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Optimization of water use based on the water-energy-food nexus concept: Application to the long-term development scenario of the Upper Blue Nile River

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Abstract: We apply a methodological approach for the water resources optimization within the water-energy-food nexus concept in the long-term scenario of the Upper Blue Nile River system in the year 2060 that consists of 37 reservoirs, 23 hydropower and 69 irrigation projects. For the conflicting targets of hydropower production and irrigation deficit, we employ the Hydronomeas tool to create Pareto optimal solutions, which we evaluate via a social cost-benefit analysis to suggest one Pareto optimal solution as the most preferred option. For this solution (i) the hydropower production is nearly 15-times greater than the current, (ii) the irrigation demand is almost 28-times greater than the current, and equal to 9.3% of the average natural river discharge, while the irrigation deficit is equal to 23% of the required amount, and (iii) the average annual discharge to downstream countries is reduced by 10.3% compared to the natural conditions.

Key words: Water-Energy-Food Nexus; Water Resources Management; Pareto Optimization; Social Cost Benefit Analysis

1. INTRODUCTION

The uninterruptedly increasing pressure on our planet´s water, energy and food resources is initiating many conflicts and challenges. We urgently need to comprehend the complex interactions among these valuable resources, diminish their conflicts and maximize the benefits for the various users. For that purpose, the nexus concept was developed that interconnects water, energy and food (Hoff 2011); the purpose of the water-energy-food (WEF) nexus concept is to reassure the smooth interactions of the resources water, energy and food, while reducing the trade-offs among them (Biggs et al. 2015).

The use of mathematical models within the WEF nexus concept may help people world-wide to compute the nexus interdependences and manage water resources efficiently (Bieber et al. 2018). Merging simulation models with optimization models can further assist the investigation of a system by identifying optimal solutions and support the decision-making process. Several such models have been created in recent years, including WEAP (SEI 2011), Hydronomeas (Koutsoyiannis et al. 2002), RiverWare (Zagona et al. 2001), OASIS (HydroLogics Inc. 2009) and MODSIM (Labadie 2010). Among these models, Hydronomeas is distinguished as a compelling tool that can be applied in complex river basins with numerous reservoirs and purposes (Stamou and Rutschmann 2018). The core of the mathematical framework of Hydronomeas is the parameterization-simulation-optimization method (Koutsoyiannis and Economou 2003), while the wider decision support system that Hydronomeas belongs to, incorporates further tools, such as Hydrognomon for data processing and Castalia for synthetic data generation (Koutsoyiannis et al. 2003). Hydronomeas performs one internal, linear optimization incorporated in the simulation procedure, and one external non-linear optimization incorporated in the optimization procedure; Linear Programming (LP) is applied to distribute the state variables within the system in the least expensive way during simulation (Efstratiadis et al. 2004), while during optimization non-linear algorithms are applied to define the control variables of the system using stochastic dynamics and optimize the objective function.

Usually, it is impossible to find just one solution, which can optimize all targets of an optimization problem in real-life at once, considering that such problems involve generally multiple targets that oppose each other. To investigate such optimization problems, we can employ Pareto optimization and examine certain optimal solutions; for these solutions that form a Pareto front, we can improve one of the targets; however, by adversely affecting another target (Reddy and Kumar 2006). In other words, every Pareto optimal solution resembles a trade-off between the targets. According to Chang and Chang (2009) an optimization problem with multiple objectives is frequently converted to multiple single-objective optimization problems, focusing at only one optimal solution each time. If no further information on the preference of the decision makers is presented, the solutions of a Pareto front are thought of as equally good compared to each other (Cheikh et al. 2010).

The Upper Blue Nile River (UBNR) basin is one of the sources of the Nile River; it starts in Lake Tana, Ethiopia, and runs to the South and then to the West, as shown in Figure 1. The river crosses the border of Ethiopia with Sudan with a mean annual flow that represents roughly 60% of the flow of the main Nile River further downstream at Aswan in Egypt (McCartney et al. 2012).

