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Pareto Optimization of Water Resources Using the Nexus Approach

Athanasia-Tatiana Stamou[1] (ORCID) · Peter Rutschmann[1]

Abstract

The continuously growing population in combination with the escalating urbanization and economic growth increase the pressure on water, energy and food resources of our planet. This entails an urgent need for proper water resources management within the water-energy-food (WEF) nexus concept. The WEF nexus considers water, energy and food as three continuously interconnected sectors, whose complex interactions lead to an increased number of trade-offs and potential conflicts. Computational modeling can be used to quantify these interactions, reduce trade-offs and promote synergies. We investigate the water resources in the Upper Blue Nile River (UBNR) basin, one of the two main sources of the Nile, using the Hydronomeas tool. Hydronomeas is based on the parameterization-simulation-optimization method; optimization is implemented in two levels, using a holistic approach and multiple criteria. We assign various targets, constraints and priorities to the UBNR system of reservoirs, hydropower plants and irrigation projects and derive a Pareto front that contains alternative, optimal solutions, for which improvement of one objective can be achieved only at the expense of another. By visualizing the trade-offs between the conflicting objectives of hydropower and irrigation, we aim to help decision makers understand changes due to different management policies and thus, achieve greater efficiency in water resources management in the Nile region.

Keywords Pareto optimization · Water resources management · Water resources optimization · Water allocation · Nexus

1 Introduction

According to projections, the current world population of 7.6 billion people will rise to 9.8 billion in 2050 (Worldometers 2017). The rising population combined with escalating urbanization and economic growth increase the pressure on water, energy and food resources and

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intensify the conflicts between them. In response to these social pressures and to those arising due to climate change, the water-energy-food (WEF) nexus concept emerged in the international community during the Bonn 2011 Nexus Conference "The water, energy and food security nexus: solutions for the green economy" (Hoff 2011). The WEF nexus means that the three sectors - water, energy and food security - are inseparably linked, and that activity in one area has impacts in one or both of the others (FAO 2018). The objectives of the WEF nexus are to promote synergies and reduce trade-offs between the three sectors in alignment with sustainable development goals (Biggs et al. 2015). In recent years there has been considerable progress in the implementation of the WEF nexus; however, there remain many challenges. One of the main challenges is to describe and address the complex interactions of the resources system and to balance the different goals and interests of the users, while maintaining the integrity of the ecosystem (FAO 2014). There are also significant challenges related to data, information and knowledge gaps in our understanding of the WEF inter-linkages and the development of systematic tools to address the trade-offs involved (Liu et al. 2017).

Computational modelling is a powerful tool that can be used to quantify the interactions within the WEF nexus and support sustainable decision making (Bieber et al. 2018). Simulation models provide additional means to investigate a system, detect problems, and identify solutions. However, they are not capable of determining the optimal solution without intermediate steps (Simonovic 1992) and have, therefore, been extended to include optimization to automatically identify the optimum solution (Wurbs 1993). Most of the water resources optimization problems in real life involve multiple, conflicting objectives. For such problems, there is usually no single solution that optimizes all objectives simultaneously; thus we need to consider many possible trade-offs between the objectives. In this approach, the sum of optimal trade-offs is presented as a Pareto front and consists of solutions, for which improvement of one objective can be achieved only at the expense of another (Reddy et al. 2006). To deal with the Pareto front, classical optimization methods suggest converting a multi-objective problem to a single objective problem by emphasizing one particular Pareto optimal solution at a time (Chang and Chang 2009).

A powerful model for the simulation and optimization of multi-purpose hydro-systems is the Hydronomeas tool, whose mathematical framework is based on the low-dimensional Parameterization-Simulation-Optimization (PSO) method (Koutsoyiannis and Economou 2003). The tool uses simulation to obtain values of an objective function (performance index) that is optimized by a nonlinear optimization procedure. Hydronomeas has the strong advantage that optimization is implemented in two levels (one internal-linear and one external-nonlinear) using multiple criteria. Specifically, during simulation, the total cost of water transfer in the network is optimized in a linear programming model according to the management policy and following the physical constraints, targets in hierarchical order and operating restrictions. This ensures full precision and high speed calculations without excessive data requirements. Furthermore, through the parameterization method, only a few unknown parameters (e.g. for the reservoir operating rules, hydropower targets) are introduced into the hydro-system and are assessed through a nonlinear optimization process. Thus, the degrees of freedom in the problem are reduced and the curse of dimensionality is avoided. Multiple criteria, such as reliability, firm hydropower generation and irrigation deficit, may be incorporated into the performance index, thus allowing the investigation of multi-objective optimization problems and the detection of Pareto optimal solutions. Another advantage of Hydronomeas is its holistic approach, which is achieved by incorporating various aspects of water resources management (e.g. technical, economic, environmental), multiple water use

