Lehrstuhl für Wasserbau und Wasserwirtschaft

Water Resources Optimization using the Nexus Approach
A Case Study of the Upper Blue Nile River Basin, Ethiopia

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Vollständiger Abdruck der von der Ingenieurfakultät Bau Geo Umwelt der Technischen Universität München zur Erlangung des akademischen Grades eines Doktors-Ingenieurs genehmigten Dissertation.

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Prüfende der Dissertation:

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Die Dissertation wurde am 05.10.2018 bei der Technischen Universität München eingereicht und durch die Ingenieurfakultät Bau Geo Umwelt am 25.01.2019 angenommen.

Abstract

The continuously increasing world population combined with the consequential economic growth and urbanization exert great pressure on the water, energy and food resources of our planet. This shows the urgent need for proper water resources management within the water-energy-food (WEF) nexus concept that considers water, energy and food as three interconnected sectors. The interactions among these sectors lead to an increased number of trade-offs and potential conflicts. Mathematical modeling can be combined with economic tools to quantify these complex interactions, support collaborations, decrease trade-offs, and propose optimized solutions for hydro-systems. In the present thesis, the water resources in the Upper Blue Nile River (UBNR) basin, which is characterized by a very high potential for water resources development, is investigated for four scenarios: natural, current, short- to medium-term and full development. The Hydronomeas model is verified and applied to produce Pareto optimal solutions of the firm hydropower production and irrigation deficit. A relatively small number of optimized solutions are compared via a social cost-benefit analysis to determine the most preferable solution in the full development. The net social benefits criterion is used to quantify and compare the net benefits for the society (hydropower production - irrigation deficit). The full development consists of 37 reservoirs (total volume: 221,452 hm^3), 23 hydropower projects (total installed capacity: 14,214 MW), and 69 irrigation project groups (total net area: 584,110 ha). For the proposed solution, the hydropower production is equal to 47,749 GWh/y, i.e. almost 15 times higher than the amount produced currently. Moreover, the actual irrigation amount is equal to 3,499 hm^3/y, i.e. 9.3% of the average river discharge of the natural conditions (49.3 km^3/y), while the irrigation deficit is equal to 23% of the required amount. Due to the increased water consumption for irrigation and increased evaporation losses, river discharges to downstream countries are reduced by 10.3%. The storage in the reservoirs provides increased control over the natural flow pattern (the standard deviation of monthly discharges is reduced from 124% to less than 1% of the average value) and thus, reduced risk for flooding and droughts to the downstream countries, while the hydropower production in the HPPs is likely to increase access to electricity and lower electricity costs in the wider region.

Keywords Water Resources Management · Nexus · Pareto Optimization · Social Cost-Benefit Analysis · Hydronomeas · Upper Blue Nile River

Zusammenfassung

Eine ständig wachsende Weltbevölkerung, die fortschreitende Urbanisierung und die globale wirtschaftliche Entwicklung verlangen eine effektive Planung und Steuerung der Ressource Wasser, sowie der Energie- und Nahrungsproduktion. Als effektives Konzept zur Wasserbewirtschaftung hat sich das *Water-Energy-Food* (*WEF*) Nexus entwickelt. Das WEF Nexus-Konzept betrachtet die Wassernutzung, sowie die Energie- und Nahrungsmittelproduktion als drei vernetzte Bereiche, die in ständiger Wechselwirkung zueinanderstehen und deren komplexe Beziehungen öfters zu Priorisierungskonflikten führen. Mithilfe von mathematischen Modellen und wirtschaftlichen Instrumenten können diese Wechselwirkungen quantifiziert werden. Somit ist es möglich, Kompensationsmaßnahmen zu treffen, Synergien zu begünstigen und es können optimierte Lösungen für Wassersysteme vorgeschlagen werden. In der vorliegenden Arbeit wurde die Verteilung der Wasserressourcen des Oberen Blauen Nils in vier Szenarien untersucht. Hierfür wurde der natürliche, der gegenwärtige, ein mittelfristiger Zustand, welcher die Auswirkungen der aktuellen Baumaßnahmen berücksichtigt, und der voll ausgebaute Zustand des Einzugsgebietes analysiert. Die Software Hydronomeas wurde verwendet, um Pareto-optimale Lösungen für die betriebliche Wasserkrafterzeugung und das Bewässerungsdefizit zu gewinnen. Für den voll ausgebauten Zustand wurden Pareto-optimale Lösungen erzeugt und mittels einer sozialen Kosten-Nutzen-Analyse bewertet. Dabei wurde die Netto-Nutzen-Differenz-Analyse angewandt, in der der Netto-Nutzen (Wasserkrafterzeugung minus Bewässerungsdefizit) quantifiziert wird. Dadurch kann die Lösung, welche den größten Netto-Nutzen aufweist, bestimmt werden. Der voll ausgebaute Zustand besteht aus 37 Speichern mit einem Gesamtvolumen von 221.452 hm³, 23 Wasserkraftwerken mit einer installierten Gesamtleistung von 14.214 MW und 69 Bewässerungsprojekten mit einer Netto-Gesamtfläche von 584.110 ha. Die Energieerzeugung aus Wasserkraft könnte bei der vorgeschlagenen Lösung auf 47.749 GWh/a gesteigert werden, was in etwa der 15-fachen gegenwärtig produzierten Menge entspricht. Damit könnten der Stromzugang verbessert und die Stromkosten in der Region gesenkt werden. Des Weiteren beträgt die Bewässerungsmenge 3,499 hm³/a und entspricht somit 9,3% des mittleren Abflusses des oberen Blauen Nils im natürlichen, also unverbauten Flusszustand (49,3 km³/a). Das Bewässerungsdefizit beträgt für diese Lösung 23% des Bewässerungsbedarfs. Aufgrund des erhöhten Wasserverbrauchs für die Bewässerung und der höheren Verdunstungsverlusten in den Speichern, würde der Abfluss an die flussabwärts liegenden Länder um ca. 10,3% reduziert werden. Durch die Nutzung der vorgesehenen Speicher ist eine verbesserte Kontrolle des natürlichen Fließzustands möglich (die relative Standardabweichung der monatlichen Durchflüsse wird von 124%

auf weniger als 1% reduziert), wodurch die Risiken von Überschwemmungen und Dürren für die flussabwärts liegenden Länder reduziert werden könnten.

Schlagwörter Wasserressourcen Management · Nexus · Pareto Optimierung · soziale Kosten-Nutzen-Analyse · Hydronomeas · Oberer Blauer Nil

Acknowledgements

First, I would like to express my special appreciation and thanks to my supervisor Professor Dr. sc. techn. Peter Rutschmann, who offered me such a great opportunity to join the Chair of Hydraulic and Water Resources Engineering of the Technical University of Munich (TUM), and gave me his support throughout my whole thesis. I would also like to express my gratitude to Professor Dr.-Ing. Wolfgang Kinzelbach for his insightful comments and for sharing with me his experience. A special thank you goes also to the chairman of my examination committee, Professor Dr.-Ing. Markus Disse.

I would also like to thank the professors from the National Technical University of Athens (NTUA) for their support and advice during my three-month stay in Athens and during my whole thesis. I am thankful to Professor D. Koutsoyiannis for the opportunity to visit NTUA, Professor N. Mamassis for the interesting and constructive discussions, Dr. A. Efstratiadis, and Mr. D. Nikolopoulos for sharing with me their experience with the Hydronomeas tool. Moreover, I am grateful to Professor D. Kaliambakos and Professor D. Damigos for their insightful suggestions in the social cost-benefit analysis field. I would also like to thank Professor E. Baltas and Professor G. Tsakiris for their valuable comments.

I am also grateful to the Ministry of Water, Irrigation and Electricity (MOWIE) of Ethiopia, the Abbay authorities in Bahir Dar, the Eastern Nile Technical Regional Office (ENTRO) in Addis Ababa, Dr. B. Kidanewold from the Addis Ababa Institute of Technology (AAIT), the Bahir Dar University, Mr. D. Fenta, Ms. M. Melaku, Mr. F. Teshome, the International Water Management Institute (IWMI) and more specifically Mr. M. McCartney, and Mr. O. Tarabih for providing me with the main data for this thesis.

Thanks are due to the German Research Foundation and the International Graduate School of Science and Engineering (IGSSE - GRC 81), and the Chair of Hydraulic and Water Resources Engineering of TUM for their financial support. I also extend my gratitude to the German Academic Exchange Service (Deutscher Akademisher Austauschdientst, DAAD) and the NeXus project that financed my trips to Ethiopia.

I would also like to thank my lab mates at the Dieter Thoma Laboratory, Sebastian Roenneberg, Stephan Hoetzl, Tobias Schechtl, Thomas Siewert and Sardar Ateeq, as well as Dr. W. Knapp, Dr. C. Rumbaur and Edward Duggan for their continued support.

Last but not least, a special thanks to my family, my parents Tassos and Gianna, to my brother Giannis, and to Giorgos for their love and endless support.

Content

1 Introduction

1.1 Background

The current world population of 7.6 billion people (Worldometers 2017) is expected to increase to almost 10 billion in 2050. The continuously increasing world population together with the consequential economic growth and urbanization exert great pressure on the food, energy and water resources of our planet, and deepen the conflicts among them. The international community established the water-food-energy (WEF) nexus concept during the Bonn 2011 Nexus Conference “The water, energy and food security nexus: solutions for the green economy” (Hoff 2011) to deal with the conflicts that arise among the three sectors due to these social pressures as well as climate change (Block and Strzepek 2010, Jeuland and Whittington 2014, Wondimagegnehu and Tadele 2015, Conway 2000). The WEF nexus interconnects water, energy and food, and states that actions in one sector have impacts in one or both the others (FAO 2018). The concept aims at encouraging synergies and decreasing trade-offs among the three sectors (Biggs et al. 2015). Although significant improvement has been made in implementing the WEF nexus concept in the past years, many challenges persist, mainly related to the complexity in understanding and describing the interactions among the sectors, balancing the interests of the various users while maintaining the integrity of the ecosystem, and developing tools that address the involved trade-offs (FAO 2014, Liu et al. 2017).

Mathematical models can be used as means to quantify the WEF nexus interconnections and assist decision makers (Bieber et al. 2018). Simulation models can be combined with optimization to study a hydro-system, identify optimum solutions and assist viable decision making. Since real-life optimization problems consist of more than one objective that are usually conflicting, it is generally not possible to find only one solution that optimizes all objectives at the same time. Thus, Pareto optimization can be applied in order to study multiple optimal solutions that correspond to various trade-offs between the objectives. For all Pareto optimal solutions, i.e. Pareto front, one objective can only be improved at the expense of another (Reddy et al. 2006). Multi-objective optimization problems are often transformed to single-objective optimization problems, where emphasis is given to one Pareto optimal solution at a time (Chang and Chang 2009).

Among the various models that have been developed in recent years, Hydronomeas is prevailing as a powerful tool that can be applied in the management of complex hydrosystems with multiple targets. It is the core of a broader Decision Support System (DSS) that includes tools for data processing, i.e. Hydrognomon, and synthetic data generation, i.e. Castalia (Koutsoyiannis et al. 2003). The mathematical framework of Hydronomeas is based on the low-dimensional Parameterization-Simulation-Optimization (PSO) method (Koutsoyiannis and Economou 2003); optimization is performed in two levels using multiple criteria. Simulation is used to obtain values of the objective function, i.e. performance index, in a linear optimization procedure; the objective function is then optimized by a nonlinear optimization. In more detail, the cost of water transfer in the model network is optimized during simulation according to the management policies and using linear programming. The physical constraints, targets in priority order and operating restrictions are thereby taken into account. The simulation ensures precision and high-speed calculations without excessive data requirements. Moreover, parameterization allows for the introduction of a low number of unknown parameters in the hydro-system, e.g. for the reservoir operating rules or the hydropower targets, which are determined in a nonlinear optimization procedure. By reducing the degrees of freedom, the curse of dimensionality is avoided. Multi-objective optimization problems can be examined by incorporating various criteria in the performance index, i.e. reliability, firm hydropower production or irrigation deficit, to detect Pareto optimal solutions. The holistic approach of Hydronomeas is one of its further advantages that allows the introduction of various water resources management features (e.g. technical, economic, environmental), various objectives for water use (e.g. water supply, irrigation, hydropower) as well as operating restrictions (e.g. aqueduct capacity, reservoir spill) that make the model suitable for demonstrating the complexities of the WEF nexus.

All Pareto optimal solutions are considered equally good, when additional subjective preference information is not available (Cheikh et al. 2010). Thus, further factors can influence the selection of the best compromise among the Pareto optimal solutions (Stamou and Rutschmann 2018). In this thesis, a systematic framework is proposed, in which Pareto optimization is combined with Social Cost-Benefit Analysis (SCBA) to identify the most preferable Pareto optimal solution. The net social benefits (NSB) criterion is used in order to evaluate the Pareto optimal solutions; the favorable effects (social benefits) and the associated losses (social costs) of each Pareto optimal solution are estimated. Subtracting the total costs from the total benefits, provides an estimate of the NSB to society. The NSB criterion suggests that one should adopt only those solutions that have positive NSB. The adoption of a solution with positive NSB involves an improvement in economic efficiency. Thus, the most preferable Pareto optimal solution is the one that yields the highest positive NSB and is considered welfare enhancing according to the Kaldor Hicks criterion (EPA 2010). The key to performing SCBA lies in the ability to measure the benefits and costs of the Pareto optimal solutions in monetary terms to make them comparable. Thus, the economic benefit of hydropower and the cost of irrigation deficit are quantified in terms of net economic benefit using measurable economic units and are compared to each other in order to contribute useful information to the decision-making process about how the resources can be put to the best social use.