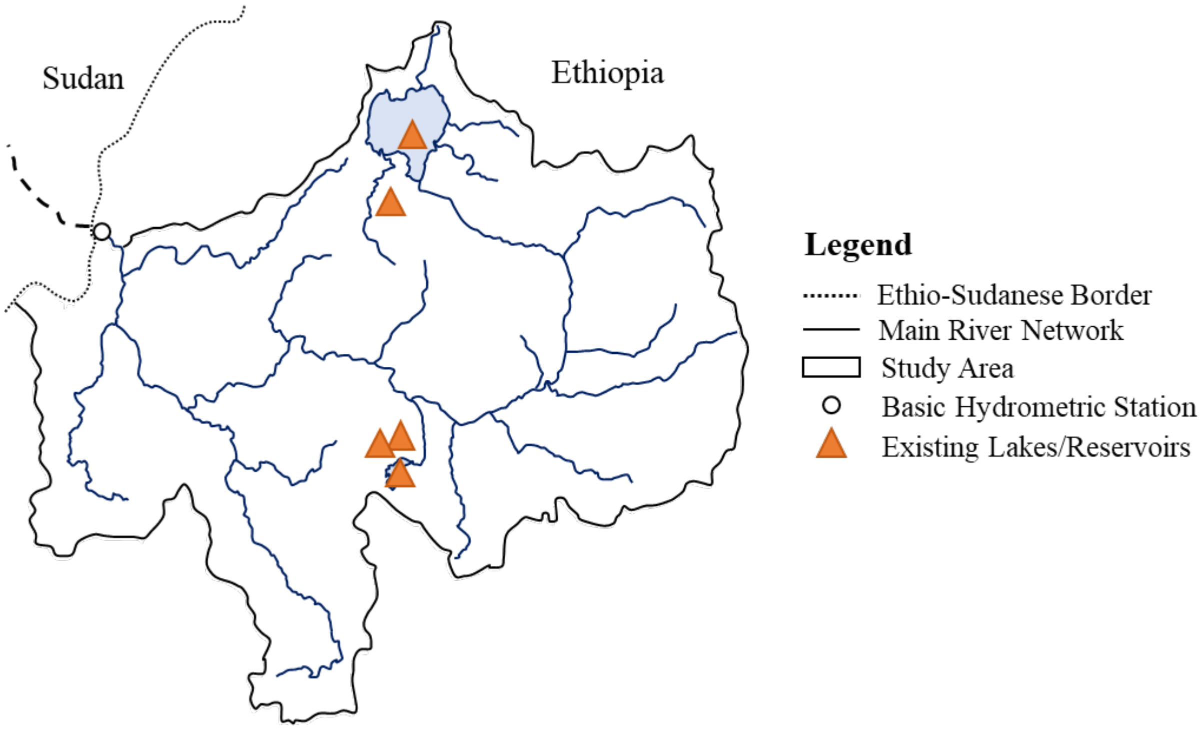

Figure 1. UBNR study area, main river network and existing lakes/reservoirs.

Conflicts of interest define the hydropolitics in the Nile region that is shared by eleven countries. According to Cascão (2012), the conflicts date back to 1959, where an agreement that allocated certain water amounts to Egypt and Sudan was signed that did not consider the remaining riparian countries. In the period 1967-1992, several unsuccessful collaboration efforts were made, while during the decade 1993-2004, the Nile 2002 conference series took place that succeeded in establishing a better foundation to promote collaborations and the exchange of knowledge. In 1997, the Cooperative Framework Agreement started to form that aimed at the sustainable development of the Nile region by forming principles, rights and obligations (NBI 2018). In 1999, the Nile Basin Initiative (NBI) was created to support efficient water management, optimal water use and equitable development in the Nile region, as well as fight poverty, and promote collaborations and economic integration. According to its strategic plan for the period 2017-2027, the main goal of NBI is “to achieve sustainable socio-economic development through equitable utilization of, and benefit from the shared Nile Basin water resources" (NBI 2017). During the last couple of years, the Nile region has come into a new period of challenges, forced by climate change, food and water shortage, and increase in population, water demand and use.

The water resources management in the UBNR is mostly driven by extreme events, such as droughts or floods. Its system has a high hydropower and irrigation potential; the technical hydropower potential is equal to 70,000 GWh/a including the Dinder and Rahad Rivers (McCartney et al. 2012), while the area of the medium- and large-scale irrigation projects with an area with more than 200 ha is estimated to 584,110 ha (BCEOM et al. 1998).

Despite the high potential of the UBNR system, just 5 reservoirs, 5 hydropower projects and 3 irrigation projects operate nowadays in the river basin, as shown in Figure 1 that define the so-called "current conditions" of the system. Since only a small amount of the UBNR system´s potential has been exploited so far, the Ethiopian government intents on implementing multiple projects in the UBNR basin to deal with the increasing population and escalating demand on the food, energy and water resources. The long-term scenario of Ethiopia for the UBNR system consists of altogether 37 reservoirs, 23 hydropower and 69 irrigation projects.

During the last years, various models have been developed for the planning and the management of the UBNR system´s water resources. Nevertheless, the majority of these models were developed to simply simulate the UBNR system, including those of McCartney and Girma (2012), Jeuland and Whittington (2014), King and Block (2014), Wheeler et al. (2016) and Zhang et al. (2016). While some researchers focused only on the simulation of UBNR, other modelling studies focused exclusively on optimization, such as the studies of Whittington et al. (2005), Block and Strzepek (2010) and Goor et al. (2010). Thus, there are only a few studies that implement simultaneously simulation and optimization (Digna et al. 2017); these include the studies of Hassaballah et al. (2012), Georgakakos (2006), Sileet et al. (2014), Stamou and Rutschmann (2018), Stamou (2019), and Stamou and Rutschmann (2019). However, Hassaballah et al. (2012) gave emphasis only on hydropower maximization, while Georgakakos (2006) employed a decision support tool to evaluate the impact of 4 proposed hydropower projects. Sileet et al. (2014) also studied the impacts of proposed projects using a similar tool, the Nile Basin Decision Support System (DSS); however, their study did not utilize the DSS optimization module. Stamou and Rutschmann (2018) performed a series of calculations to develop the Pareto front for the conflicting objectives of hydropower production and irrigation deficit for the medium-term scenario of the UBNR basin that consisted of 7 reservoirs, 5 hydropower and 8 irrigation projects (see Stamou and Rutschmann 2017) and proposed to include additional economic and social factors in the optimization of the hydrosystem for the long-term scenario that was described above. Stamou (2019) improved Stamou and Rutschmann's (2018) calculations via the introduction of an approach that combines Pareto optimization and social cost-benefit analysis for the long-term (full) development scenario within the WEF nexus concept.