options/objectives (e.g. water supply, irrigation, hydropower) and operating restrictions (e.g. aqueduct capacity, reservoir spill); thus making the model well suited for representing the complexities of the WEF nexus.

We apply this analysis in the Upper Blue Nile River (UBNR), one of the two main sources of the Nile, in which water resource management is event driven. Numerous models have been developed over the last years concerning the water resources planning and management within the UBNR basin. However, most of these models are designed to only simulate the hydro-system (McCartney and Girma 2012, Jeuland and Whittington 2014, King and Block 2014, Wheeler et al. 2016, Zhang et al. 2016). Other studies deal solely with the optimization aspect (Whittington et al. 2005, Block and Strzepek 2010, Goor et al. 2010). There are, however, relatively few studies that consider both simulation and optimization (Digna et al. 2017). Some of the recent, notable studies include that of Hassaballah et al. (2012), who focused on hydropower maximization, and the study of Georgakakos (2006) that utilized the Nile River basin decision support tool to assess the hydropower impact of four proposed hydropower plants (HPPs). Sileet et al. (2014) utilized the Nile Basin Decision Support System (DSS) to assess the impacts of planned projects; however, this was performed without applying the DSS optimization module. Recognizing the limitations of previous studies, we designed a multi-objective optimization system for the UBNR basin using the PSO method as implemented in Hydronomeas. To further broaden the investigation, we defined two scenarios, the current hydro-system configuration (2017), and a medium-term future scenario, and analyzed the results for both. For the medium-term scenario that includes projects that are currently under construction, we calculated Pareto optimal solutions for the conflicting objectives of hydro-power and irrigation. The resulting Pareto front graphically illustrates the effects of different water management policies and is a useful tool for decision makers.

2 Upper Blue Nile River Basin

2.1 General Overview

People in Ethiopia depend on the UBNR because it supplies the country with water for hydropower, irrigation, domestic, industrial, livestock and touristic purposes. Approximately 27 million out of the nearly 79 million Ethiopians live within the UBNR basin (2008) (Yilma and Awulachew 2009, from the Central Statistics Authority Ethiopia 2007). The UBNR originates at Lake Tana in the Ethiopian highlands. It flows initially to the south, and then to the west, before crossing the border into Sudan (see Fig. 1). The UBNR consists of 16 sub-basins. This paper deals with 14 of these sub-basins, namely Tana, Beshilo, Welaka, Jemma, North Gojam, Muger, Guder, Finchaa, South Gojam, Anger, Didessa, Wenbera, Dabus and Beles (Fig. 1). These sub-basins cover an area of approximately 176,465 km^2 (Yilma and Awulachew 2009, from the Ministry of Water Resources Ethiopia 1999). The Dinder and Rahad sub-basins are excluded from the present study since they flow into the Blue Nile River downstream of the Ethiopia-Sudan border.