In the present work, a multi-objective optimization system was designed for the Upper Blue Nile River (UBNR) basin, one of the two main sources of the Nile River, where water resources management is event driven. Various such models have been developed in recent years regarding the water resources planning and management within the UBNR basin (Stamou and Rutschmann 2018). The majority of these models are, however, 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). Further studies deal solely with optimization (Whittington et al. 2005, Block and Strzepek 2010, Goor et al. 2010). Digna et al. (2017) identified only few studies that consider both simulation and optimization. Some of the more prominent, recent works include (1) the study of Hassaballah et al. (2012) that focused on the maximization of hydropower, (2) the study of Georgakakos (2006) that used the Nile River basin decision support tool to assess the hydropower influence of four proposed hydropower plants (HPPs). Moreover, Sileet et al. (2014) used the Nile Basin DSS to investigate the impacts of planned projects; without, however, applying the optimization module of the DSS. Identifying the limitations of past studies, this thesis focuses on the combined analysis of the PSO method, Pareto optimization and social cost-benefit analysis, to analyze the water resources in the UBNR basin within the nexus concept by taking into account ecological, economic, social and political criteria.

The present work was funded by the German Research Foundation through the International Graduate School of Science and Engineering (GRC 81) of the Technical University of Munich. The research was carried out in the framework of a larger project on water resources management of the Nile River Basin also referred to as NIMA-NEX (NIle MAnagement Nexus EXpert tool).

1.2 Objectives and Research Questions

The main objectives of the present work are the following: (1) the management and optimization of water resources, and specifically of reservoirs, hydropower and irrigation projects in a river basin within the nexus concept, (2) the optimization of water allocation to hydropower (energy) and irrigation (food), and (3) the maximization of economic, ecological and social benefits. By achieving these objectives, a better understanding of the river basin as well as a common point of reference, thus improved management policies, are to be gained.

The objectives aim at answering the following four main research questions.

“Which are the most likely water resources development scenarios for the UBNR basin?” Little use is made currently of the UBNR waters. According to the Abbay Master Plan Studies (BCEOM et al. 1998), however, this is to change in the future, when the consumptive water use, e.g. irrigation, will increase. Possible water resources development scenarios are presented for the period 2016-2060. The scenarios include various water demand sites and targets, e.g. hydropower production and irrigation, as well as ecological flows.

“What are the optimal solutions to allocate water resources between the conflicting users?” Current water resource management in the UBNR basin is largely event-reactive. By implementing new projects in the river basin in the future, the need of proper management and water resources allocation will grow. Pareto fronts are created for the possible water resources development scenarios. The Pareto fronts include optimal solutions and will help decision makers allocate the water among the targets, without having to consider the whole range of options. Hydropower and irrigation are thereby considered as the major water users, since most likely no surface water subtraction will take place for domestic, livestock or industrial water use.

The third research question that concerns socio-economic aspects is “How can decision makers choose the most preferable among the optimal solutions?” A Pareto front includes optimal solutions for a given development stage of the hydro-system that are considered equally good if no decision makers’ preferences are provided. In order to decide, which Pareto solution would be the best compromise, a social cost-benefit analysis is performed. Thus, the most beneficial solution from a socio-economic point of view is calculated by assigning monetary values to hydropower and irrigation. The Pareto optimal solutions of the full development are compared to each other and evaluated.

The fourth research question that deals with the fact that the UBNR is one of the two main sources of a transboundary river is the following: “At which extent are downstream countries affected by different management policies in the UBNR basin?” The hydropolitics within the Nile Basin are strongly shaped by conflicts between the eleven riparian countries. It is studied, at which extend each possible development scenario of the UBNR basin and the proposed solution affect the downstream countries according to its possible management policies.

1.3 Research Framework

The research framework of the present work consists of a series of predefined steps, which are shown in Figure 1.1 and summarized in the following. During preliminary tasks (1), a literature review was conducted with emphasis on the available simulation-optimization tools that have been developed in recent decades to assist water resources management. Based on a series of criteria, the PSO method, as implemented in the Hydronomeas tool, was selected as the most suitable method for the thesis purposes. Subsequently, the required data were collected from visits in the study area, the available literature and contacts with experts and researchers. The collected data were analyzed and prepared for further use. During the second phase (2), the UBNR hydro-system was developed using Hydronomeas and the collected data. The hydro-system was schematized for four different development scenarios, including the baseline scenario, the current configuration and two future developments. The scenarios were defined by taking into account various projects that are proposed for the study area, such as reservoirs, hydropower and irrigation projects. This allowed the investigation of the downstream effect of the projects during different stages of the basin development. In the third phase (3), various targets, constraints and priorities were assigned to the UBNR hydro-system for the various development scenarios, to optimize the conflicting objectives of maximizing hydropower and minimizing irrigation deficit within the nexus concept. Pareto optimal solutions were calculated by assigning various weights to the two objectives, since no single solution exists that optimizes both simultaneously. The resulting Pareto fronts graphically illustrate the effects of different water management policies and are useful tools for decision makers. To further broaden the investigation (4), a social cost-benefit analysis was performed on the optimization results of phase 3. Monetary values were assigned to the hydropower and irrigation results, calculating the economic benefit of hydropower and economic cost of the irrigation deficit. Thus, the net social benefit of each Pareto optimal solution was calculated to help decision makers select the best compromise among the Pareto optimal solutions.

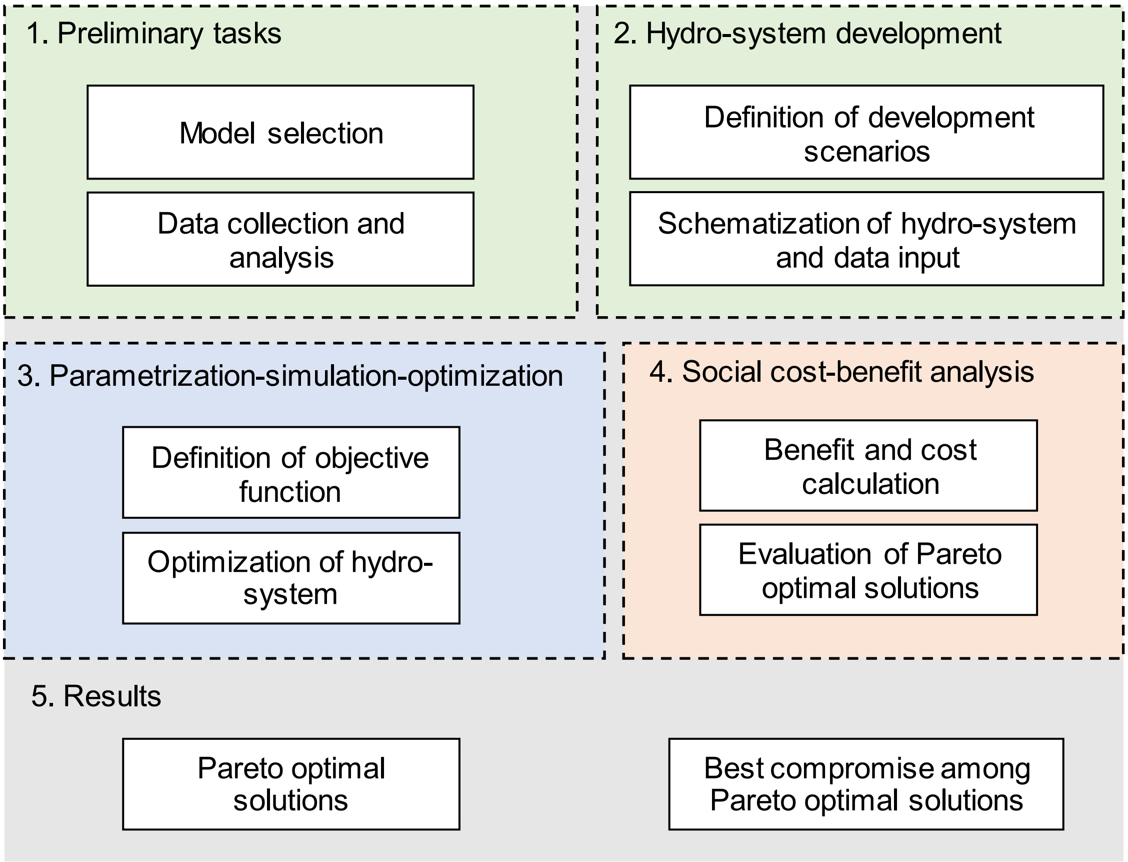

Figure 1.1 Simplified chart of the applied research framework

1.4 Thesis Structure

The present work comprises six main chapters. Chapter 1 provides an introduction to the thesis and presents the background, research framework, and motivation as well as the objectives, research questions, and thesis structure. In Chapter 2 the area of study, the Upper Blue Nile River (UBNR) basin in Ethiopia, is described. An overview is given on different sectors, e.g. water resources and hydro-politics. Furthermore, general information is provided regarding the topography, geology, land use, climate, hydrology, agro-ecology and demography of the basin.

Chapter 3 addresses the materials and methods used and developed for the thesis purposes. More precisely, this chapter provides information on the materials used during this thesis, concentrating on the data collection and analysis. The materials include the following main data categories: hydrological, meteorological, reservoir, hydropower, irrigation, and economic data. Chapter 3 also presents the literature research conducted to select the proper simulation-optimization tool for the purposes of the thesis. It provides an overview of the models, which were taken into consideration during the selection, and states the reasons for the selection of the Hydronomeas tool. Hydronomeas is described and information is provided on its theoretical background, characteristics, optimization procedures and applications. Furthermore, Chapter 3 provides information regarding the Castalia tool, which was used for the generation of synthetic time-series. Moreover, the Pareto optimization is described. The advantages of Pareto optimization are addressed, and the combination with the social cost-benefit analysis method is presented. At the end of the chapter, the tool developed to determine the cost of irrigation deficit is presented.

In Chapter 4 the development scenarios created for the thesis are described. Development scenarios represent the implementation of various projects in the UBNR basin for the natural conditions, current conditions, short- to medium-term, and full development of the river basin. Emphasis is given on the sectors: hydropower and irrigation. While defining the scenarios, ecological, economic, social and political factors were taken into account.

Chapter 5 presents and discusses the results of the present work in three different sections. In the first section, the results of the simulation and optimization of the UBNR hydro-system in the proposed modeling tool, Hydronomeas, are presented and discussed for the natural and current conditions, as well as the short- to medium-term and full development, with hydropower and irrigation having the same importance during optimization. In the second section, the results of the Pareto optimization are presented, analyzed and discussed for the short- to medium-term and full development of the UBNR basin. In the last section of Chapter 5, the results of the social cost-benefit analysis are presented and discussed for the full development of the UBNR basin.

Finally, in Chapter 6 conclusions are drawn and recommendations for future research are formulated.

2 Study Area: Upper Blue Nile River

2.1 General Overview

The UBNR is one of the two main sources of the Nile River and is located in Ethiopia, north-east Africa. The river originates at Lake Tana in the Ethiopian highlands and flows initially to the South, and then to the West, before crossing the border into Sudan. The UBNR is the largest in Ethiopia in terms of volume of discharge and second largest in terms of area (Conway 2000). The basin comprises 16 sub-basins; the present thesis deals with 14 of these, namely Tana, Beshilo, Welaka, Jemma, North Gojam, Muger, Guder, Finchaa, South Gojam, Anger, Didessa, Wenbera, Dabus and Beles (Figure 2.1). The two remaining sub-basins Dinder and Rahad are excluded, since they flow into the Blue Nile River downstream of the Ethiopia-Sudan border. The study area covers approximately 176,465 km² (Yilma and Awulachew 2009); its size is comparable to the size of the Rhine River basin in Europe.

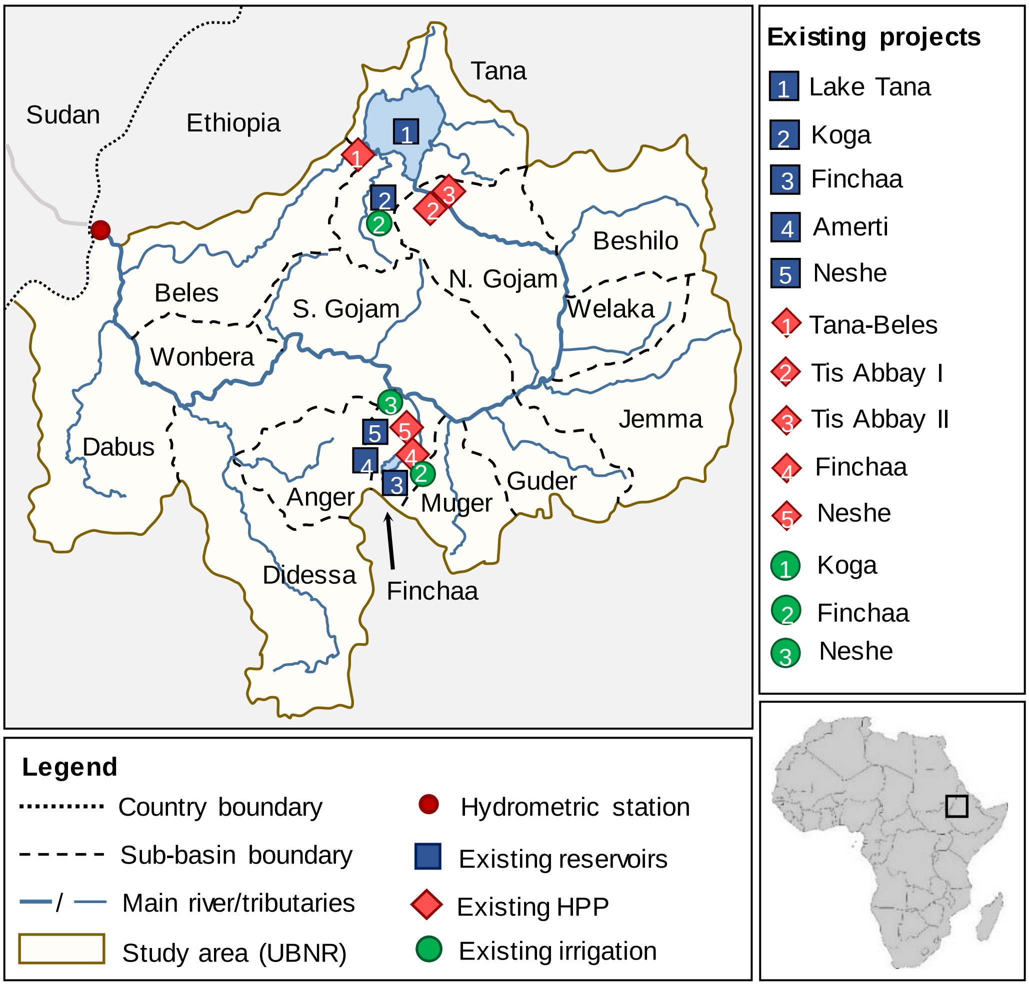

Figure 2.1 Main river network, sub-basins and main existing projects in the UBNR (Stamou and Rutschmann 2018, edited)

The topography of the UBNR basin has two significant features: the highlands, ragged mountainous areas in the central and eastern part, and the lowlands in the western part. Altitude ranges from 498 m in the lowlands, e.g. Sudan border, to 4,261 m in the highlands, e.g. Mount Guna. According to Ministry of Water, Irrigation and Electricity (MOWIE), about two-thirds of the basin area fall in the highlands, where elevations range from 1,500 to over 4,000 m and a slope greater than 25% is present. In the lowlands, elevations drops down to approximately 500 m and the slope is lower than 7%. The topographic characteristics of the basin together with the with the near-equatorial location of the UBNR basin have a significant effect on the water resources distribution as well as the rainfall pattern in the basin (Awulachew et al. 2007, Amare 2007).