In the present work, we apply the methodological approach of Stamou (2019) and answer the following research question: "Which is the most preferred option that produces the highest benefit in the long-term scenario for the UBNR system?". Considering various criteria, we create a Pareto front for hydropower and irrigation, and rank the Pareto optimal solutions employing a social cost benefit analysis. Based on the results, we suggest one solution as the most preferred option with respect to the selected criteria, aiming at supporting decision making in the water resources management of the UBNR.

2. MATERIALS AND METHODS

2.1 Hydronomeas tool

Hydronomeas was developed in the National Technical University of Athens (NTUA) aiming at detecting optimal management policies in complex river basins with various reservoirs and several purposes (Koutsoyiannis et al. 2002, Koutsoyiannis et al. 2003); it encompasses the following 5 key steps that are shown in Figure 2:

1. The user converts the real-world system into a digraph model-network using the various components provided by the tool, such as reservoirs, junctions and river segments, and determines the input data.
2. The operation of the system, e.g. the hydropower production targets, are parameterized.
3. The user formulates the objective function, adopting the parameters of step 2 as control variables.
4. The system is simulated and optimized in accordance to the targets and constrains specified by the user.
5. The objective function solution, namely the performance index of the system, is determined.

The parameterization-simulation-optimization method is the core of the mathematical framework of Hydronomeas (Koutsoyiannis and Economou 2003). The tool performs optimization in 2 stages: (1) the internal linear optimization contained by the simulation procedure, and (2) the external non-linear optimization contained by the optimization procedure.

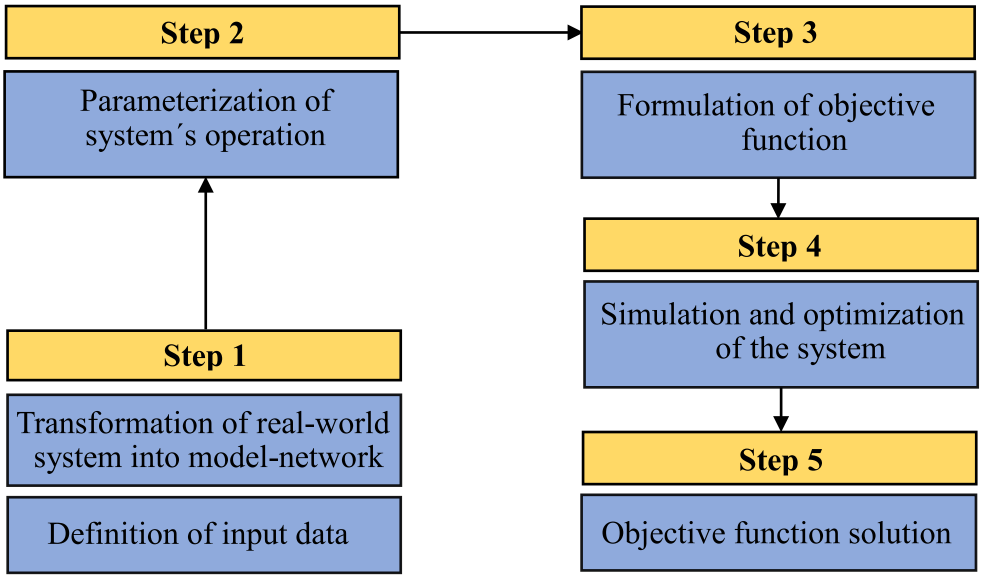

Figure 2. Key steps of Hydronomeas tool (Koutsoyiannis et al. 2002).

Generally, a flow distribution question arises in networks, as the flow can be transferred via multiple routes, while various targets must be fulfilled. During simulation, Hydronomeas uses an LP model to distribute the state variables within the system in the least expensive way (Efstratiadis et al. 2004), while during optimization, non-linear algorithms are applied to define the control variables of the system, e.g. the hydropower production targets, using stochastic dynamics and optimize the objective function. Hydronomeas is a part of the wider decision support system that includes Hydrognomon that is a tool for data processing and Castalia for synthetic data generation and an information subsystem with database, GIS and telemetric system (Koutsoyiannis et al. 2003). The holistic approach of Hydronomeas, which is achieved by incorporating various aspects of water resources management, such as technical and environmental, multiple water use options and targets such as water supply, irrigation and hydropower as well as operating restrictions such as aqueduct capacity and reservoir spill, makes the tool well suited for representing the complexities of the WEF nexus. Hydronomeas has been applied in various studies on water resources planning and management in Greece, including the work of Koukouvinos et al. (2015) for the Acheloos-Peneios region.