The UBNR basin is characterized by highlands in the central and eastern part, and lowlands in the western part. Elevations range from 498 to 4261 m a.s.l. (Yilma and Awulachew 2009). Rainfall in the UBNR basin ranges from 787 to 2200 mm per year and varies both spatially and temporally; potential evapotranspiration ranges from 1056 to 2232 mm (Yilma and Awulachew 2009). The UBNR is highly seasonal; more than 80% of the annual runoff at
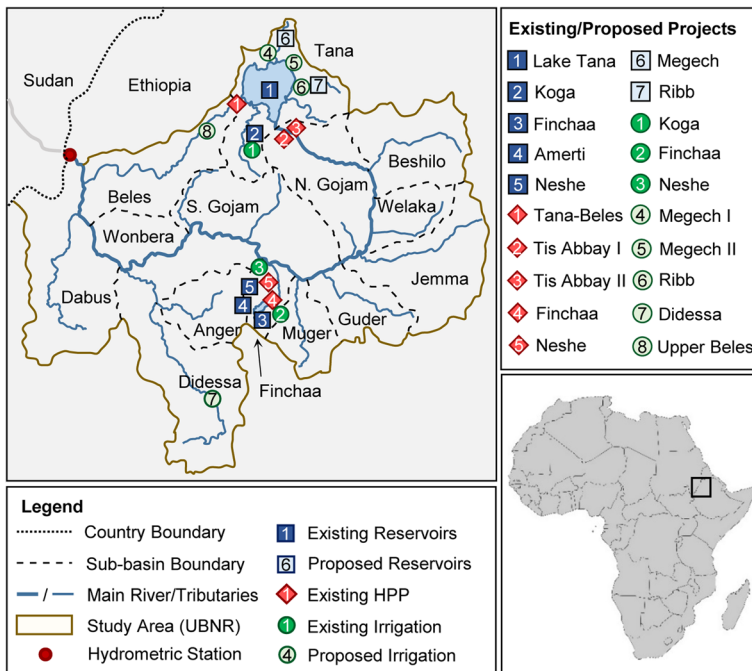
Fig. 1 Main river network, sub-basins, and existing/proposed reservoirs, HHPs and irrigation projects in the UBNR

the border between Ethiopia and Sudan occurs during the rainy season, while several of the UBNR tributaries dry out during the dry season. The average annual flow of the UBNR basin at the border between Ethiopia and Sudan is estimated at 50.6 km³ (McCartney et al. 2012), measured at a hydrometric station located in Ethiopia (see Fig. 1).

2.2 Current and Potential Future Water Resource Use

Five reservoirs exist currently within the UBNR basin: Lake Tana, Koga, Finchaa, Amerti and Neshe, all located in only two of the 14 sub-basins (see Fig. 1), and serving the following main purposes: flow regulation, irrigation, hydropower generation, flood control, navigation and recreation. Lake Tana is located in the Tana sub-basin and is Ethiopia's largest freshwater lake with a volume of approximately 29 km³ and a surface area of 3062 km² at a water elevation of 1786 m a.s.l. Water from Lake Tana is used to generate hydropower at three HPPs: Tana-Beles, Tis Abbay I and Tis Abbay II. The latter two are currently operating only as stand-by stations with an installed capacity of 12 MW and 73 MW respectively, since the recent inception of Tana-Beles (2009) that has an installed capacity of 460 MW. The utilized water at the Tana-Beles HPP is then released to the Beles River, the last tributary of the UBNR before the border with Sudan. The Koga reservoir, also located in the Tana sub-basin, has a reservoir volume of 83.1 hm³ and an area of 18.6 km² at a water elevation of 2015 m. Koga irrigates a net area of 5100 ha with an annual demand of 50 hm³/y. The Finchaa, Amerti and Neshe reservoirs are located in the south of the UBNR basin. The Finchaa reservoir was the first multipurpose reservoir commissioned to generate hydropower at the HPP with an installed capacity of 134 MW and irrigate a net area of 6205 ha with a demand of 47 hm³/y. Finchaa has a volume

of 1120 hm^3 and an area of 345 km^2 at a water elevation of 2219 m. The Amerti reservoir was created to regulate the flow to the Finchaa reservoir with additional water for hydropower and irrigation. Neshe is a multipurpose reservoir with a volume of 196 hm^3 and an area of 21 km^2 at a water elevation of 2221 m. It generates hydropower at the HPP with an installed capacity of 97 MW and irrigates a net area of 7217 ha with a demand of 67 hm^3/y.

The UBNR basin has great water resources potential, providing approximately 60% of the Nile River flow at Aswan, Egypt (84.5 km^3) as per the Nile Agreement (McCartney et al. 2012). Due to its water resources and topography, the UBNR has great hydropower potential that is estimated equal to 70,000 GWh/y according to the Ministry of Water Resources of Ethiopia (technical potential), including the Dinder and Rahad Rivers (McCartney et al. 2012). Agriculture is the major driver of the Ethiopian economy. It constitutes half of the country's Gross Domestic Product (GDP) and provides work for the vast majority of Ethiopians (Awulachew et al. 2005). However, agriculture in the UBNR basin is heavily dependent on rainfall, which varies geographically and seasonally (Awulachew et al. 2005). Storing rain- and surface water represents a way of coping with the rainfall issue and exploiting the UBNR basin's great irrigation potential, which is estimated to be 680,000 ha (maximum gross irrigable area of medium and large scale irrigation projects) with an annual average water requirement of 4895 hm^3 (BCEOM et al. 1998). Although the UBNR basin has great water resources, hydropower and irrigation potential, it is one of the least utilized basins in Ethiopia.