According to MOWIE, the variety of local climates in the UBNR basin is rich, ranging from hot and desert-like along the Sudan border to temperate on the high plateau and cold on the mountain peaks. The mean temperature in the basin is 18.5 °C with a minimum and maximum average daily temperatures of 11.4 and 25.5 °C respectively. The highest temperature is observed in the north-western part of the basin, namely in parts of the sub-basins Beles and Dabus, whereas lower temperature is observed in the highlands in the central and eastern part of the basin. Moreover, rainfall ranges from 787 mm to 2,200 mm per year in the UBNR basin (Yilma and Awulachew 2009) with a mean value of 1420 mm (MOWIE), and varies spatially and temporally. The Ethiopian highlands receive the highest rainfall (1,500 to 2,200 mm), whereas the lowlands receive less than 1,500 mm. The lowest rainfall recorded accounted for less than 1,000 mm per year in the regions Beshilo, Welaka, Jemma, Muger and Guder.

Potential Evapotranspiration (PET) ranges from 1,056 mm to 2,232 mm per year (Yilma and Awulachew 2009). High PET (1,800 mm to 2,232 mm per year) is observed in the north-western parts of the basin, e.g. in parts of the Beles and Didessa sub-basins, in accordance with the spatial variation of temperature (Amare 2007). In the eastern and southern part of the basin lower PET is observed, ranging from 1,200 mm to 1,800 mm per year. The lowest PET (below 1,200 mm per year) is observed in parts of the highlands.

High seasonality is observed in the UBNR with more than 80% of the annual runoff at the Ethiopia-Sudan border arising in the rainy season, and several tributaries drying out in the dry season. The UBNR average annual flow at the border between Ethiopia and Sudan, measured at a hydrometric station in Ethiopia (see Figure 2.1), is estimated equal to 50.6 km^3. This corresponds to approximately 60% of the Nile River flow at Aswan, Egypt (84.5 km^3), as per the Nile Agreement (McCartney et al. 2012). In terms of average discharge, the UBNR with 1,603 m³/s is comparable to the European river Po with 1,470 m³/s (Montanari 2012).

The geology of the UBNR basin signifies different formations, such as basalt, alluvium, lacustrine deposit, sand stone, granite and marbles. The dominant rock is basalt and specifically Tarmaber basalt, followed by Ashange basalt and Amba Aiba basalt. Furthermore, the basin is mainly characterized by dominantly cultivated land in the eastern part and grass land, wood lands and forest in the western part, according to the land classification of MOWIE. The major dominant soil types in the basin are Alisols and Leptisols, followed by Nitosols, Vertisols, Cambrisols, Fluvisols and Luvisols.

The hydrogeological features within the UBNR Basin are characterized primarily by volcanic rocks and basement rocks, which create productive groundwater aquifers in depths between 60 and 252 m. High variations in groundwater recharge exist between low- and highlands; the groundwater quality in the basin can be seen as ‘naturally good’ (MacAlister et al. 2012, in Awulachew et al. 2012). It is worth mentioning that the groundwater potential in Ethiopia is lower in comparison to the surface water resources. Over the last decade groundwater has become the primary source of domestic water for the urban population because it is cheaper than develop other alternatives, it has a reliable supply and it plays a buffer role against drought (Johnston 2012).

The UBNR basin is subject to severe erosion issues. A main driving factor are high rainfall intensities, leading to a fraction of 50 to 80% of annual soil loss within “the five most intense storms in a year” (Amare 2007). Additionally, steep and long slopes in combination with poorly structured erosion-prone soils, as well as poor and intermittent vegetative cover worsen the situation. Erosion leads to soil degradation, reducing in turn infiltration capacity and vegetation cover. Erosion problems in the basin are connected to negative effects including lowered agricultural productivity (Amare 2007).

According to the current regional structure, the UBNR basin covers three regional states of Ethiopia: Amhara, Oromia and Benishangul-Gumus regional state. Almost 30 million out of the Ethiopian population of nearly 80 million, live within the UBNR basin (2008) according to the Central Statistics Authority (CSA) of Ethiopia (Yilma and Awulachew 2009). The highest share of the population (>90%) in the UBNR Basin is rural residents. The population density is unevenly distributed; the highest population density is observed in the highlands, where most of the rainfall is received.

2.2 Current and Future Development of Water Resources

The UBNR supplies Ethiopia with water for hydropower, irrigation, domestic, industrial, livestock and touristic purposes; thus, people in the country depend highly on the UBNR. Although the UBNR basin has great water resources potential, providing annually approximately 60% of the Nile River flow at Aswan, Egypt (84.5 km^3) as per the Nile Agreement (Okoth-Owiro 2004), it is one of the least utilized basins in Ethiopia (McCartney et al. 2012).

Currently, there exist five reservoirs, five hydropower plants (HPPs) and three medium- to large-scale irrigation projects within the UBNR basin that are shown in Figure 2.1 with the characteristics that are depicted in Table 2.1. The reservoirs that are Lake Tana, Koga, Finchaa, Amerti and Neshe are located in only two of its 14 sub-basins. They serve the purposes of flow regulation, irrigation, hydropower production, flood control, navigation and recreation.

Table 2.1 Currently existing reservoirs, HPPs and irrigation projects in the UBNR basin

Sub-basin	Reservoir	Capacity (hm^3)	HPPs	Installed capacity (MW)	Irrigation project	Net area (ha)
Tana	Koga	83	-	-	Koga	5,100
	Lake Tana	38,686	Tana-Beles	460	-	-
			Tis Abbay I	12	-	-
			Tis Abbay II	73	-	-
Finchaa	Finchaa	1,120	Finchaa	134	Finchaa	6,205
	Amerti	107	-	-	-	-
	Neshe	196	Neshe	97	Neshe	7,217
Total		40,192		776		18,522

Lake Tana, located in the Ethiopian highlands at an altitude of 1800 m, is a natural reservoir and Ethiopia’s largest freshwater lake with a volume of approximately 29 km^3 and a surface area of 3,062 km^2 at a water elevation of 1786 m, while its spill level is at 1789 m. Lake Tana provides water for three HPPs: Tana-Beles, Tis Abbay I and Tis Abbay II (see Figure 2.1). The lake has two outlets; one to the West to the Tana Beles HPP and one in the South (regulated by the Chara Chara weir) to the. Since the more recent operation of Tana-Beles in 2009 that has an installed capacity of 460 MW, the HPPs Tis Abbay I and Tis Abbay II, commissioned in 1964 and 2001, are operating only as stand-by stations, with an installed capacity of 12 MW and 73 MW, respectively. The water from Lake Tana that is utilized at the Tana-Beles HPP is released to the Beles River, the last tributary of the UBNR before the Ethiopia-Sudan border.

Furthermore, the Koga reservoir that is also located in the Tana sub-basin, has a reservoir volume of 83.1 hm^3 and an area of 18.6 km^2 at a water elevation of 2015 m. The Koga reservoir irrigates a net area of 5,100 ha with an annual demand of 50 hm^3/y.

The three remaining reservoirs Finchaa, Amerti and Neshe are located in the south of the UBNR basin (see Figure 2.1). The Finchaa reservoir was the first multipurpose reservoir in the basin. It was created to generate hydropower at the HPP with an installed capacity of 134 MW and irrigate a net area of 6,205 ha with a demand of 47 hm^3/y. Its reservoir has a volume of 1120 hm^3 and an area of 345 km^2 at a water elevation of 2219 m. Moreover, the Amerti reservoir was created to control the flow to the Finchaa reservoir and provide it with additional water for hydropower and irrigation. Finally, the Neshe reservoir is a multipurpose project with a volume of 196 hm^3 and an area of 21 km^2 at a water elevation of 2221 m, which generates hydropower at the HPP with an installed capacity of 97 MW and irrigates a net area of 7,217 ha with a demand of 67 hm^3/y.

The ongoing population pressure within the UBNR basin leads to an intensification of the demand on water, energy and land resources. Poverty is prevalent throughout the population, and satisfaction of immediate food needs and the minimization of risk are required (Amare 2007). Due to its great water resources and its topography, the UBNR basin has great hydropower potential that is valued to 70,000 GWh/y (technical potential); a figure that includes the Dinder and Rahad sub-basins (McCartney at al. 2012). Furthermore, the basin has great irrigation potential, which is estimated to be approximately 584,110 ha (net irrigable area of the medium- and large- scale irrigation projects with an area greater than 200 ha) with an annual average water requirement of 4,568 hm^3 (BCEOM et al. 1998). To take advantage of this great water resources, hydropower and irrigation potential, and cover the needs of people, Ethiopia plans various water resources development for the UBNR. Thus, 37 reservoirs, 23 HPPs and 117 irrigation projects (categorized in 69 irrigation project groups) are proposed for the UBNR basin for the long-term future.

The water resources management in the UBNR basin is currently reactive to floods or droughts, which leaves both water resource managers and the local population at the mercy of natural events (Stamou and Rutschmann 2018). Furthermore, the ambitious future plans of Ethiopia for water resources development and expansion of water use in the UBNR are likely to cause conflicts among riparian countries in the Nile River basin. Therefore, there is an immediate need for proper and sustainable water resources management in the UBNR basin.

2.3 Management Policy and Organizations

Ethiopia has a national water policy, the Water Resources Management Policy that was developed in 1999 and incorporates important elements, such as general intent, community participation, institutional changes and duty of care (Haileslassie et al. 2012). However, the policy had limited success in the past. The water strategies are criticized for a lack of specific goals, strategies for future challenges, integrated approaches, strategies dealing with climate change, upstream-downstream linkage and the role of education and research.

The authorities responsible for water resources management in Ethiopia are categorized in local-, regional- and federal-level, as well as basin-level organizations (Haileslassie et al. 2012).

On the local level, organizations include irrigation cooperatives and water user associations that undertake the tasks of water distribution, rehabilitation and maintenance of canals, and the task of addressing water-related conflicts. The informal institutions organized locally are seldom linked to each other.

On the federal and regional level on the other hand, formal institutions are present. The main actors on federal level are the (1) Ministry of Water, Irrigation and Electricity, (2) Ministry of Agriculture and Rural Development, and the (3) Ethiopian Environmental Protection Authority. Their key objectives are (1) the inter alia inventory and development of the country’s surface water and groundwater resources, basin-level water management and benefit-sharing, (2) the development and implementing of a strategy for food security, rural development, and natural resources protection, development of rural infrastructure and agricultural research and (3) the formulation of policies, strategies, laws and standards to foster social and economic development and the safety of the environment, respectively.

According to Haileslassie et al. (2012), although the main actors have properly defined objectives, their work areas overlap, coordination between them is poor and there is a lack of formal information flow. These factors lead to increased work load and resources wastage. The ministries and bureaus are characterized by weak enforcement capacity and the organizations in water management have been often subject to restructuring that leads to uncertainties in the development of capacities.

2.4 Hydro-politics within the Nile River Basin

The hydro-politics among the eleven riparian countries that share the Nile River, i.e. Burundi, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, South Sudan, Tanzania and Uganda, are formed by conflicts. The timeline of hydro-politics within the Nile River basin includes the following:

1891-1929: Between 1891 and 1925, the United Kingdom of Great Britain entered into five agreements on the utilization of the waters of the Nile; these were followed by the "The 1929 Nile Waters Agreement", which is the most controversial of all the Nile Water Agreements and also the most important (Okoth-Owiro 2004). The purpose of the 1929 Nile Waters agreement was to guarantee and facilitate an increase in the volume of water reaching Egypt; it was based on the outcome of political negotiations between Egypt and Great Britain in 1920s, and in particular on the report of the 1925 Nile Waters Commission, which was attached to the agreement as an integral part thereof. The main provisions of the Agreement are the following

I. Save with the previous agreement of the Egyptian Government, no irrigation or power works, or measures are to be constructed or taken on the River Nile or its branches, or on the lakes from which it flows in the Sudan or in countries under British administration, which would, in such a manner as to entail prejudice to the interests of Egypt, either reduce the quantities of water arriving in Egypt or modify the date of its arrival, or lower its level.