2.2 Pareto optimization

River basins with various reservoirs incorporate several, often conflicting targets. In such cases, there is no single solution that can optimize all targets at the same time, and the detection of optimal management policies requires compromises. Consequently, the relations between the conflicting water users and the potential compromises among the targets ought to be examined comprehensively. Pareto optimal solutions are combinations between the targets, i.e. objectives that maximize the objective function. Thus, they represent compromises between the targets and form a Pareto front, where one cannot improve both targets at once (Reddy and Kumar 2006).

In the present work, we create a Pareto front using the WEF nexus concept for the conflicting targets of hydropower production and irrigation deficit. We appoint weights to the objective function criteria to consider various management policies and perform multiple calculations. Thus, we estimate the solution of the objective function, i.e. the performance index of the system, and create the Pareto front that can support decision makers in the process of identifying optimal management policies.

2.3 Social cost-benefit analysis

In the process of Pareto optimization, multiple Pareto optimal solutions might be detected. When no information regarding the decision makers′ preference is given, the Pareto optimal solutions are treated as equally good among each other (Cheikh et al. 2010). Social cost-benefit analysis can be employed to evaluate the Pareto optimal solutions with respect to different criteria. In order to rank the Pareto optimal solutions, their net social benefits are assessed by applying the net social benefits criterion; thus, calculating the positive impacts, i.e. social benefits, and the related costs, i.e. social costs, and subsequently subtracting the total costs from the total benefits. According to the net social benefits criterion, only solutions with positive net social benefits ought to be accepted, since they implicate an improvement in economic efficiency (EPA 2010). The solution with the highest positive benefits is the most preferable option with respect to the selected criteria and welfare enhancing according to the Kaldor Hicks criterion. Monetary terms can be used to estimate the benefits and costs of the Pareto optimal solutions and compare them among each other.

In the present work, we evaluate a Pareto front, and suggest one Pareto optimal solution as the best option, by appointing monetary values to the targets of hydropower and irrigation. Thus, we apply measurable economic units and estimate the benefit from hydropower production using the kWh-export price. For the estimation of the cost from irrigation deficit, we develop a tool that considers the crop characteristics and comprises of the key steps shown in Figure 3 and described below. Initially, the user determines the key variables, such as the number of crops, cropping patterns and irrigation projects as well as the simulation period, and inserts the necessary irrigation data into the program, such as the general input data, e.g. crop prices, and the data of the Pareto optimal solutions, e.g. irrigation deficit.

The performed calculations are categorized in water requirement calculations and water deficit calculations. In the water requirement calculations, we estimate (1) the irrigated area of each irrigation project and crop, (2) the water requirement of each irrigation project, month and crop, (3) the monthly water requirement, irrigation area, and 'water needs per ha' of each crop. In the water deficit calculations, we estimate (1) the water deficit of each project, simulation month and crop, (2) the non-irrigated areas of each crop due to the calculated water deficit, (3) the non-produced quantities of each crop due to the non-irrigated areas, (4) the income loss of each crop due to the non-produced quantities, and (5) the total income loss. The total income loss represents the cost from irrigation deficit for each Pareto optimal solution.

For a second simplified approach, we introduce the Net Return (NR) as an indicator to quantify the cost from irrigation deficit. The NR is considered equal to 0.05 US$/m^3; this value is consistent with international experience (Whittington et al. 2005, Goor et al. 2010). Thus, we estimate the cost from irrigation deficit by multiplying the NR with the irrigation deficit of each Pareto optimal solution.

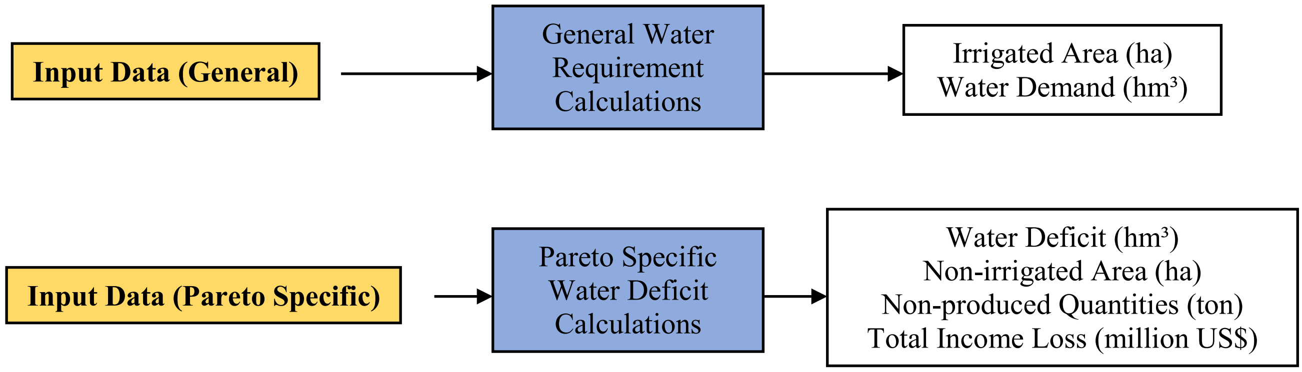

Figure 3. Estimation of the cost from irrigation deficit.