Current water resource management in the UBNR basin is largely reactive to flooding or drought, leaving both water resource managers and the local population at the mercy of natural events. The water resources development plans of Ethiopia for the UBNR and the future expansion of water use are likely to become a source of conflict among riparian countries. These two facts highlight the necessity for proper water resources management in the region.

2.3 Hydro-Politics in the Nile Region

The hydro-politics within the Nile Basin are strongly shaped by conflicts between the eleven riparian countries. In 1929 the First Nile Water Agreement between Egypt and Great Britain, colonial power at the time being, was signed, followed by the 1959 Agreement for Full Utilization of the Nile Water between Egypt and Sudan. This agreement granted specific volumetric allocations per year only to Egypt and Sudan with 55.5 km^3 and 18.5 km^3 respectively (Erlich 2002). As it did not include other riparian states, these considered the agreement unfair. The highly controversial agreement marked the beginning of conflicts between downstream and upstream riparians, which up to now have not legally recognized it (Cascão 2012). Further attempts for basin-wide transboundary cooperation were made, such as Hydromet, Undugu and TeccoNile in 1967, 1983 and 1992, respectively; however, they failed due to the absence of key upstream riparians. Nevertheless, the developments in the 1990s can be seen as first steps of transboundary collaboration (Cascão 2012). The ongoing cooperation process within the Nile Basin can be described as a two-track approach (Cascão 2012). The first track of cooperation, the Nile Basin Initiative (NBI), was established in 1999 with its major objective being "to achieve sustainable socio-economic development through the equitable utilization of, and benefit from, the common Nile Basin water resources" (NBI 1999). The Cooperative Framework Agreement (CFA) may be viewed as the second track of cooperation and was set as a condition by upstream riparian states to join the NBI. The negotiations ended in June 2007, when the riparian states had agreed on all articles within the CFA except for one that deals with the status of the 1929 and 1959 Agreements. Even though

the cooperation process was influenced by strong conflicts and periods of deadlock, an environment of increasing trust and dialogue has been established over the years.

3 Materials and Methods

3.1 Data Collection

The collected data for the purposes of the present paper are categorized into the following data groups: (1) river flow, (2) reservoir, (3) irrigation, (4) hydropower and (5) meteorological. These data were collected from the literature and the International Water Management Institute (IWMI), as well as during visits to local authorities, offices and project sites in Ethiopia, e.g. the Ministry of Water, Irrigation and Electricity, the Abbay Basin Authorities, the Eastern Nile Technical Regional Office (ENTRO) (Stamou and Rutschmann 2017). Data were also generated from discussions with experts and researchers from the Addis Ababa and Bahir Dar Universities.

There are 126 hydrometric stations in the 14 sub-basins of the study area as described in the hydrometric basin monitoring map of the Nile Basin Water Resources Atlas (NBI 2016). Most of them were installed in the early 1960's (NBI 2016); however, data availability is limited. River flow data for the purposes of the present work, namely the flows in particular river locations, e.g. tributary inflows, were obtained from IWMI (McCartney et al. 2012). Main reservoir data, e.g. elevation-area-volume curves, were obtained from the Ministry of Water, Irrigation and Electricity of Ethiopia as well as ENTRO, and from site visits to currently operating reservoirs, HPPs and irrigation projects.

Irrigation data for the medium and large scale projects were collected from the Abbay River Master Plan Project (BCEOM et al. 1998). Irrigation projects in the UBNR basin are classified as small scale (<200 ha), medium scale (200-3000 ha) and large scale (>3000 ha) projects.