II. In case the Egyptian Government decides to construct in the Sudan any works on the river and its branches, or to take any measure with a view to increasing the water supply for the benefit of Egypt, they will agree beforehand with the local authorities on the measures to be taken to safeguard local interests. The construction, maintenance and administration of the above-mentioned works shall be under the direct control of the Egyptian Government.

The Agreement also expressed recognition by Great Britain, of Egypt's "natural and historic rights in the waters of the Nile", even though the precise content of these rights was not elaborated.

1959: The Agreement for Full Utilization of the Nile water between Egypt and Sudan was signed (Cascão 2012). This granted specific volumetric allocations per year to Egypt, i.e. 55.5 km^3, and Sudan, i.e. 18.5 km^3 (Erlich 2002). Other riparian countries that were not included, considered the agreement unfair. The highly controversial agreement marked the beginning of conflicts between downstream and upstream riparian countries, which up to now have not legally recognized it. The reasons for the agreement's persistence are according to Cascão (2012) the strong asymmetries in terms of material, bargaining and ideational power between riparian countries.

1967-1992: Various attempts for basin-wide transboundary cooperation. These attempts, such as the Hydromet, Undugu and TeccoNile in 1967, 1983 and 1992, respectively, were unsuccessful due to the absence of upstream riparian countries, such as Ethiopia, Kenya and Tanzania, which argued that the initiatives were only beneficial for downstream riparians and are not addressing a renegotiation of the legal water allocation. Nonetheless, the 1990s developments can be seen as primary steps of transboundary cooperation (Cascão 2012).

1993-2004. Nile 2002 Conference series. These conference series started in February 1993 and have continued through 2002 to be held each year in one of the Nile River Basin countries as follows:

I. 1993: Aswan, Egypt “Getting Started”.

II. 1994: Khartoum, The Sudan “The Vision Ahead”.

III. 1995: Arusha, Tanzania “Taking Off”.

IV. 1996: Kampala, Uganda “An Action Plan”.

V. 1997: Addis Ababa, Ethiopia “Basis for Cooperation”.

VI. 1998: Kigali, Rwanda “Benefits for all”.

VII. 1999: Cairo, Egypt “A Shared Vision”.

VIII. 2000: Addis Ababa, Ethiopia “Priorities for the Millennium”.

IX. 2002: Nairobi, Kenya “Building a Nile Basin Community”.

The Conferences managed to create a better environment for learning and confidence and trust building among the participants of the Nile riparian states; this was due to the continued process of dialogue and reflective conversation, which has undoubtedly contributed greatly to consensus-building (Hefny 2001). In these Conferences a systematic approach was adopted; each meeting was connected to the others by a series of themes focused to bring about a specific outcome. Each topic had its own function within the sequence and was based on the assumption that each function corresponds to a distinct phase in the riparian policy-making process, whether for collaborative action or for water resource management and sustainable development (Hefny and Amer 2005).

1997-2015. Cooperative Framework Agreement (CFA) (NBI 2018a). The CFA intends to establish principles, rights and obligations to ensure long-term and sustainable management and development of the shared Nile waters. According to its provisions, the Nile Basin States would assume the obligation to cooperate on the conservation, management and development of the basin and its waters. The CFA would establish a legal basis for a permanent and joint management institution, the Nile River Basin Commission (NRBC), which would be vested with legal personality as well as enhance Nile cooperation. The NRBC will ensure that national development projects are coordinated with basin-wide development to achieve optimal use of the Basin's resources and increase national benefits of regional cooperation. The CFA could play a key role in catalyzing economic growth, reducing poverty, facilitating regional integration, and promoting regional peace and stability. Its adoption by all Basin States would represent a sign of their commitment to cooperate in the development and utilization of their shared water resources. Such a sign of commitment could facilitate access to international finance and relations to development partners from the public and private sector.

The intended scope of the CFA and use of terms are defined in Articles 1 and 2. The remainder of the text is divided into six parts as follows:

I. General principles, which include to a large part well established customary principles of international water law; the principle of equitable and reasonable utilization, the obligation not to cause significant harm, and the principle of protection and conservation of the river's ecosystem. These principles serve as guidance to countries on how to implement the treaty and how to manage and develop the River's resources in a sustainable manner.

II. Rights and obligations, which outline specific rights and obligations of State Parties, including obligations to regularly exchange data and information, to notify planned measures and to observe the subsidiarity principle in development and protection of the Nile. Detailed notification procedures would be developed by the NRBC. State Parties would be under an obligation to carry out environmental impact assessments for planned measures that may have significant adverse effect, and to conduct environmental audits of these measures where this is warranted by the circumstances.

III. Institutional structure and role of the Nile River Basin Commission (NRBC), which would comprise the following organs; the Conference of Heads of State and Government, the Council of Ministers, the Technical Advisory Committee, Sectoral Advisory Committees, and the Secretariat. The NRBC is to succeed to the rights, obligations and assets of the NBI. The possibility to establish subsidiary institutions is provided for in Part IV of the treaty.

IV. Subsidiary institutions that may established.

V. Miscellaneous provisions, which outline the procedures by which disputes that might arise from the implementation and application of the CFA would be settled. Furthermore, it envisages the establishment of bilateral or plurilateral instruments (agreements) that would supplement the CFA.

VI. Final clauses, which defines the procedures for amendments, ratification and entry into force of the CFA.

1999: Establishment of the Nile Basin Initiative (NBI). The NBI is an intergovernmental partnership of 10 Nile Basin countries, namely Burundi, DR Congo, Egypt, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda. Eritrea participates as an observer; its major objective is “to achieve sustainable socio-economic development through the equitable utilization of, and benefit from, the common Nile Basin water resources” (NBI 2018b, NBI 2001).

The objectives of the NBI are:

I. To develop the Nile Basin water resources in a sustainable and equitable way to ensure prosperity, security, and peace for all its people.

II. To ensure efficient water management and the optimal use of the resources.

III. To ensure cooperation and joint action between the riparian countries, seeking win-win gains.

IV. To target poverty eradication and promote economic integration.

V. To ensure that the program results in a move from planning to action.

The NBI is comprised of:

I. the Council of Ministers of Water Affairs of the Nile Basin States (Nile-COM),

II. the Technical Advisory Committee (Nile-TAC) comprised of 20 senior government officials that supports Nile-COM,

III. the Secretariat (Nile-SEC) that is responsible for the overall corporate direction and is located in Entebbe, Uganda,

IV. two Subsidiary Action Programs (SAPs) offices that are:

   a. the Eastern Nile Technical Regional Office (ENTRO) for the Eastern Nile Subsidiary Action Program (ENSAP) and

   b. the Nile Equatorial Lakes Subsidiary Action Program Coordination Unit (NELSAP-CU), for the Nile Equatorial Lakes Subsidiary Action Program (NELSAP).

ENTRO and NELSAP-CU support identification, negotiation, and implementation of cooperative investment projects, with a focus on mutual and sustainable benefits for the countries involved. This set up has enabled NBI to leverage the unique potentials and mitigate risks in the respective sub-basins.

The NBI recently announced its ten-year (2017-2027) strategy (NBI 2017), which translates the shared vision objective “to achieve sustainable socio-economic development through equitable utilization of, and benefit from the shared Nile Basin water resources” into basin development goals that NBI will work towards; and further expounds on what contributions NBI will make over the ten-year period. The ten-year strategy will be implemented through five-year programs prepared by the three NBI Centers and will be funded by the Nile Riparian countries with support from Development Partners. The goals of the 10-year strategy are:

1. Goal 1 Enhance availability and sustainable utilization and management of transboundary water resources of the Nile Basin.

2. Goal 2 Enhance hydropower development in the basin and increase interconnectivity of electric grids and power trade.

3. Goal 3 Enhance efficient agricultural water use and promote a basin approach to address the linkages between water and food security.

4. Goal 4 Protect, restore and promote sustainable use of water related ecosystems across the basin.

5. Goal 5 Improve basin resilience to climate change impacts.
6. Goal 6 Strengthen transboundary water governance in the Nile Basin.

Nowadays: The Nile basin is entering into a new era of challenges and opportunities primarily driven by population explosion, food and water shortage, increase in water demand and water use, climate change, and complicated water right issues. More importantly, upstream countries started to assert their right to develop the Nile water resources challenging the long-held water right hegemony of Egypt and Sudan. An agreement between the riparian countries is very important for the future cooperation within the Nile basin to provide economic, environmental and political benefits to all co-basin states (Shady et al. 1994).

2.5 Literature Review: Existing Approaches

Numerous models have been developed over the last years concerning the water resources planning and management within the UBNR basin. The models are distinguished in (1) simulation, (2) optimization and (3) combined simulation and optimization models. Most of the models concerning the UBNR basin were designed to only simulate the hydro-system. Some of the recent studies include that of McCartney and Girma (2012) that investigated the implications of climate change on existing and future water resource development in the UBNR basin using dynamic climate modelling in combination with the models SWAT and WEAP. Jeuland and Whittington (2014) proposed a framework that relies on a simulation model that includes linkages between climate change and system hydrology, combined with sensitivity analyses that explore how economic outcomes of investments in new dams vary with forecasts of changing runoff and other uncertainties. Wondimagegnehu and Tadele (2015) dealt with evaluation of climate change impact on the operation of three proposed reservoirs using the hydrological model HEC-HMS to simulate the current and future inflow volume to the reservoirs. Jeuland (2010) developed a hydro-economic modeling framework to integrate climate change impacts into the problem of planning water resources infrastructure development of four proposed reservoirs. King and Block (2014) evaluated numerous filling policies for the Grand Ethiopian Renaissance Dam (GERD) through a climate-sensitivity approach to estimate impacts on reservoir filling time, hydropower production and downstream flows. Zhang et al. (2016) performed a modelling study to evaluate inter-annual and decadal-scale discharge variability into the GERD reservoir and compare various filling strategies for hydropower and downstream releases. Wheeler et al. (2016) analyzed strategies for filling GERD and implications for downstream water resources using the river basin planning model RiverWare. ENTRO also investigated existing and planned reservoirs in the Eastern Nile River basin that includes the UBNR, using various simulation models, e.g. SWAT, HEC-ResSim, within the Eastern Nile Planning Model Project (ENPMP). However, their results are only included in study reports and not published widely in scientific journals.

Other notable studies have dealt with the optimization aspect of the UBNR basin. Whittington et al. (2005) developed an economic optimization model for the Nile River called NEOM, to determine the economic value of cooperation in the river basin. Block and Strzepek (2010) developed a deterministic water resources system optimization model for four proposed reservoirs, called Investment Model for Planning Ethiopian Nile Development (IMPEND). Goor et al. (2010) used a stochastic hydro-economic model to evaluate the impacts of four planned reservoirs upstream development in the Blue Nile Basin on the allocation decisions and reservoirs operating strategies, and assess the economic value of regulation in Ethiopia.

According to Digna et al. (2017), there are relatively few studies that consider both simulation and optimization. Some of the more recent, notable works include the study of Hassaballah et al. (2012) that investigated a filling strategy for the planned Mandaya reservoir using MIKEBASIN and NSGA-2 focusing on hydropower maximization. Furthermore, the study of Georgakakos (2006) utilized the Nile River basin decision support tool to assess the hydro-power 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.

Identifying the limitations of previous work, this thesis focuses on the design of a multi-objective optimization system for the UBNR basin using the PSO method as implemented in Hydronomeas by taking into account multiple criteria. Four different development scenarios are defined, from the natural conditions to the full development of the UBNR basin. Pareto optimal solutions are calculated for the conflicting objectives of hydropower and irrigation within the nexus concept. The resulting Pareto front graphically illustrates the effects of different water management policies and is a useful tool for decision makers. To further broaden the investigation, a social cost-benefit analysis is performed and the net benefit of each Pareto optimal solution is calculated to assist the decision makers in the selection of the best compromise among the Pareto solutions.

3 Materials and Methods

3.1 Data Collection and Analysis

As expected, data collection for the UBNR basin was a challenging and difficult task, as noted by many researchers and characteristically expressed by Kim and Kaluarachchi (2008): “The Upper Blue Nile River Basin of Ethiopia is an example where data are limited, water resources are valuable, and competition for water among riparian countries is strong”.

The required data were collected mainly during visits in the study area and discussions with experts and researchers, and specifically to:

I. The Ministry of Water, Irrigation and Electricity (MOWIE) in Addis Ababa.

II. The Universities of Addis Ababa and Bahir Dar.

III. Local authorities, mainly the Abbay Basin Authorities in Bahir Dar.

IV. Engineering offices, such as the Eastern Nile Technical Regional Office (ENTRO).

V. Project sites, such as Grand Ethiopian Renaissance Dam (GERD) construction site, Tana-Beles HPP and Koga irrigation project.

Furthermore, data were collected from:

I. the literature,

II. the International Water Management Institute (IWMI), and

III. the Food and Agriculture Organization (FAO) of the United Nations.

The collected data are divided into six main categories: (1) river flow, (2) reservoir, (3) hydropower, (4) irrigation, (5) meteorological and (6) economic.

3.1.1 River flow data

The hydrometric basin monitoring map of the Nile Basin Water Resources Atlas (NBI 2016) includes 126 hydrometric stations in the 14 sub-basins of the study area. The majority of the stations were installed in the early 1960’s (NBI 2016); however, data availability is limited. Flow data for the purposes of the present work, namely the discharges in particular river locations, were obtained from MOWIE, IWMI, ENTRO, BCEOM et al. (1998) and previous studies. The UBNR flow varies significantly between seasons with more than 80% of the flow occurring during the wet season, while only 4% occurs during the dry season. Figures 3.1 and 3.2 show the mean monthly flow of the UBNR for the key hydrometric stations of Bahir Dar at the southern outlet of Lake Tana, and at the border between Ethiopia and Sudan, respectively. Apart from the great seasonal variability, the UBNR flow also experiences great inter-annual variability (see Figure 3.3).