2.4 Data collection in the Upper Blue Nile river system

Data collection in the area of study was particularly challenging. We collected the majority of the required data via on site visits in Ethiopia, that included the Ministry of Water, Irrigation and Electricity, the Addis Ababa University, the Bahir Dar University, the Abbay Basin Authorities, the Eastern Nile Technical Regional Office, as well as project and construction sites, such as the Grand Ethiopian Renaissance Dam. Also, we collected data from the International Water Management Institute, the Food and Agriculture Organization of the United Nations and the literature.

The main data included (a) river discharges, (b) reservoir data, i.e. inflows, outflows, rainfall, evaporation, catchment area, spill-initial-intake elevation, elevation-volume and elevation-area curves, (c) hydropower project data, i.e. installed capacity, discharge capacity, head, (d) irrigation project data, i.e. location, area, irrigation demand, cropping pattern, crops, crop yield, (e) economic data, e.g. kWh-export price, crop prices, and (f) environmental as well as social targets and constraints, e.g. ecological flows, maximum and minimum reservoir operation levels.

3. RESULTS AND DISCUSSION

3.1 Simulation and optimization calculations

Using the collected data, we performed the schematization of the UBNR system for the long-term scenario that is shown in Figure 4; our system consists of 37 reservoirs with a total reservoir capacity of 221,452 hm^3, 23 hydropower projects with an installed capacity of 14,214 MW, and 69 irrigation projects with an annual irrigation of 4,568 hm^3/a, 25 crops, 7 irrigation patterns and an area of 584,110 ha. Among the hydropower projects, the Grand Ethiopian Renaissance Dam that is situated close to the border between Ethiopia and Sudan, covers approximately 42% of the installed capacity. Approximately, 50% of the potential irrigation area is identified in the north-west of the basin, while there are areas in the eastern part, where no irrigation projects are identified. The kWh-export price was set equal to 0.08 US $/kWh (Goor et al. 2010), while the crop prices fluctuate between 90 and 1,200 US $/ton.

We applied Hydronomeas to (a) maximize the total firm hydropower production and (b) minimize the average annual irrigation deficit, which is the water that does not reach the irrigation projects and thus, fails to serve the chosen target.

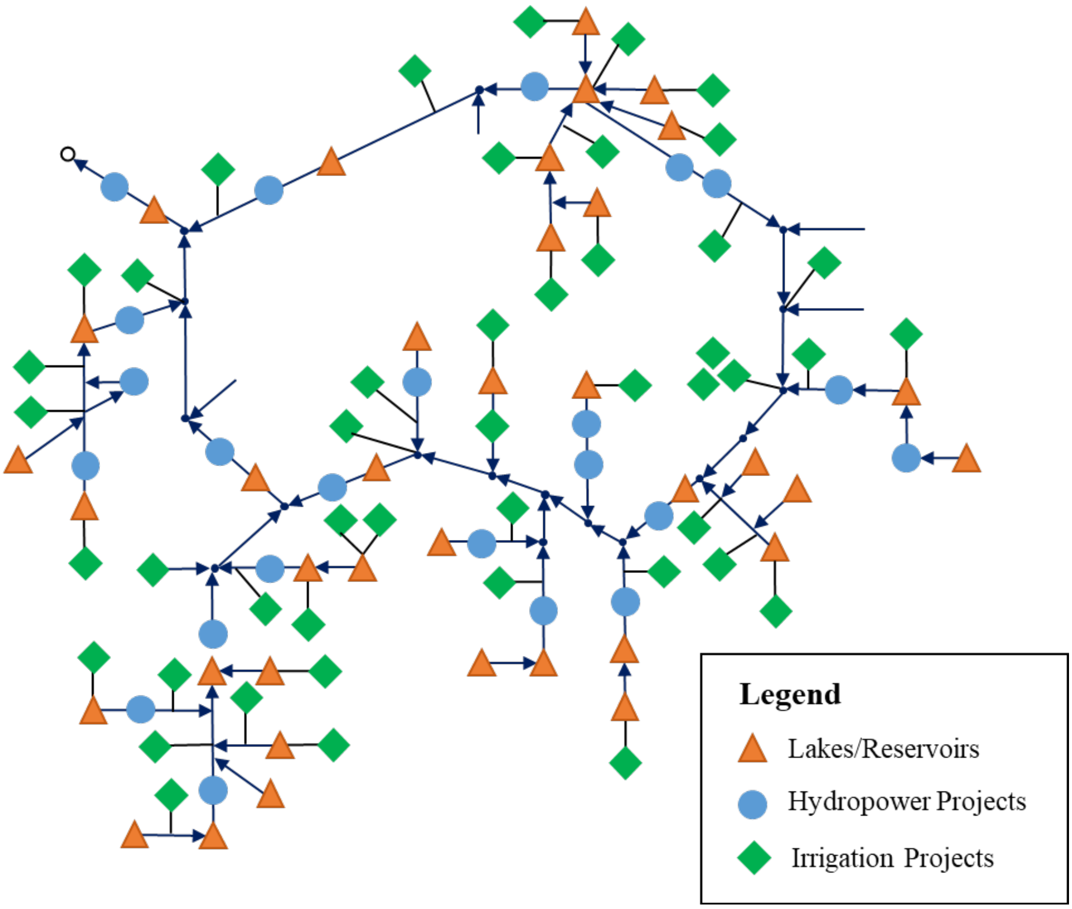

Figure 4. Long-term scenario of the UBNR system.