Key hydropower data for existing and planned HPPs in the UBNR basin were obtained from several sources, including the Abbay Basin Authority in Bahir Dar, the Ministry of Water, Irrigation and Electricity of Ethiopia, ENTRO, the Abbay River master plan project (BCEOM et al. 1998), and project site visits. Apart from these HPPs, the Abbay Basin Authority distinguishes possible hydropower development from already identified irrigation projects.

The meteorological basin monitoring map of the Nile Basin Water Resources Atlas (NBI 2016) includes 262 meteorological stations in the 14 sub-basins of the study area. However, data availability is limited. Moreover, most of the stations record only rainfall, whereas few stations record more variables (NBI 2016). Meteorological data, e.g. rainfall and evaporation, were collected from ENTRO and various reports.

3.2 Simulation and Optimization Tool

Various simulation-optimization models have been developed in recent decades to assist water resources management. For the management and optimization approach adopted in the present paper, we have chosen, based on a series of criteria (Stamou and Rutschmann 2016), the Hydronomeas tool that was developed in an Object Pascal environment (Delphi) at the National Technical University of Athens (Koutsoyiannis et al. 2002; Koutsoyiannis et al. 2003). Hydronomeas was improved in its current version within the research project "Combined Renewable Systems for Sustainable Energy Development" (ITIA 2018) and has

been applied in several water planning and management studies in Greece, including the case study of the Acheloos-Peneios region (Koukouvinos et al. 2015).

Hydronomeas is the core of a broader DSS that also includes tools for data processing (Hydrognomon), synthetic data generation (Castalia), and the information subsystem of the DSS that encompasses the database, GIS and telemetric system (Koutsoyiannis et al. 2003). The tool is capable of identifying the optimal management policy, which maximizes the system yield and the overall operational benefit and minimizes the risk for the management decisions (Koutsoyiannis et al. 2002). The five main steps of Hydronomeas are the following:

1. Transformation of the real-world system into a digraph model-network and definition of the input data.
2. Parameterization of the hydro-system operations, such as reservoir operating rules and hydropower generation targets.
3. Definition of the objective function, using the above mentioned parameters as control variables.
4. Simulation and optimization of the hydro-system.
5. Solution of the objective function of the hydro-system.

The mathematical framework of Hydronomeas is based on the low-dimensional PSO method (Koutsoyiannis and Economou 2003) that uses simulation to obtain values of the objective function (performance index) that is optimized by a nonlinear optimization procedure. According to the PSO approach a reservoir system becomes a typical stochastic optimization problem. More specifically, within the process of simulation a network linear programming model is applied to optimally allocate the state variables through the hydro-system in the least expensive way by performing static optimization for a single time period and imposing virtual attributes to the digraph components (linear internal optimization) (Efstratiadis et al. 2004). For the iterative, external optimization of the hydro-system nonlinear algorithms are used to optimize the objective function by determining the control variables, such as reservoir operating rules (Nalbantis and Koutsoyiannis 1997) or hydropower generation targets, using stochastic dynamics (nonlinear external optimization).

The PSO method exhibits several advantages over a high-dimensional method (Koutsoyiannis and Economou 2003), including (1) simplicity, (2) low computational times, (3) ability to incorporate stochastic and deterministic components and concepts, and (4) independence of the model parameters and operation policy on forecasted values of inflows. Celeste and Billib (2009) highlighted these advantages in their investigation of the performance of various stochastic models that were based on implicit stochastic optimization (ISO), explicit stochastic optimization (ESO) and the PSO approach. The PSO approach comprised a variant of the standard operating policy (SOP), reservoir zoning, and a two-dimensional hedging rule to define optimal reservoir operating rules. They concluded that simple ISO and PSO models perform better than SDP and the SOP, and provide release rules similar to the ones found by perfect forecast optimization; moreover, they argued that these models might be more acceptable to reservoir operators compared to SDP.