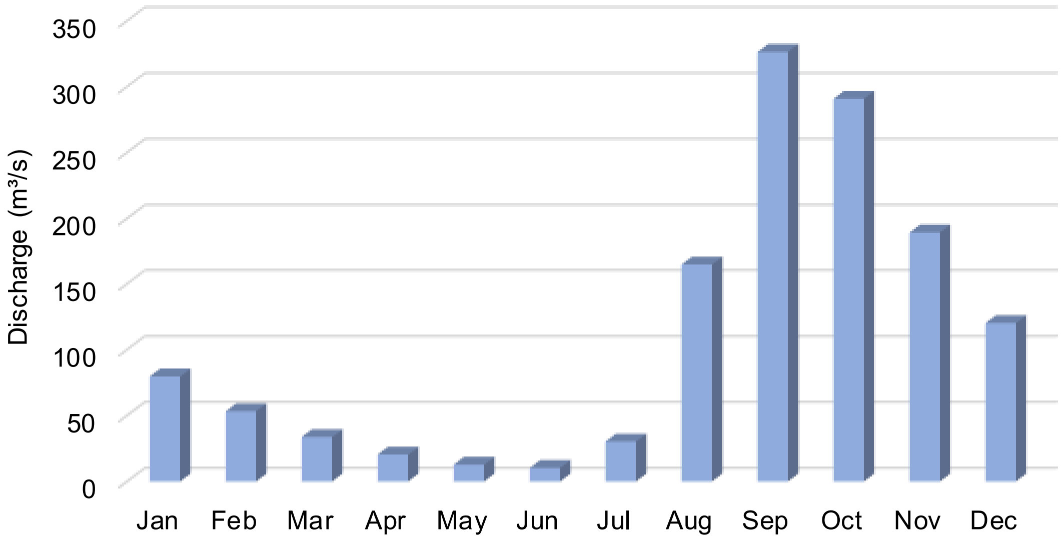

Figure 3.1 Mean monthly UBNR discharge (m³/s) at Bahir Dar

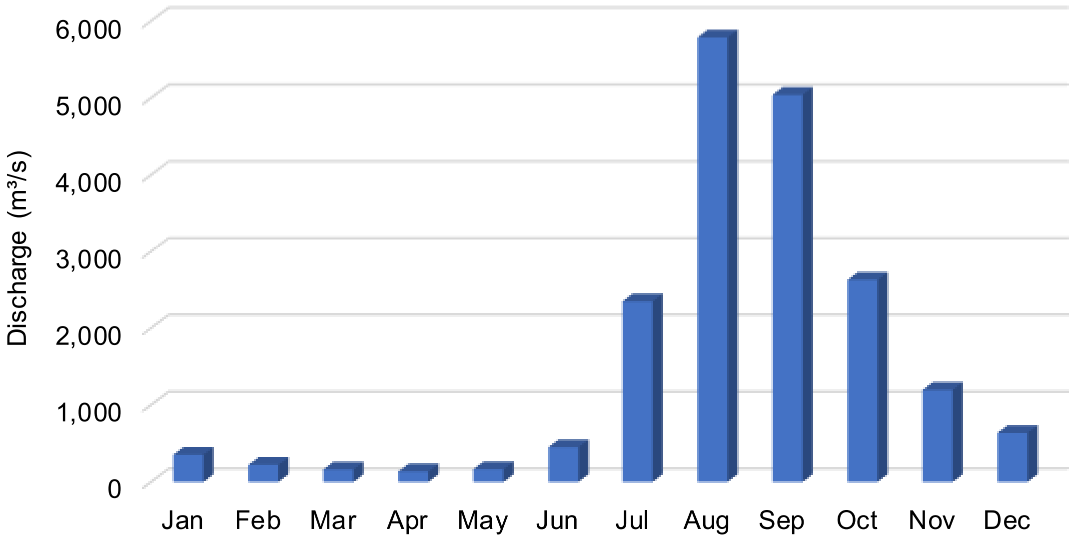

Figure 3.2 Mean monthly UBNR discharge (m³/s) at the Ethiopia-Sudan border

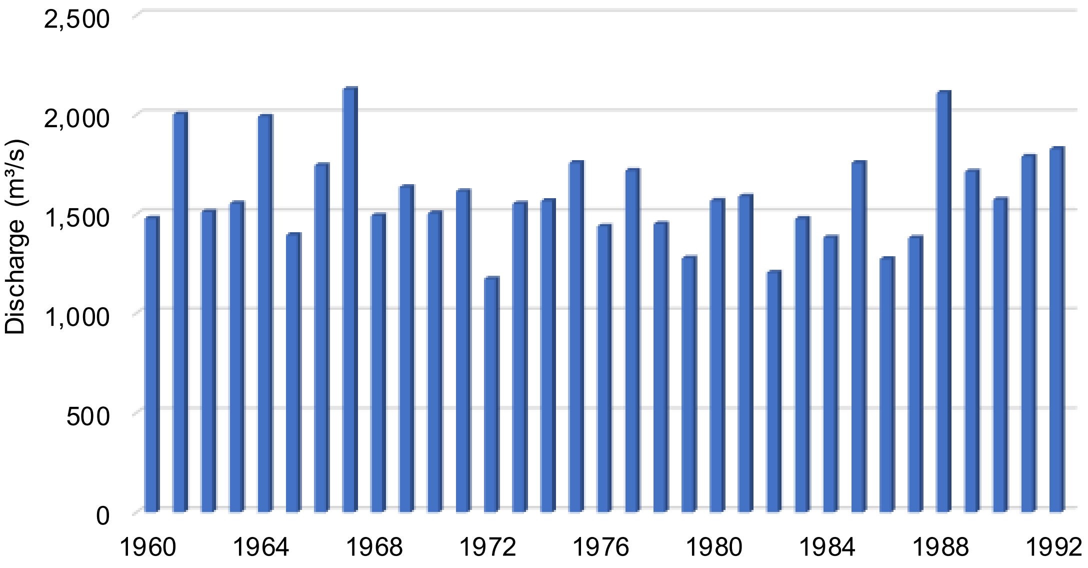

Figure 3.3 Mean UBNR discharge (m^3/s) per year at the Ethiopia-Sudan border

3.1.2 Meteorological Data

The meteorological basin monitoring map of the Nile Basin Water Resources Atlas (Nile Basin Initiative 2016) includes 262 meteorological stations in the study area; however, data availability is limited. Most of the stations record only rainfall, while only few stations record more variables (NBI 2016). Meteorological data, e.g. rainfall and evaporation for the reservoirs, were collected from ENTRO and previous studies. Figure 3.4 shows the mean annual rainfall for the UBNR basin.

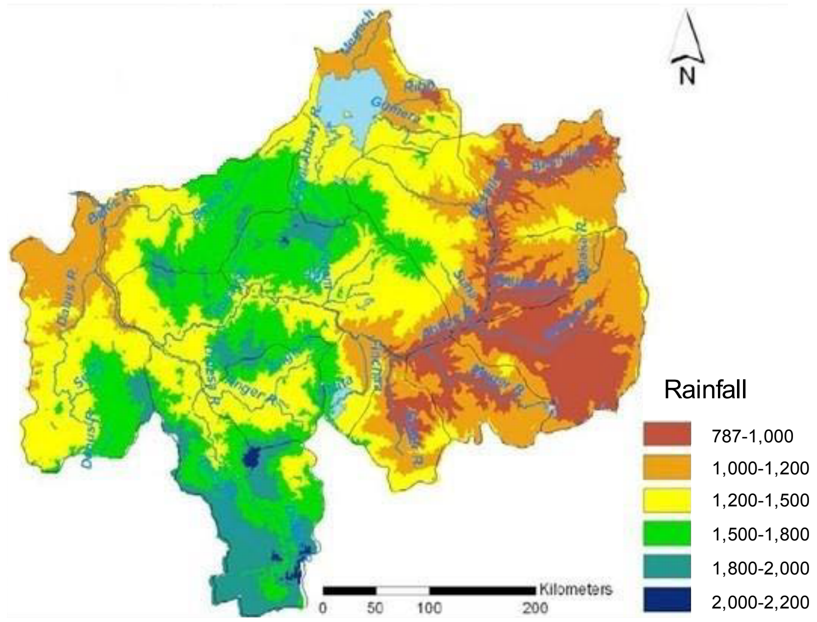

Figure 3.4 Rainfall (mm/year) in the UBNR basin (Yilma and Awulachew 2009, edited)

3.1.3 Reservoir Data

Reservoir/lake data, e.g. inflows, outflows, rainfall, evaporation, catchment area, spill-initial-intake elevation, elevation-volume and elevation-area curves, were obtained from MOWIE, ENTRO, visits to currently operating projects (in the year 2015), and previous studies. There are five existing and 32 proposed reservoirs for the UBNR basin with a total capacity of approximately 221 km³. Indicatively, the elevation-volume and elevation-area relationships for Lake Tana are shown in Table 3.1. The number of reservoirs per sub-basin, their main purposes related to hydropower and irrigation, and the reservoir storage (km³) are shown in Table 3.2. The reservoirs with the largest capacity are located in the Tana and Didessa sub-basins, and on the main stem of the UBNR.

Table 3.1 Elevation-volume and elevation-area relationships for Lake Tana

Elevation (m)	Volume (hm³)	Area (km²)
1772	0	0
1774	209	942
1780	12,120	2,509
1782	17,401	2,769
1784	23,147	2,958
1785	26,135	3,018
1786	29,175	3,062
1787	32,273	3,134
1788	35,444	3,207
1789	38,686	3,351

Table 3.2 Number of reservoirs, purpose and storage (hm³) per sub-basin

Sub-basin	Reservoirs	Main purpose	Storage (km³)
Tana	7	Hydropower, Irrigation	39.9
Beshilo	-	-	0
Welaka	-	-	0
Jemma	2	Hydropower, Irrigation	1.3
North Gojam	-	-	0
Muger	3	Irrigation	0.5
Guder	2	Hydropower, Irrigation	4.3
Finchaa	3	Hydropower, Irrigation	1.4
South Gojam	3	Hydropower, Irrigation	3.3
Wonbera	-	-	0
Anger	2	Hydropower, Irrigation	7.0
Didessa	7	Hydropower, Irrigation	16.9
Dabus	3	Hydropower, Irrigation	5.1
Beles	1	Hydropower, Irrigation	4.6

Main River	4	Hydropower	136.3
Total	37		221

3.1.4 Hydropower Data

Hydropower data for existing and proposed HPPs, e.g. installed capacity, discharge capacity and head, were obtained from MOWIE, the Abbay Basin Authority, ENTRO, BCEOM et al. (1998), project site visits, and previous work. Five HPPs exist currently in the UBNR basin, while 18 projects are proposed for the long-term future (see Chapter 4, Section 4.2.4) with a total installed capacity of 14,214 MW. Table 3.3 and Table 3.4 show the number of HPPs per sub-basin and their installed capacity. The largest HPPs are located in the main stem of the UBNR, while the GERD prevails with more than 40% of the total installed capacity.

Table 3.3 Number of HHPs and installed capacity (MW) of the HPPs per sub-basin

Sub-basin	HPPs	Installed capacity (MW)
Tana	3	545
Beshilo	-	0
Welaka	-	0
Jemma	2	418
North Gojam	-	0
Muger	-	0
Guder	1	82
Finchaa	2	231
South Gojam	3	419
Wonbera	-	0
Anger	1	200
Didessa	3	385
Dabus	3	791
Beles	1	143
Main River	4	11,000
Total	23	14,214

Table 3.4 Installed capacity (MW) of the HHPs

Sub-basin	HPP	HPP No	Installed capacity (MW)
Tana	Tana Beles	1	460
	Tis Abbay I	2	12
	Tis Abbay II	3	73
Beshilo	-	-	0

Welaka	-	-	0
Jemma	Aleltu East	4	204
	Aleltu West	5	214
North Gojam	-	-	0
Muger	-	-	0
Guder	Lower Guder	6	82
Finchaa	Finchaa(-Amerti)	7	134
	Neshe	8	97
South Gojam	Chemoga I	9	140
	Chemoga II	10	140
	Fetam	11	139
Wonbera	-	-	0
Anger	Nekemte	12	200
Didessa	Upper Didessa	13	40
	Dabana	14	100
	Lower Didessa	15	245
Dabus	Upper Dabus I	16	225
	Upper Dabus II	17	326
	Lower Dabus	18	240
Beles	Lower Bales	19	143
Main River	Karadobi	20	1,600
	Mabil	21	1,400
	Mendaia	22	2,000
	GERD	23	6,000
Total			14,214

3.1.5 Irrigation Data

Irrigation data for the medium and large-scale irrigation projects in the UBNR basin, e.g. location, gross area, net area, irrigation demand, cropping pattern, crops and crop yield, were collected from MOWIE, ENTRO, FAO, BCEOM et al. (1998), and previous studies. Currently, three irrigation projects exist in the UBNR basin, while 112 projects are proposed for the full development (see Chapter 4, Section 4.2.4). In the present work, the projects were categorized in 69 irrigation project groups (IRGs) according to their location, sub-basin and cropping patterns. The irrigation projects cover a total maximum gross irrigable area of 687,167 ha, while the net area equals 584,110 ha, as shown in Table 3.5. Almost 50% of the total gross potential irrigation area is located in the Tana and Beles sub-basins, while in the Beshilo sub-basin no irrigation projects are proposed. The total annual irrigation demand was estimated to 4,568 hm^3/y. Table 3.6 shows the net area (ha), annual demand (hm^3/y) and irrigation pattern of each irrigation project group. There are totally 25 crops in the 14 sub-basins that follow the seven irrigation patterns, as shown in Table 3.7. Furthermore, the crop yield of each crop is shown in Figure 3.5.