For the river discharges, we generated synthetic time series of 1,000 years based on historical data of the years 1968-1992 and using the Castalia tool (Efstratiadis and Koutsoyiannis 2002).

For the optimization of the UBNR, we appointed various targets and constrains in the system considering different aspects. Firstly, we appointed targets to the hydropower and irrigation projects that have an influence on the region´s electricity production and food security, and thus on life quality (Stamou and Rutschmann 2017). For reservoirs, we set minimum ecological flows considering social and political issues, such as the minimum ecological flow at Lake Tana in the North of the UBNR system to provide adequate water for the Blue Nile falls downstream. For Lake Tana, we also set a minimum reservoir level to permit navigation. Each target and constraint received levels of priority. The agricultural sector is considered especially important in Ethiopia; thus, it was assumed that irrigation projects receive a higher level of priority than hydropower projects or the constraint of minimum ecological flow.

For the conflicting targets of hydropower production and irrigation deficit, we performed 101 optimization calculations of the UBNR system for the long-term scenario of Figure 4, selecting different sets of weights to consider different management policies.

3.2 Pareto optimization results

Based on the 101 series of calculations, we developed a Pareto front with 9 Pareto optimal solutions within the WEF nexus concept that are shown in Figure 5 (orange circles).

The Pareto optimal solutions "1" to "9" correspond to feasible solutions and can support decision makers in the process of identifying optimal management policies. Near solution "1" a slight increase in irrigation deficit causes a significant improvement for hydropower production, while near solution "9" a slight decrease in hydropower production causes a significant improvement for irrigation.

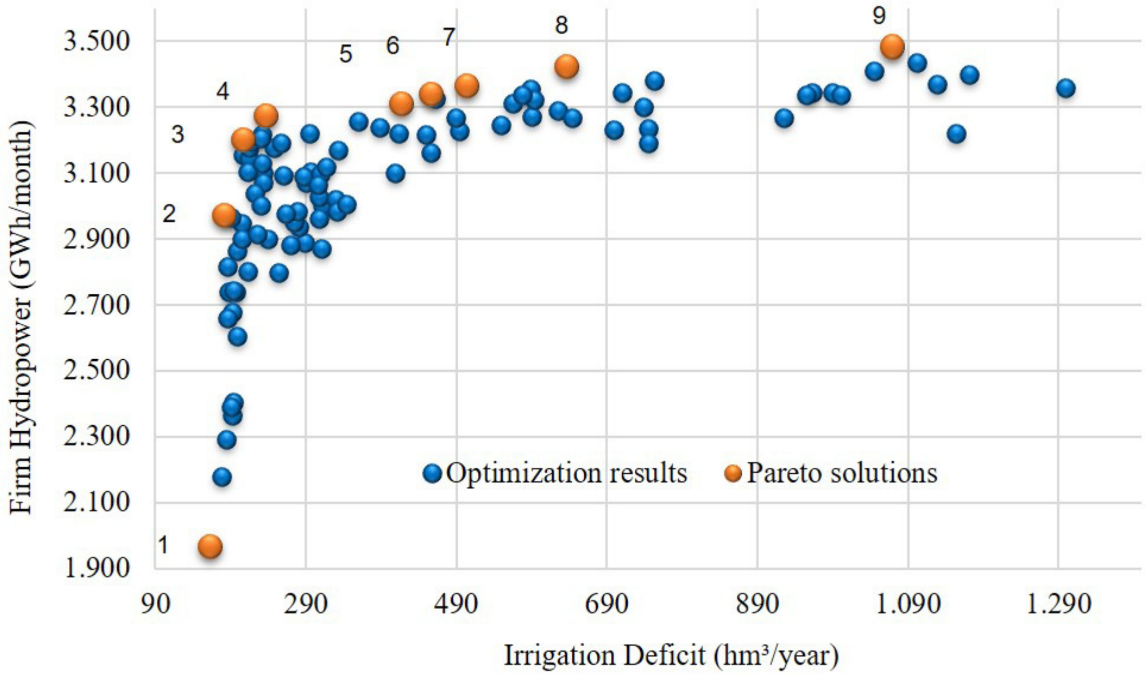

Figure 5. Pareto optimal solutions for the long-term scenario in the UBNR system.

The mean annual hydropower production of the Pareto optimal solutions "1" to "9" ranges from 43,711 to 47,749 GWh/a, the actual irrigation amount from 3,499 to 4,406 hm³/a, the annual irrigation deficit from 162.0 to 1,069.0 hm³/a, and the mean monthly discharge at the border of Ethiopia and Sudan from 1,333 to 1,401 m³/s. Pareto optimal solution "1" that yields a hydropower production of 1,966.9 GWh/month and an irrigation deficit of 162.0 hm³/a denotes a management policy, where irrigation is more significant, and the UBNR follows more its natural regime. On the contrary, for Pareto optimal solution "9" that yields a much higher hydropower production than solution "1", i.e. 3,479.6 GWh/month, and a much higher irrigation deficit, i.e. 1,069.0 hm³/a, hydropower production plays a more vital role, and the UBNR regime changes to a more evenly distributed flow throughout the year. The Pareto optimal solutions "2" to "8" correspond to intermediate cases.