3.3 Pareto Optimization

In a hydro-system, there are usually many conflicting objectives and no single solution exists that optimizes all simultaneously. Thus, there is the need to consider multiple trade-off solutions

between the objectives. The trade-off Pareto optimal solutions, for which no improvement of one objective can be achieved without the expense of another, build together the Pareto front. Classical optimization methods suggest converting multi-objective problems to single objective problems by emphasizing one particular Pareto optimal solution at a time (Chang and Chang 2009). In the present paper, we generate the Pareto front of a medium-term future scenario of the UBNR hydro-system, within the WEF nexus concept, with the objectives to: (1) maximize the total monthly firm hydropower generated by the hydro-system and (2) minimize the average annual irrigation deficit of the irrigation projects. The irrigation deficit is the amount of water that does not reach the irrigation projects and represents the failure of a given target; the threshold for the firm energy reliability is set to 90%. To optimize these two conflicting targets, we perform multiple iterations of the simulation and optimization procedure using the firm hydropower generation of the HPPs as control variables. By assigning various weights to the two objectives that translate to different management policies, we calculate the solution of each objective function and generate the Pareto front that can help decision makers select from these specific optimal solutions without considering the entire range of solutions.

3.4 Multidimensionality – Ecological and Social Factors

As in most hydro-systems, optimization of water resources in the UBNR basin is a multi-dimensional problem. In the present paper, we account for this complexity by introducing targets, constraints and priorities into the hydro-system. In particular, minimum environmental flows are assigned to the reservoirs to consider the protection of the river as well as tourism. As an example, a minimum flow requirement is set at the southern outlet of Lake Tana, to provide sufficient flow to the Blue Nile falls, which attracts a large number of tourists every year. Furthermore, minimum reservoir levels are assigned to Lake Tana to assure sufficient water levels for navigation, a parameter that is important for the everyday lives of people living in the area, and also for tourism. Social factors are also indirectly accounted for in the decision making by weighting hydropower, which affects electricity generation and irrigation, which has an impact on food security (Stamou and Rutschmann 2017).

4 Schematization and Scenario Definition

The schematization and the definition of input parameters of the current configuration and one medium-term future scenario of the UBNR basin are the first steps before simulation and optimization. The basin was schematized using the available collected data and Google Earth, as shown in Fig. 2. The current configuration includes five reservoirs, five HPPs and three medium and large scale irrigation projects; for the medium-term future scenario, two additional reservoirs and five additional irrigation projects, currently under construction, were added.

The model input parameters include the characteristics of the rivers and their tributaries (discharges), the reservoirs (inflows, outflows, rainfall, evaporation, catchment area, spill-initial-intake elevation, elevation-volume and elevation-area curves), the HPPs (discharge and installed capacity, head), the irrigation projects and the associated targets (irrigation demand, hydropower generation target) and constraints imposed by environmental and social aspects (maximum and minimum reservoir operating levels, environmental flows that were assumed equal to a percentage of the reservoir inflow). We have used monthly time series for the river discharges based on historical data of the years 1968-1992; indicatively, Fig. 3 shows the discharge from the Muger sub-basin.
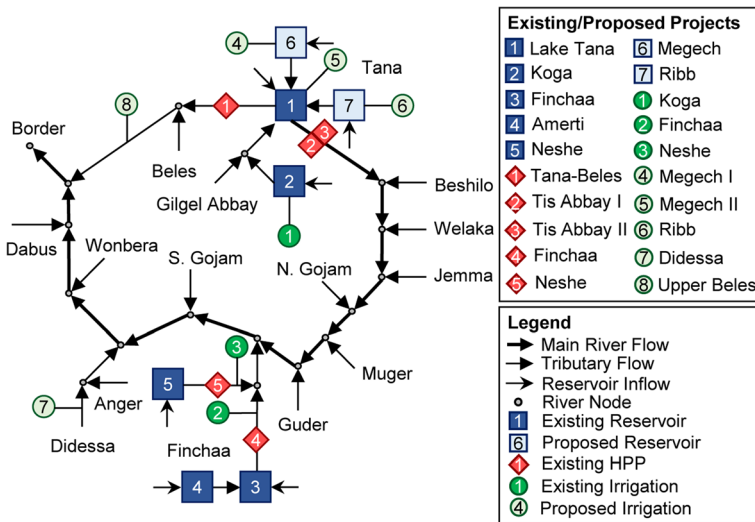
Fig. 2 Schematization of the UBNR hydro-system for the current configuration and the medium-term future scenario

Furthermore, priorities were assigned to the targets and constraints; the most important thereby have a "priority of level 1". Since agricultural production plays a vital role in Ethiopia, irrigation projects are given a higher priority than HHPs. In addition, reservoir environmental flow is given a lower priority than irrigation and hydropower. Different priorities for different HPPs and irrigation projects would result in different management policies. We further assumed that firm hydropower is the power that is guaranteed to be provided at least 90% of the time and is lower than the mean monthly hydropower generation over the simulation period. Table 1 summarizes the basic model input data of the reservoirs, HPPs and irrigation projects for the current configuration (S1) and the medium-term future scenario (S2).