Table 3.5 Gross area (ha), net area (ha) and demand (hm^3) of the irrigation project groups (IRG) per sub-basin

Sub-basin	IRGs	Gross area (ha)	Net area (ha)	Demand (hm^3/y)
Tana	1-12	146,953	124,919	1,043
Welaka	13	1,271	1,080	7
Jemma	14-20	36,924	31,387	153
North Gojam	21-24	26,310	22,366	152
Muger	25-27	7,444	6,327	26
Guder	28-30	30,834	26,209	165
Finchaa	31-32	20,421	17,358	151
South Gojam	33-44	72,361	61,511	444
Wonbera	45-46	13,998	11,899	102
Anger	47-52	52,658	44,759	311
Didessa	53-61	86,623	73,631	432
Dabus	62-66	18,170	15,444	119
Beles	67-69	173,200	147,220	1,464
Total		687,167	584,110	4,568

Table 3.6 Net area (ha), demand (hm^3/y) and pattern (pat) of the irrigation projects (IRG)

Sub-basin	IRG	Net area (ha)	Demand (hm^3/y)	Pat	Sub-basin	IRG	Net area (ha)	Demand (hm^3/y)	Pat
Tana	1	5,100	50	6	South Gojam	35	2,170	10	7
	2	7,786	57	1		36	2,817	10	7
	3	12,687	96	1		37	1,369	8	7
	4	364	3	1		38	4,638	33	7
	5	3,220	17	1		39	22,977	183	1
	6	6,213	60	6		40	8,500	61	1
	7	13,976	113	1		41	1,845	10	7
	8	19,925	197	6		42	2,656	22	7
	9	7,311	58	1		43	3,248	20	7
	10	31,230	250	1		44	3,174	24	7
	11	5,475	46	1	Wonbera	45	8,728	79	4
	12	11,632	96	1		46	3,171	23	4
Beshilo	-	0	0	-	Anger	47	14,450	92	4
Welaka	-	0	0	-		48	1,119	8	4
Jemma	13	1,080	7	4		49	11,220	71	4
	14	10,608	51	7		50	1,963	14	4
	15	1,964	6	7		51	15,114	119	4
	16	13,056	61	7		52	893	7	4
	17	799	4	1	Didessa	53	1,190	7	4

	18	1,425	8	7
	19	1,351	12	7
	20	2,184	10	7
North Gojam	21	4,132	34	1
	22	5,883	49	1
	23	1,284	11	1
	24	11,067	59	7
Muger	25	4,420	17	4
	26	578	3	7
	27	1,329	6	7
Guder	28	4,896	27	5
	29	3,450	17	5
	30	17,863	121	4
Finchaa	31	6,205	47	3
	32	11,153	104	3
South Gojam	33	5,202	32	7
	34	2,915	31	7
	54	22,815	121	4
	55	6,170	39	4
	56	14,280	85	4
	57	4,803	30	4
	58	1,105	7	4
	59	17,663	108	4
	60	4,633	28	4
	61	972	7	4
Dabus	62	1,092	7	4
	63	3,469	21	4
	64	4,335	31	4
	65	4,590	46	4
	66	1,958	14	4
Beles	67	53,720	530	3
	68	8,500	83	2
	69	85,000	851	2
Total		584,110	4,568	

Table 3.7 Area (ha) of the 25 crops and 7 irrigation patterns (Pat1 to Pat7)

Crop	No	Pat1	Pat2	Pat3	Pat4	Pat5	Pat6	Pat7	Total
Barley	1	17,157	0	0	0	0	0	0	17,157
Castorbeans	2	0	5,844	0	0	0	0	0	5,844
Coffee	3	0	0	0	0	0	0	0	0
Cotton	4	0	0	0	0	0	0	0	0
Fieldpeas	5	0	0	0	0	0	0	0	0
Fruits	6	8,579	0	0	21,137	1,043	3,905	18,399	53,063
Ginger	7	0	0	0	0	0	0	0	0
Grapes	8	0	0	0	21,137	1,043	0	0	22,180
Groundnut	9	0	0	0	21,137	1,043	0	9,200	31,380
Lentils	10	0	0	0	0	0	0	0	0
Maize (dry)	11	34,314	23,375	8,885	42,274	2,087	0	9,200	120,134
Maize (wet)	12	0	0	0	0	0	0	0	0
Noug	13	0	0	0	0	0	0	0	0
Onion	14	8,579	0	0	10,569	522	0	4,600	24,268
Potatoes	15	8,579	5,844	0	0	0	0	9,200	23,622
Red pepper	16	8,579	5,844	4,442	10,569	522	1,952	4,600	36,507
Rice	17	0	0	0	0	0	23,429	0	23,429
Sesame	18	0	0	0	0	0	0	0	0
Sorghum/Teff	19	0	0	0	0	0	0	0	0
Soybean	20	0	11,688	0	21,137	1,043	0	0	33,868
Sudan grass	21	0	0	4,442	0	0	0	0	4,442
Sugarcane	22	17,157	11,688	53,309	0	0	1,952	0	84,105
Sunflower	23	17,157	23,375	0	0	0	0	0	40,532
Tobacco	24	0	5,844	0	0	0	0	0	5,844
Wheat	25	17,157	0	0	21,137	1,043	0	18,399	57,736
Total		137,256	93,500	71,078	169,096	8,346	31,238	73,596	584,110

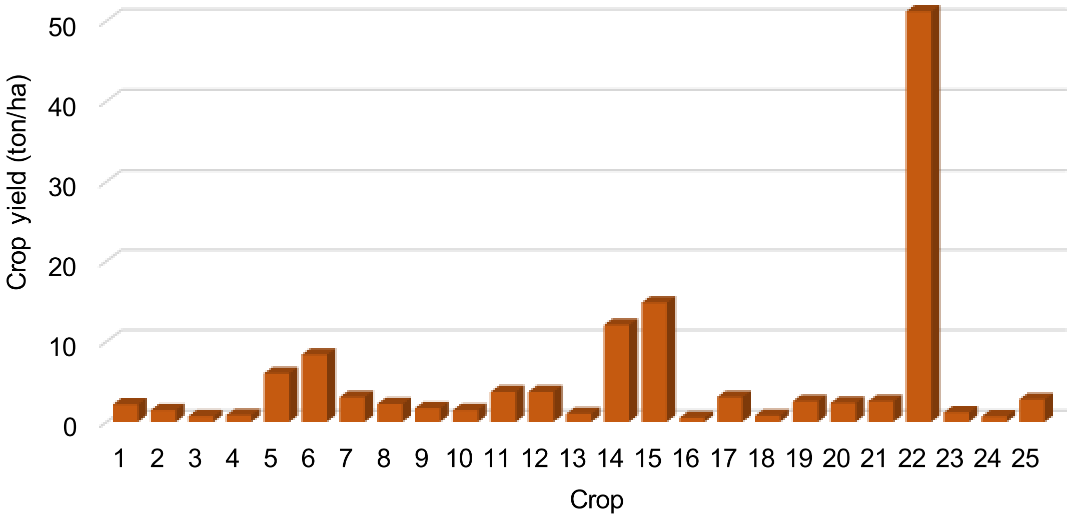

Figure 3.5 Crop yield (ton/ha) of the 25 crops

3.1.6 Economic Data

Information regarding the crop prices in Ethiopia was collected from FAO. The crop prices for the 25 crops, which are used to quantify the economic cost of irrigation, were obtained in the form of agricultural producer price and are shown in Figure 3.6. The agricultural producer price is the price received by farmers for their produce at the farm gate; i.e. at the point where the commodity leaves the farm.

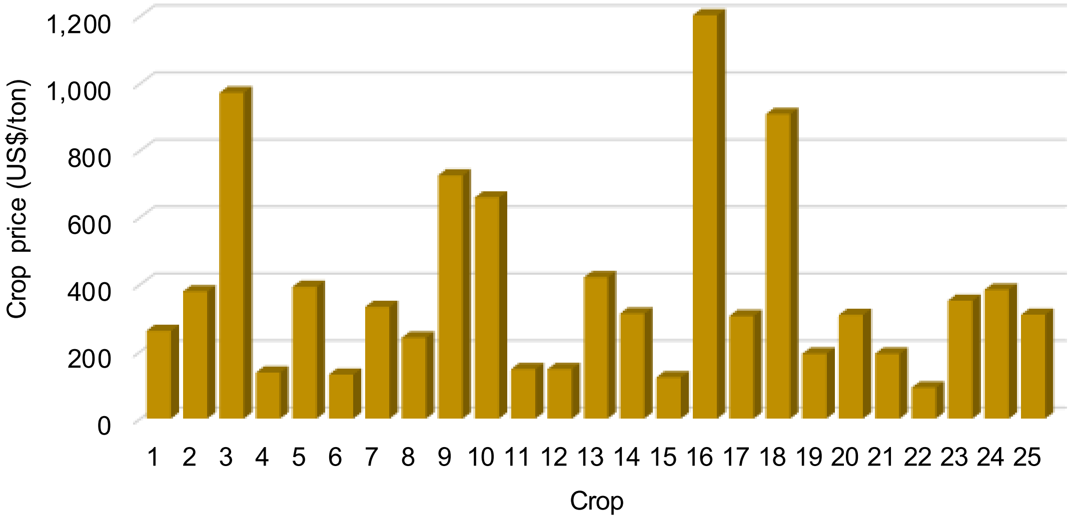

Figure 3.6 Crop price (US$/ton) for the 25 crops in the UBNR basin

For a second, simplified investigation and in order to quantify the water used for irrigation, the Willingness-to-Pay (WTP) was introduced as a parameter, since farmers in the UBNR basin do not pay for irrigation water. The WTP was assumed equal to 0.003

US$/m³ (0.07 ETB/m³) (Kassahun et al. 2016). Apart from the WTP, the simplified investigation was performed for the Net Return (NR) that was assumed equal to 0.05 US$/m³ (1.4 ETB/m³); a value that is consistent with international experience (Goor et al. 2010). Respectively, in order to quantify hydropower production the export price of hydropower was used that equals 0.08 US$/kWh (2.2 ETB/kWh) (Goor et al. 2010).

3.2 Model Selection

In recent decades, numerous models have been developed to assist water resources management. A review of available models was carried out in order to choose the most appropriate model for the purposes of the present work. Based on this review, the most well-known models that include both the aspect of simulation and optimization were selected (Stamou and Rutschmann 2015) and are quoted in Table 3.8. All models are generalized models that may be used in different case studies.

Table 3.8 Selected models and their field of application

Name of model	Field of application
AQUATOOL	Water Resources planning and management
AQUATOR	Tool for water resources modelling
HEC-ResPRM	Optimization of reservoir system operations
Hydronomeas	Simulation and optimal management of water resource systems
MIKE HYDRO BASIN	Integrated river basin analysis, planning and management
MODSIM	River basin Decision Support System and network flow model
OASIS	Operational Analysis and Simulation of Integrated Systems
REALM	REsource ALlocation Model
RiverWare	Modeling river systems
WARGI-DSS	WAter Resources Graphical Interface
WASP	Water Assignment Simulation Package
WaterWare	Water resources management
WEAP	Water Evaluation and Planning System
WRIMS	Water Resources Integrated Modeling System
WRMM	Water Resources Managament Model

The Hydronomeas tool (Koutsoyiannis et al. 2003) was chosen for the management and optimization approach adopted in the present thesis, based on the following criteria:

1. WASP (Kuczera and Diment 1988) was excluded because, although it has the capability of readily modelling a wide range of water supply systems, it is not able to model those with hydropower.

2. The WaterWare web-based system (ESS GmbH 2010) was excluded due to practical reasons (difficulty of handling).

3. The commercial software that were developed by companies or Universities, such as MIKE HYDRO BASIN (DHI 2016), AQUATOR (Oxford Scientific Software Ltd 2014), OASIS (HydroLogics Inc. 2009), and RiverWare (Zagona et al. 2001) were excluded for further analysis due to the lack of availability of the open source.

4. The software with poor technical support or insufficient documentation in English (including scientific papers in peer reviewed journals) was also left out; these are AQUATOOL (Andreu et al. 1996), which was developed at the Universidad Politecnica de Valencia, because the available documentation in English was not sufficient, and Hec-ResPRM (US Army Corps of Engineers 2011) because the US Army Corps of Engineers that developed it, does not provide technical support to non-Corps users.

Among the remaining models (Hydronomeas, REALM, MODSIM, WARGI-DSS, WEAP, WRIMS and WRMM), Hydronomeas was chosen because of its strong two-level optimization implementation and its ability to be combined with other software, e.g. the tool Castalia for the generation of synthetic time-series. More specifically, in the models REALM (Victoria University 2008), MODSIM (Labadie 2010), WEAP (SEI 2011), WRIMS (Parker 2012) and WRMM (Alberta 2013), the optimization aspect is carried out to calculate the optimal water allocation within the simulation procedure. In contrast to that, optimization in Hydronomeas is implemented in two levels: one internal-linear and one external-nonlinear. In more detail, within the process of simulation in Hydronomeas a linear programming model is applied to optimally allocate the state variables through the hydro-system in the least expensive way (Efstratiadis et al. 2004). On the other hand, for the iterative, external optimization of the hydro-system nonlinear algorithms are used to optimize the objective function by determining the control variables using stochastic dynamics. Moreover, Hydronomeas is the core of a broader DSS that includes tools for data processing (Hydrognomon), synthetic data generation (Castalia), and the information subsystem with database, GIS and telemetric system (Koutsoyiannis et al. 2003). Hydronomeas has further advantages. Its mathematical framework is based on the low-dimensional PSO method that exhibits several advantages over a high-dimensional method (Koutsoyiannis and Economou 2003), e.g. simplicity (see Section 3.3.2). 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.

