in Sudan is taken as a case study to present the usefulness of the WEP in providing a better understanding of the WEN. The impetus of the selection of the WN relies on its nature as a transboundary river that is understudied in the literature.

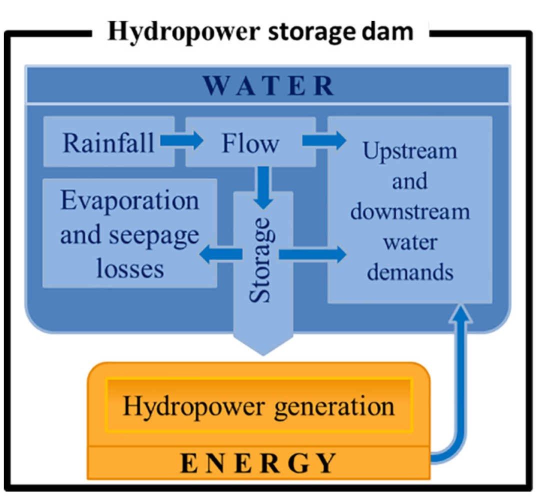

Fig. 1. Water-Energy Nexus (WEN) represented by hydropower storage dams.

2. Study area and problem statement

The WN, a major river in Sudan, joins the Blue Nile at the capital of Sudan, Khartoum, to form the Main Nile River (Fig. 2). The WN starts at Malakal in South Sudan near the confluence of Bahr El Ghazal River and Sobat River. The WN basin covers an area of around 259,610 km^2. The baseflow of the WN is highly dominated by many lakes and swamps upstream of Malakal. Bahr El Jebel River, whose source is Lake Victoria in Uganda, is considered the main source of the WN water at Malakal, other sources include Bahr El Ghazal River and some streams which originate in Ethiopia where high rain falls (Sutcliffe and Parks, 1999; Tate et al., 2001). The WN contributes only 15% of the annual flow of the Nile, but it has the advantage of having a steady flow throughout the year compared to the rest of the Nile tributaries (NBI, 2012). The Sudd swamps are responsible for a loss of around 50% of the water coming from Bahr El Jebel River, consequently reducing the WN flow (Sutcliffe and Parks, 1999). The annual flow of the White Nile, measured at Malakal, ranges approximately between 26 BCM (Billion Cubic Meters) and 35 BCM, with an average of around 31 BCM (see Fig. 3). Most of the WN basin area (~72%) is located in Sudan, around 25% of the basin is located in South Sudan while a very small portion is located in Ethiopia (~3%). The climate of the WN is characterized by a strong latitudinal pattern. Local precipitation patterns develop due to a complex interplay of topography, lakes, and swamps (Sutcliffe and Parks, 1987). The WN basin has its highest amount of precipitation in the Ethiopian part, with 1576 mm per annum on average, while the lowest amount is at the mouth of the basin at Khartoum with 109 mm per annum on average (Camberlin, 2009).

Jebel Aulia Dam is located 40 km south of Khartoum, and is the only dam existing on the WN (see Fig. 2). The dam was constructed by the Egyptian government during 1933 to 1937 with a reservoir storage volume of 3.5 BCM (Sobeir, 1983). The main purpose of the dam was to store water in the wet season for use in Egypt during the peak summer season when the Blue Nile flow is at its lowest level. JAD is the only dam worldwide that is built in a country for the benefit of another country (Sobeir, 1983; Salman, 2016). The dam has lost its original functions due to the high storage provided by the High Aswan Dam in Egypt. Therefore, the ownership of the dam was transferred to Sudan in 1977. Since then, the operation of JAD has been mainly governed by the demands of both the WN and the Main Nile pump schemes, when the discharge of the Blue Nile falls to the minimum, and is also purposed for flood control in the Main Nile when the flow of the Blue Nile rises to the maximum (Sobeir, 1983). Due to the location of JAD in the vicinity of a center of energy demand, 80 turbine generators with a total capacity of 30.4 MW were installed in 40 out of the 50 available discharge openings of the dam from 2002 to 2005 (ANDRITZ Hydro, 2013).

Pump abstraction upstream of JAD for both large- and small-scale irrigated agricultural development is ongoing. Three large sugar irrigation schemes exist in the WN, namely Kenana Scheme (established in 1975 with an area of 635 km^2), Assalaya Scheme (established in 1980 in an area of 166 km^2), and the White Nile Scheme (established in 2012 with an area of 693 km^2). Additional water abstraction from the WN goes for small-scale farming (ENTRO, 2009).

The dam will soon experience major changes in its operation policy due to the construction of the Grand Ethiopian Renaissance Dam (GERD). The GERD, which is the largest hydropower plant in Africa and the tenth largest globally, is currently under construction on the Blue Nile River around 20 km from the Sudanese-Ethiopian border (Fig. 2), and is expected to be completed by the end of 2017 (Swanson, 2014; Salman, 2016; Salini Impregilo, 2016). Research has shown that the long-term operation of the GERD, following its impoundment, is expected to change the flow pattern of the Blue Nile from a varied flow to a more regular flow (IPoE, 2013; Tesfa, 2013; MIT Abdul Latif Jameel World Water and Food Security Lab, 2014; MoWRIE, 2014; Wheeler et al., 2016). Since the current operation policy of JAD is based on the natural flow pattern of the Blue Nile as indicated earlier, the long-term

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