5 Results and Discussion

Our simulations for the current configuration show that the generated hydropower by the five existing HPPs are: Tana-Beles = 2025 GWh/y, Finchaa = 667 GWh/y, Neshe = 233 GWh/y, Tis Abbay I = 20 GWh/y and Tis Abay II = 81 GWh/y; the total hydropower amounts to 3026 GWh/y. The simulation also yielded a discharge of 48.3 km³/y at the border between Ethiopia
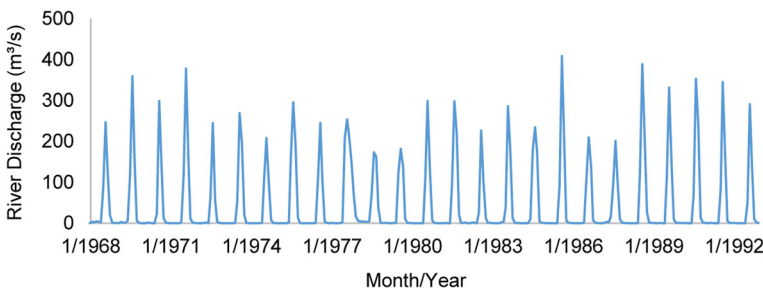

**Fig. 3** Discharge (m³/s) from the Muger sub-basin for the years 1968-1992

Table 1 Basic model input data of the reservoirs, HHPs and irrigation projects for the current configuration (S1) and the medium-term future scenario (S2)

Reservoir	Purpose	Net Irrigation Area (ha)	Irrigation Demand (hm³/y)	Installed capacity (MW)	Scenario
Lake Tana	Hydropower, Irrigation	15,993	128	460, 12, 73	S1, S2
Koga	Irrigation	5100	50	–	S1, S2
Finchaa	Hydropower, Irrigation	6205	47	134	S1, S2
Amerti	Flow Regulation	–	–	–	S1, S2
Neshe	Hydropower, Irrigation	7217	67	97	S1, S2
Megech	Irrigation	7311	58	–	S2
Ribb	Irrigation	19,925	197	–	S2
–	Irrigation (Didessa)	4803	30	–	S2
–	Irrigation (Beles)	53,720	530	–	S2
SUM		120,274	1107	776	

and Sudan, while the annual irrigation demand of the existing irrigation projects is determined equal to 164 hm³.

McCartney and Girma (2012) investigated the downstream implications of water resource development in the UBNR basin (i) without considering the more recent Tana-Beles HPP and the Neshe multi-purpose reservoir (see Fig. 1), but assuming (ii) a permanent operation of the HPPs Tis Abbay I and Tis Abbay II and (iii) a larger area for the Finchaa irrigation project. We compared our simulations with their results and found that they calculated a 54% lower total hydropower (1397 GWh/y) and a 22% lower irrigation demand (128 hm³/y).

For the medium-term future scenario, we generated the 2D-Pareto front that is shown in Fig. 4, whose six points A to F represent feasible cases. Points A (167 GWh/month, 80.2 hm³/y,) and F (205 GWh/month, 116.6 hm³/y) represent extreme cases in which both the irrigation deficit and the firm hydropower generation are minimized and maximized, respectively, while the points B, C, D and E represent intermediate cases with different weighting of the two objectives. Thus, point A is the worst case for hydropower generation and the best case for
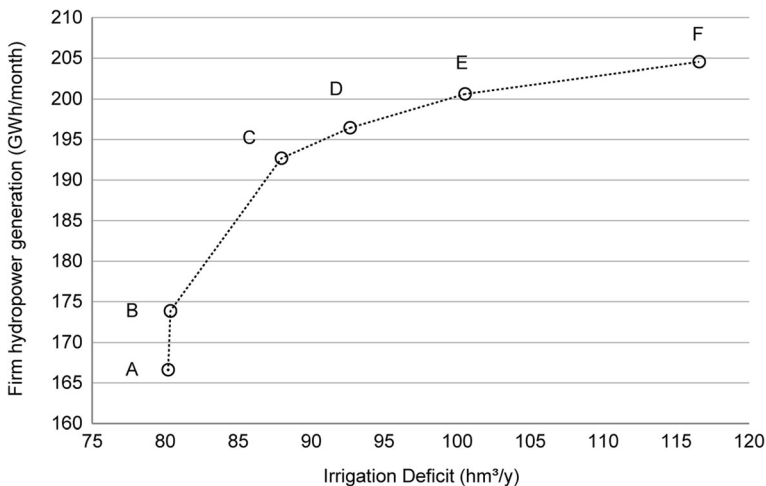
Fig. 4 2-D Pareto front of the UBNR hydro-system for the medium-term future scenario