3.3 Hydronomeas

Hydronomeas is a tool for the planning and management of complex multi-reservoir multi-purpose hydro-systems (Koutsoyiannis et al. 2002, Koutsoyiannis et al. 2003) that can be adapted to various hydro-systems. It was developed in an Object Pascal environment (Delphi) by the Department of Water Resources of the National Technical University of Athens (NTUA) in cooperation with companies NAMA Consulting Engineers and Planners SA, and Marathon Data Systems.

Hydronomeas is the core of a broader DSS that also includes

1. tools for data processing (Hydrognomon),
2. synthetic data generation (Castalia), and
3. information subsystem with database, GIS and telemetric system (Koutsoyiannis et al. 2003).

The tool can identify optimal management policies that maximize the system yield and overall operational benefit, and minimize the risk for management decisions (Koutsoyiannis et al. 2002). Hydronomeas comprises of six main steps (Figure 3.7) that 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 production targets.
3. Definition of the objective function, using the parameters as control variables.
4. Simulation and optimization of the hydro-system.
5. Solution of the objective function of the hydro-system.
6. Decision Making.

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.

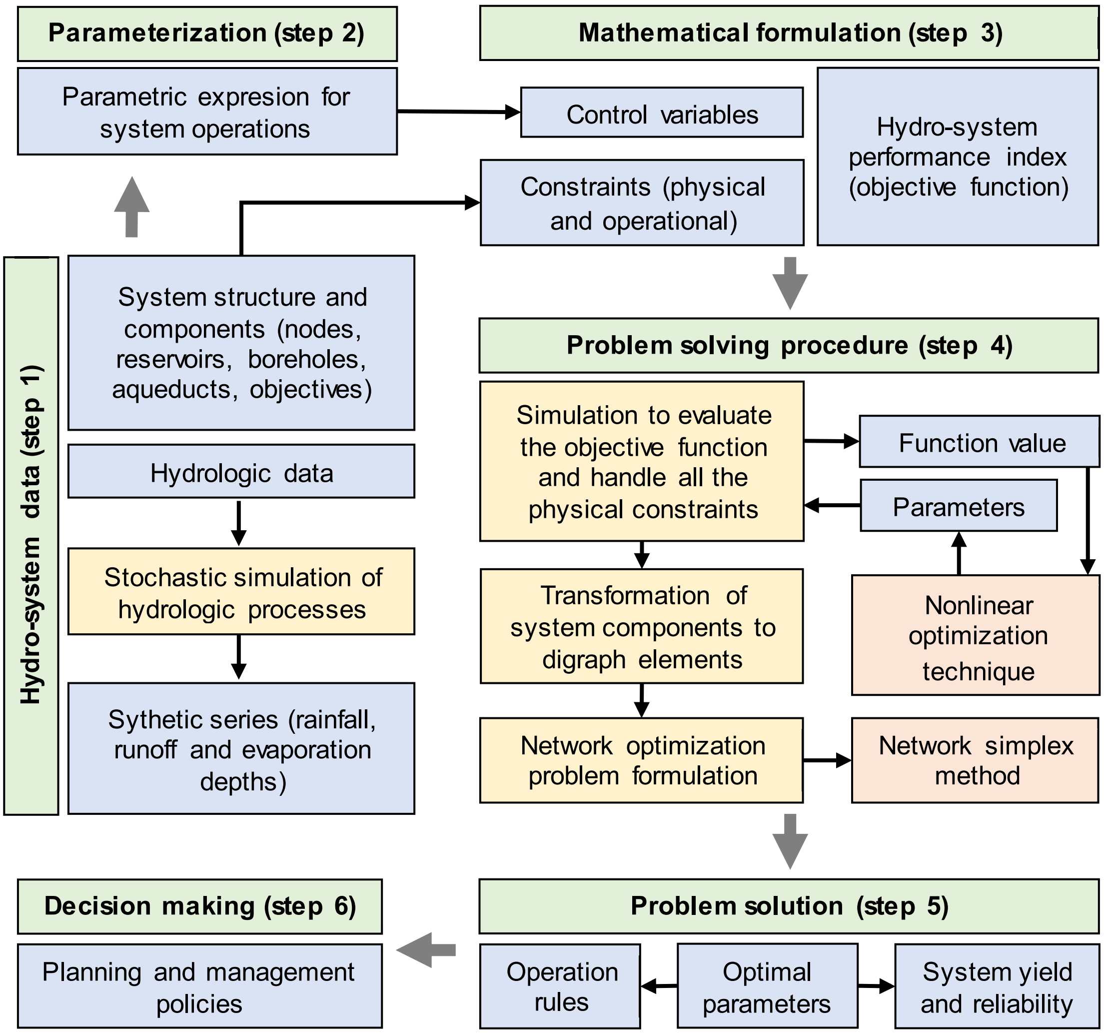

Figure 3.7 Six main steps of Hydronomeas (Koutsoyiannis et al. 2001)

3.3.1 Schematization

A hydro-system can be “described” in Hydronomeas using the various components provided by the tool. These include: junctions (components with no storage capability that correspond to water demand locations or geometry/property changes of the hydro-system), inflow junctions (locations with given water supply), reservoirs (locations where surface water is stored), boreholes (locations where water may be pumped from underground aquifers), river segments (natural components that transfer water without a capacity limit), aqueducts (artificial components that transfer water with limited capacity), turbines (segments where energy may be produced) and pumps (where energy may be consumed).

3.3.2 Parametrization

Hydronomeas uses simulation to obtain values of the objective function (performance index) that is optimized by a nonlinear optimization procedure. Its mathematical framework is based on the PSO method (Koutsoyiannis and Economou 2003). The main idea of this low-dimensional method is the parametric formulation of the hydro-system operation, e.g. reservoir operating rules, hydropower operation. Parametrization is performed by introducing unknown targets to the hydro-system, e.g. HPP targets, during schematization. The targets are treated as unknown control variables that are calculated during a non-linear optimization procedure. The PSO method shows numerous advantages over a high-dimensional method (Koutsoyiannis and Economou 2003), which include (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 (Stamou and Rutschmann 2018).

3.3.3 Simulation

The simulation model in Hydronomeas represents the hydro-system with high accuracy based on physical constraints and imposed operational targets such as irrigation consumption or ecological minimum flow. Since the flows in the network can usually be conveyed via multiple paths, and multiple, contradictory operational targets must be satisfied simultaneously, a flow allocation problem arises. The flow allocation problem demands to strictly satisfy all physical constraints of the hydro-system, handling all operational targets according to a predefined priority series and minimize the total water conveyance cost and system’s losses that are due to spill. At the same time, the deviations between the actual and the desired releases have to be minimized in order to satisfy (or, if not possible, approach) the rules of the system. This is accomplished by formulating the mathematical model of the system as a network optimization problem, which is solved at each time step, assuming that the system’s components and attributes are represented in a digraph form (see Figure 3.8). In the digraph each reservoir is replaced by three nodes: (1) an inflow node, (2) a storage node, and (3) a release node. Virtual arcs are used to represent each variable of the water balance equation and the sum of water that is stored, spilled or consumed is diverted to a “dummy” node. At each arc of the digraph two attributes are imposed, the conveyance capacity and the unit cost. The objective of the problem is the identification of the appropriate flow values in the network that minimize the total transportation cost.

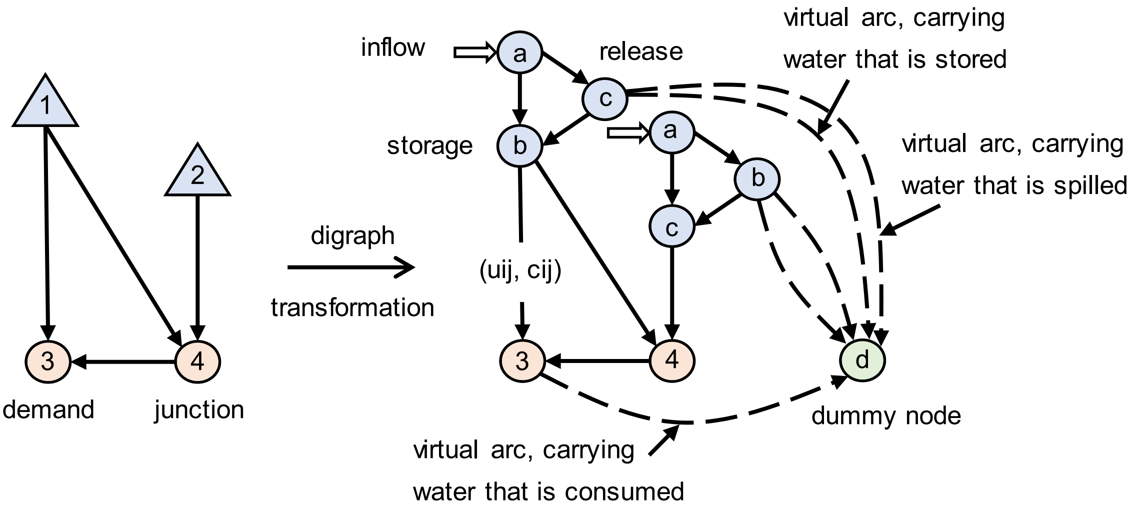

Figure 3.8 Transformation of the hydro-system to a digraph model (Koutsoyiannis et al. 2002)

The mathematical constraints are (a) the continuity equations at each node of the digraph and (b) the capacity constraints at each arc of the digraph. The above optimization model, also known as the transshipment problem, can be solved via linear programming methods like the simplex method, which proceeds by moving from one feasible solution to another, at each step improving the value of the objective function (Bradley et al. 1977). Thus, the simulation procedure at each time step can be described by the following steps:

Step 1: The total net storage of the system is estimated and the target releases from each reservoir are calculated.

Step 2: The system's components are transformed into digraph components and the values of the digraph attributes (inflows, capacities and unit costs) are specified.

Step 3: The flow allocation (transshipment) problem is formulated and solved.

Step 4: The optimal flow values are assigned to the variables of the mathematical model of the hydro-system, in order to express the actual flow quantities.

The flow allocation problem, which is a linear optimization problem, is solved separately in each simulation step (e.g. month). In other words, the system simulation embraces a linear optimization routine that is executed a vast number of times. Fortunately, the linear character of the flow allocation problem enables a fast simulation execution. It is worth mentioning that the Hydronomeas tool may be used as a stand-alone simulation model, without implementation of the optimization module.

3.3.4 Optimization

A hydro-system is usually required to meet multiple and conflicting targets. In such cases, the simulation context, in which the only optimization criterion is the minimization of the transport cost from the resource source to the users, does not ensure viability and sufficient resources over a long-term time period because the concepts of cost and reliability are contradicting. Thus, a more macroscopic view of the problem is required. This is achieved by considering typical management figures of the hydro-system as unknown, and assessing them based on universal criteria that refer to the entire control horizon. These figures are considered as the control variables of an external nonlinear optimization problem, which is to be solved with respect to the criteria (Figure 3.9). The solution of the optimization problem leads to the most appropriate management policy.

In Hydronomeas, a management policy is expressed through parameters of the hydro-system operation, such as the operating rules of reservoirs or the targets. These parameters function as control variables and have a parametric mathematic formulation. The search for the control variables values is performed within a finite interval, which is the feasible space defined by a minimum and maximum value. The management policy is quantified by a performance index, the global numeric indicator that is defined as shown in Equation 3.1:

$$F = \Sigma w_j f_j \tag{3.1}$$

where fj represents the individual criteria and wj represents the weight coefficients. The weight coefficients express the relative importance of several criteria including (1) the average annual water consumption at nodes and reservoirs, (2) the average annual failure probability of selected targets and constraints, (3) the average annual deficit of selected targets and constraints, and (4) the annual firm hydropower production, etc. Based on the definition of the performance index, it is impossible to attribute a physical meaning to it. The performance index is just a mathematical quantity that corresponds to the objective function of the optimization problem and is used as a comparison tool for alternative solutions. In this context, a solution is the set of feasible values for the control variables, suggesting a particular management policy. Introducing different criteria, or changing their corresponding weights, results in different management policies. The procedure of searching for the optimal management policy, represented by the control variables

$x=(x_1, x_2 \ldots x_n)$, is conventionally expressed as a problem of minimizing the function *F* as follows:

$$min\ F(x) = \Sigma wj\ fj(x) \qquad (3.2)$$

The solution to the problem that is non-linear with respect to the x variables is derived through an evolutionary algorithm (Efstratiadis 2001, Efstratiadis and Koutsouyiannis 2002, Rozos et al. 2004). The methodology has been developed to handle water resources optimization problems that are of considerable difficulty due to the particular features of the search space, such as the existence of local extremes on multiple scales and discontinuity. The heuristic technique attempts to combine different methodological approaches by integrating local and global search strategies into a single algorithm to ensure flexibility, aiming at effectively manipulating various geometric features and at the same time investigate the convex areas of the space. The evolutionary annealing-simplex method is used; a heuristic, population-based global optimization technique, originally developed by Efstratiadis and Koutsoyiannis (2002), that couples the strength of simulated annealing with the efficiency of the downhill simplex method. The method is based on the following principles:

1. an evolutionary search process for the parallel exploration of the feasible space of a population of points
2. a set of population evolution rules that use a modified downhill simplex for the offspring generation and mutation procedures
3. a simulated annealing strategy that regulates the degree of randomness in assessing the suitability of the solutions that are produced during the search process.

The computational process begins by generating a random point population, evenly distributed in the search space. The population maintains a constant size that is defined by the user and does not exceed the limits of the feasible space. The optimization process requires a sufficient number of simulations to measure the value of the performance index with respect to different values for the control variables. Every time a new solution is tested, the current values of the control variables are given to the simulation algorithm, which calculates the corresponding value of the performance index. In the initial search stages, the algorithm course is almost random, but progressively stabilizes towards an improving performance index value until converging to a final value. Occasionally, solutions are produced away from the current optimal, in order to escape from possible local extremes.