3.2 Social cost-benefit analysis results

For the evaluation of the Pareto front of Figure 5, we carried out a social cost-benefit analysis and suggested a single Pareto optimal solution as the most preferred option for the long-term scenario of the UBNR system. We applied measurable economic units to the hydropower production and irrigation deficit of each Pareto optimal solution "1" to "9" and estimated their net benefits that are shown in Table 1 and 2, respectively for the 2 suggested approaches. More specifically, using the kWh-export price, we estimated the benefit from hydropower production that fluctuates between 1,888 million and 3,340 million US $/a for the Pareto optimal solutions "1" to "9".

For the cost from irrigation deficit, we first estimated the non-irrigated area and the non-produced quantities of crops, which vary from 8,533 to 45,602 ha/a, and from 72,200 to 573,140 ton/a, respectively, for the Pareto optimal solutions "1" to "9". The resulting cost from irrigation deficit for the Pareto front of Figure 5 fluctuates between 11.8 million and 75.3 million US $/a. Furthermore, we calculated the equivalent annual capital cost and the operating and maintenance cost of the irrigation projects that equal 282 US $/a and 108 million US $/a, respectively. The corresponding equivalent annual capital cost and the operating and maintenance cost of the hydropower projects equals 1,657 million US $/a and 285 million US $/a, respectively. The resulting net benefits for the Pareto optimal solutions “1” to “9” for this approach vary from -444 to 944 million US $/a as shown in Table 1.

Table 1. Net benefits (million US $/a) for the Pareto optimal solutions “1” to “9”.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Net benefit (million US $/a)	- 444	519	739	804	821	848	873	918	**944**

For the second simplified approach, we quantify the cost from irrigation deficit using the NR, and the resulting cost from irrigation deficit for the Pareto front of Figure 5 fluctuates between 8.1 million and 53.4 million US $/a. Thus, the resulting net benefits for the Pareto optimal solutions “1” to “9” for the second approach vary from -441 to 966 million US $/a as shown in Table 2.

Table 2. Net benefits (million US $/a) for the Pareto optimal solutions “1” to “9” (simplified approach).

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Net benefit (million US $/a)	-441	523	744	810	838	866	885	937	**966**

Regardless the approach that is used to calculate the cost from irrigation deficit, the Pareto solution “9” is the option that yields the highest net benefit according to the chosen criteria, i.e. 944 and 966 million US$/a for the first and second approach, respectively. Thus, we suggest the Pareto optimal solution “9”, which generates the highest net benefits for the long-term scenario of the UBNR system, as the most preferred option with respect to the selected criteria; thus, hydropower is prevailing.

3.3 Suggested Pareto optimal solution

The Pareto optimal solution “9” from Figure 5 is suggested as the most preferred option with respect to the selected criteria, since it generates the highest net benefits for the long-term scenario of the UBNR system. According to the optimization calculation, the Pareto optimal solution “9” yields a hydropower production of 47,749 GWh/a. Furthermore, the estimated annual irrigation demand and the actual irrigation amount are equal to 4,568 hm³/a and 3,499 hm³/a, respectively, resulting to an irrigation deficit of 1,069 hm³/a. The average annual discharge at the border between Ethiopia and Sudan for Pareto optimal solution “9” amounts to 44.2 km³/a, while the flow regime for this solution shows an almost even distribution throughout the year.

We compared our results with the results of Goor et al. (2010), McCartney et al. (2012) and Arjoon et al. (2014). Goor at al. (2010) studied seven hydropower projects, including the four large hydropower projects in the main UBNR, and calculated a 11 % lower hydropower production, namely 42,500 GWh/a (from figure). McCartney et al. (2012) also studied fewer reservoirs and ignored the Grand Ethiopian Renaissance Dam, while their estimated irrigation area accounted for 461,000 ha. Thus, they calculated a 34% lower annual hydropower production, i.e. 31,297 GWh/a, a 17% lower annual irrigation amount, i.e. 3,810 hm³/a, and a flow at the border between Ethiopia and Sudan that equals 42.7 km³/a; an amount that is 6% lower in comparison to natural conditions of the UBNR in their study. The observation that the flow regime of the UBNR at the border between Ethiopia and Sudan changes to a more even distribution in future scenarios compared to its natural conditions, was also made by Goor et al. (2010) and Arjoon et al. (2014).