irrigation deficit. Close to point A, for a relatively small increase in the irrigation deficit (from 80.2 to 80.4 hm^3/y), a relatively large increase in hydropower generation occurs (from 167 to 174 GWh/month). Correspondingly, point F represents the opposite case. Close to point F, a relatively small increase in hydropower generation (from 205 to 201 GWh/month) results in a relatively large decrease in irrigation deficit (from 116.6 to 100.5 hm^3/y). The irrigation projects Koga, Megech, Ribb and Beles and the HPPs Tana-Beles, and to a lesser extent Tis Abbay I and Tis Abbay II are the most sensitive to changes in the management policies. This is due to the fact that the existing Koga reservoir and the two currently in-construction reservoirs Megech and Ribb are located upstream of Lake Tana, while the HPPs Tana-Beles, Tis Abbay I and Tis Abbay II are located downstream. Moreover, the three HPPs that are located in two different lake outlets share the same water source (Lake Tana).

It is a very difficult task to select the best compromise among the Pareto optimal solutions without knowing the decision maker's preferences (Cheikh et al. 2010); thus, none of the corresponding trade-offs can be said to be better than the others. Absent known preferences of the decision makers, additional factors can influence the selection of the best compromise among the Pareto optimal solutions. For example, if the objectives are considered to be of equal importance in the selection process, point C (193 GWh/month, 88 hm^3/y), which is closest to the theoretical "utopian solution", is preferred. If however, economic criteria, such as the price of electricity, are considered, point F (205 GWh/month, 116.6 hm^3/y) is preferred because it maximizes hydropower generation.

6 Conclusions

Computational models are powerful tools that can be used to quantify the interactions within the WEF nexus. They are able to address water resources optimization problems with multiple objectives, by incorporating various management aspects, targets and restrictions into the hydro-system. However, when objectives are conflicting, we need to examine a number of possible trade-offs between them, since no single solution exists that optimizes all objectives simultaneously. Such an examination is performed in the present paper. We used the Hydronomeas tool to investigate the current configuration and a medium-term future scenario in the UBNR basin, where current water resource management is event driven. We optimized the use of water, energy and food considering them as three continuously interacting sectors, following the WEF nexus approach and recognizing their coupled nature and inter-linkages. Although all currently operating reservoirs, HPPs and irrigation projects are located in just two of the 14 sub-basins of the UBNR, the investigation reveals the overall great water resources-hydropower-irrigation potential of the basin. Our simulation and optimization calculations using Hydronomeas generated a Pareto front for the firm hydropower generation and the irrigation deficit of a medium-term future scenario in the UBNR basin. The Pareto front significantly reduces the trade-offs, thus enabling a co-benefit scenario within the concept of WEF nexus. Based on the shape of the Pareto front, and for a case in which the objectives are of equal importance, we propose point C (193 GWh/month, 88 hm^3/y), which is close to the theoretical "utopian solution", as the best compromise. However, if economic criteria, such as the price of electricity, are considered, then point F (205 GWh/month, 116.6 hm^3/y) is preferred because it maximizes hydropower generation. The proposed WEF nexus approach that is based on Pareto optimization can be applied to similar water resource optimization problems with multiple objectives.

It is proposed to extend and improve the present model by including additional important factors, such as economic and social, for the determination of the best compromise solution; for example, via a social cost-benefit analysis. Moreover, the proposed model can be extended to be used for the optimization of the long-term future scenarios that include the full development of the UBNR basin, in which possible climate change effects can also be taken into account.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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