To evaluate the effects that the Pareto optimal solution “9” would have for the UBNR system, we also compared its results with the UBNR natural and current conditions. Some of the effects mentioned below were also observed by other researchers, such as NBI (2012), Whittington et al. (2014), Beyene (2013), Egyptian Chronicles (2013), Ethiopian NPoE (2013), Blackmore and Whittington (2008), Wheeler et al. (2016), Mulat and Moges (2014), and Block and Strzepek (2010). The hydropower production of the 23 hydropower projects that amounts for 47,749 GWh/a in the Pareto optimal solution “9” is nearly 15-times greater than the hydropower produced in the current conditions. This increase in hydropower production is expected to have an influence on the kWh-price as well as the electricity access in the region. Furthermore, the annual irrigation demand for the 69 irrigation projects in the long-term scenario of the UBNR system that is estimated to 4,568 hm^3/a, is 28-times greater than the current demand that equals 164 hm^3/a. The current annual irrigation requirement of the three existing irrigation projects amounts to less than 1% of the average UBNR flow in its natural conditions, while the respective requirement in the long-term scenario with the 69 irrigation projects amounts to 9.3%. This increase in annual irrigation requirement, together with the increase in evaporation losses due to the construction of the 32 new reservoirs, are expected to reduce the average annual discharge at the border between Ethiopia and Sudan by 10.3% in comparison to the natural UBNR conditions. Due to this flow decrease, the risk of deficiency in recessional agriculture for Sudan and the risk of lower hydropower production in Egypt increase.

The construction of new infrastructure projects is expected to cause further impacts to downstream countries. The UBNR regime changes to a more evenly distributed flow throughout the year with a standard deviation of 11 m^3/s, which accounts for roughly 1% of the average value. This change is likely to increase the flow reliability for downstream countries and reduce the threat of extreme events such as flooding and droughts, while reducing the cost of water pumping, and enhancing navigation and the efficiency of hydropower projects in Sudan. Furthermore, the sediment amount in downstream countries is also expected to be affected by the new infrastructure projects; a fact that is positive in terms of reservoir and agricultural management, but also undesirable in terms of soil fertility or brick production. The filling of larger reservoirs, and especially the filling of the Grand Ethiopian Renaissance Dam, is also likely to cause challenges in flow availability downstream. Thus, the procedure of reservoir filling should be performed with caution. As already noted by other researchers (Bates et al. 2013, MIT 2014), there is certainly a need for more independent investigations within the Nile region, as well as for political dialogue considering multiple aspects (Whittington et al. 2005).

Our social cost-benefit analysis calculations for the Pareto optimal solution “9” show a total non-irrigated area and non-produced quantity of crops equal to 45,602 ha and 573,140 ton/a, respectively. Furthermore, the benefit from hydropower production equals 3,340 million US $/a, the cost from irrigation deficit equals 75.3 million US $/a and 53.4 million US $/a for the first and second approach, respectively, while the total net benefits amount for 944 million US $/a and 966 million US$/a for the first and second approach, respectively. Maize, sugarcane and wheat comprise the three most significant crops during irrigation, covering almost 50% of the total irrigated area. Together with rice and sunflower, they represent the highest part of the non-produced quantities of crops, while together with onion and rice they cause the highest cost from irrigation deficit.

4. CONCLUSIONS

The increasing pressure on our planet´s water, energy and food resources illustrates the urgent need to comprehend their complex interactions, diminish their conflicts and maximize the benefits for all users as part of an appropriate water resources management plan within the WEF nexus concept. The importance of an appropriate water resources management plan increases in cases such as the UBNR system, where a high potential in water resources, hydropower and irrigation is observed, whose utilization might cause conflicts among the riparian countries.

In the present work, we constructed a Pareto front within the WEF nexus concept for the conflicting targets of hydropower production and irrigation deficit in the long-term scenario of the UBNR. Nine Pareto optimal solutions constitute the Pareto front for this scenario, where the UBNR system consists of 37 reservoirs, 23 hydropower projects and 69 irrigation projects. By conducting a social cost-benefit analysis to evaluate the Pareto front, we suggest the Pareto optimal solution “9” as the most preferred option with respect to the selected criteria, since it generates the highest net benefits for the UBNR system, i.e. 944 and 966 million US$/a for the first and second approach, respectively. We anticipate that solution “9” with the highest hydropower production is likely to be viewed as the most preferred option in similar study cases, but also in transboundary river cases with a preference in hydropower production in the upstream part of the river. The hydropower produced in the Pareto optimal solution “9” is nearly 15-times greater than the hydropower produced currently; this is expected to have an influence on the kWh-price as well as electricity access in the entire region. The construction of new infrastructure projects is expected to cause further impacts to downstream countries. The increase in evaporation losses due to the construction of new reservoirs and the annual irrigation demand that is 28-times greater than the current, are expected to reduce the average annual discharge to downstream countries by 10.3% compared to the natural conditions. The filling of larger reservoirs, and especially the filling of the Grand Ethiopian Renaissance Dam, is also likely to cause challenges in flow availability downstream. The UBNR regime that changes to a more evenly distributed flow throughout the year is likely to increase the flow reliability for downstream countries, reduce the threat of extreme events such as flooding and droughts, and enhance hydropower efficiency.

The methodological approach that is based on the combination of Pareto optimization and social cost-benefit analysis might prove as a useful tool for similar water resources optimization problems with multiple targets. We propose the expansion of the model to investigate the suggested option in the long-term scenario of the UBNR system considering the effects of climate change as well as the transient conditions of reservoir filling.

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