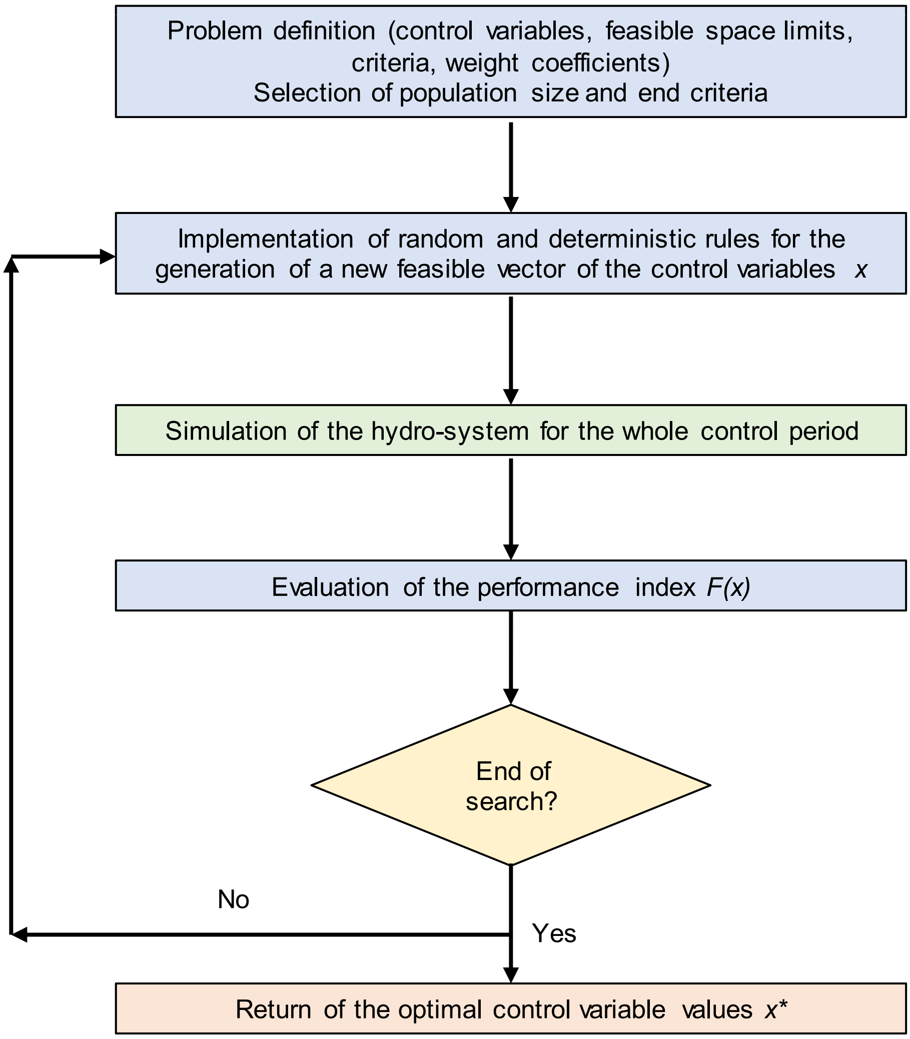

Figure 3.9 Flow diagram of the optimization process (Nikolopoulos 2015)

Before optimization, the user formulates the components of the problem including (1) the number of control variables xi, (2) the limits of the feasible space, i.e. the minimum and maximum values of each control variable, and (3) the number of criteria fj and the corresponding weight coefficients wj, as well as the main arguments of the evolutionary algorithm including (1) the population size and (2) the two optimization termination criteria (the maximum number of simulations and the convergence rate). The population size must be greater than the number of control variables; the greater the population size, the more reliable the search process, but the slower it evolves. A recommended value is two or three times the number of control variables. The maximum number of simulations, which defines the termination criterion usually met first, is empirically set to be at least

100 times greater than the number of control variables. The convergence rate takes values from 1 to 5 % and expresses the relative difference between two successive optimal solutions.

3.3.5 Summary of Advantages and Key Characteristics

The key components of Hydronomeas and their advantages are summarized below.

The schematization of the hydro-system makes it possible to describe all important physical or artificial components without limitations regarding their scale or layout. The user may configure the network of a water resources system of any topology, including water supply and water demand sites, as well as multiple water paths. The characteristics of the various projects as well as the objectives and constraints may change over time, which makes it possible to investigate the effect of changes due to the addition of new projects, the reinforcement of existing ones or the temporary shutdown of certain projects due to maintenance or damage.

Hydronomeas provides a realistic representation of the natural hydrological and hydraulic processes of the hydro-system as well as its management practices. To this aim, the simulation module in Hydronomeas is formulated to ensure that the physical constraints, objectives and operating restrictions of hydro-system are met in accordance with the management policy and order of priority set by the user. This is accomplished without a complicated description of the processes, superfluous and unclear parameters, or excessive data requirements. The user may monitor the simulation dynamically, check the model processes, and identify possible data or schematization errors.

Hydronomeas uses a holistic approach to model the hydro-system, which provides versatility and is highly compatible with IWRM and the WEF nexus approach.

Synthetic input samples in Hydronomeas allow for the probabilistic estimation of the sum of responses of the simulation model. In a steady-state simulation, where the hydro-system conditions are considered unchanged, a single estimate of long-term risk can be calculated. This is particularly useful in case of e.g. design or management studies, where the estimation of certain characteristics for a given level of reliability (or the other way around) is required.

Another strong advantage of Hydronomeas is the introduction of optimization at various scales of the model, with the use of multiple criteria. More precisely, on the time-scale, the model optimizes the total cost of water transfer in a network following the physical constraints (e.g. continuity equations, capacity constraints), meeting the current targets and operating constraints in the predetermined order of priority, and at the same time deviating as little as possible from the desired reservoir output given by the operating rules. These criteria may be integrated in a linear programming model, which ensures precision by using specific algorithms. On the other hand, the parameters of the operating rules of the hydro-system are assessed through a nonlinear optimization process in terms of a universal performance index that includes a wide range of criteria. The criteria are set by the user and may include reliability, economic data, energy and water supply data, which result from the statistical analysis of the simulation results. Thus, two optimization levels are implemented in Hydronomeas; one external, which is non-linear in terms of the operating rule parameters, and one internal, which is linear in the step-by-step decisions.

Last but not least, the PSO method as implemented in Hydronomeas exhibits several advantages over a high-dimensional method (Koutsoyiannis and Economou 2003), such as low computational times (see Section 3.3.2). The simulation and optimization schemes minimize computational demand, which makes it possible to model even very large hydro-systems.

3.3.6 Objective function criteria and control variables for the generation of the Pareto front

In order to optimize the two conflicting targets of hydropower and irrigation in the UBNR hydro-system, multiple iterations of the simulation and optimization procedure are performed. The objective function criteria of the optimization, thereby, were: (1) the total firm hydropower production and (2) the average annual irrigation deficit. Various weights are assigned to the criteria of the objective function that translate to different management policies. Since the irrigation deficit is the amount of water that does not reach the irrigation projects, it represents the failure of a given target. Thus, in the optimization procedure the target of firm hydropower production is to be maximized and the target of irrigation deficit to be minimized, while the firm hydropower production of all HPPs is used as control variable. A minimum and a maximum value was set for each control variable, in order to cover the whole solution range, but also to avoid non-realistic hydropower production targets. The performance index (the solution to the objective function) of the hydro-system is calculated for each optimization run. Thus, every performance index includes the optimum values for the targets of hydropower production and irrigation deficit for a given sets of weights. Based on the concept of Pareto efficiency, which says that an allocation is efficient if an action makes some individuals better off and no individual worse off, the Pareto optimal solutions are selected.

Hydropower and irrigation are treated as conflicting targets, because if water is given to irrigation upstream or earlier in terms of time, it may not be used to generate hydropower downstream or later in terms of time (Stamou and Rutschmann 2017).

3.4 Castalia Tool

The analysis of the historic samples and the generation of synthetic time series in Castalia is performed in three basic steps (Efstratiadis and Koutsoyiannis 2000). First, a synthetic time series at annual timescale is generated. Next, a monthly-scale time series is generated, followed by daily-scale. The synthetic time series are generated with different stochastic models for the different time-scales. In the annual timescale, stochastic models are used that reproduce the long-term persistence of the hydrological processes, known as the Hurst phenomenon. In the monthly and daily timescales, stochastic models are used that reproduce the periodicity and other characteristics of the processes within the finer timescale. In both cases, the stochastic models reproduce the minimum set of the main statistic parameters, namely:

1. the parameters of the margins of the distribution functions of each variable, e.g. average value, dispersion and asymmetry factor, and
2. the parameters of the common distribution functions of the variables, e.g. first-order autocorrelation coefficients and zero-order cross-correlation coefficients.

Thus, the synthetic time series are statistically equivalent to the historic time series. The synthetic time series are generated using the gamma distribution of three parameters. The distribution is considered suitable for describing the hydrological variables at the investigated time scales (annual, monthly, and daily) since it is defined only for positive variable values and can reproduce the asymmetry of very large historic samples.

The generated time series must be consistent at the different time scales, i.e. the monthly time scale should be consistent with the annual time scale and the daily with the monthly. In Castalia, the monthly variables are produced independently from the annual variables and with a different simulation pattern. The daily variables are also produced without any reference to the monthly variables. For this reason, after the initial generation of the time series, a reduction is performed through a “shared methodology”. The methodology is first applied to the monthly values so that their sum is equal to the corresponding annual synthetic value and then to the daily values so that their sum is equal to the corresponding monthly synthetic value; thus obtaining the final daily and monthly output values of the system.

3.5 Pareto Optimization

The Pareto optimization is used to answer research question RQ2 “What are the optimal solutions to allocate water resources between the conflicting users?”

Generally, the aim of the Pareto optimization is to discover how the UBNR hydro-system should work in order to achieve its highest performance, while taking into account various factors, such as constraints. In the UBNR hydro-system, there are more than one conflicting targets and constraints. Thus, this is not the case of a trivial optimization problem with only one single solution that optimizes each objective. Instead, there are conflicting objectives and multiple Pareto optimal solutions (Pareto front). In a Pareto optimal solution, none of the objectives can be improved without degrading some of the objective values. All Pareto optimal solutions are considered equally good, when additional subjective preference information is not available. The Pareto front may assist decision makers and help them to select one compromise without considering the entire solution range.

Pareto efficiency says that an allocation is efficient, if an action makes some individual better off and no individual worse off. A limitation of Pareto efficiency, some ethicists claim, is however that it does not suggest which of the Pareto efficient outcomes is best; thus, Pareto efficiency may not be the only benchmark that a society may wish to use in choosing between alternative public policies (Martorana 2007). It can, however, be a very helpful guide.

3.6 Social Cost-Benefit Analysis

3.6.1 Concept

Via the Pareto optimization, multiple optimal solutions were identified, for which none of the objectives can be improved without degrading one or more of the others; all Pareto optimal solutions are considered equally good without additional subjective preference information (Cheikh et al. 2010).

In the present work, a social cost-benefit analysis (SCBA) is applied to compare the Pareto optimal solutions and identify the most preferable using the net social benefits (NSB) criterion. Thus, the favorable effects (social benefits) and the associated losses (social costs) are estimated for each Pareto optimal solution. Subtracting the total costs from the total benefits, provides an estimate of the NSB to society. The NSB criterion suggests that one should adopt only those solutions that have positive NSB. The adoption of a solution with positive NSB involves an improvement in economic efficiency. The most preferable Pareto optimal solution is the one that yields the highest positive NSB and is considered welfare enhancing according to the Kaldor Hicks criterion. The Kaldor-Hicks compensation test states that a reallocation is a welfare-enhancing improvement to society, if:

1. The winners could theoretically compensate the losers and still be better off; and
2. The losers could not, in turn, pay the winners to not have this reallocation and still be as well off as they would have been if it did occur.

It is worth mentioning that the compensation test is stated in terms of potential compensation. Whether and how the beneficiaries of a policy should compensate the losers involves a value judgement and is a separate decision for a government to make. CBA can be thought of as an accounting framework of the overall social welfare of a solution that illuminates the trade-offs involved in making different social investments (EPA 2010).

3.6.2 Quantification of the Benefits and Costs

The key to performing SCBA lies in the ability to measure the benefits and costs of the Pareto optimal solutions in monetary terms to make them comparable. The maximization of net social benefits in the public sector is thereby equivalent to the maximization of profits in the private sector.

The economic benefit (hydropower production) and the cost (irrigation deficit) are quantified in terms of net economic benefit by using measurable economic units as follows:

1. Benefit of hydropower production. These are calculated by multiplying the annual GWh generated from the HPPs by the export price of kWh; see Section 3.1.6.
2. Cost of irrigation deficit. The cost of irrigation deficit is calculated via a relatively complicated procedure that takes into account the characteristics (e.g. areas, prices) of all non-irrigated irrigated crops; this procedure is described in Section 3.6.3.

For comparison purposes, a simpler approach was also employed, in which the Willingness-To-Pay (WTP) or the Net return (NR) are used as indicators for the economic value of irrigation water; see Section 3.1.6. The cost of irrigation deficit is calculated by multiplying the WTP or NR by the irrigation deficit that is determined by Hydronomeas.

3.6.3 Program IRIDE for the Calculation of the Cost of Irrigation Deficit

The calculation program (Figure 3.10) that was developed in FORTRAN is called IRIDE and consists of three main steps, which are described below.

In the first step of IRIDE, the main parameters are defined such as the number of crops, the number of cropping patterns, the number of irrigation projects and the simulation period (in months).

In the second step of IRIDE, the required input data are provided to the calculation program and checked. These data include (a) the general irrigation data that are described in Section 3.1.5 and (b) the Pareto solution-specific data derived by the calculation with Hydronomeas, as described in Section 3.3.

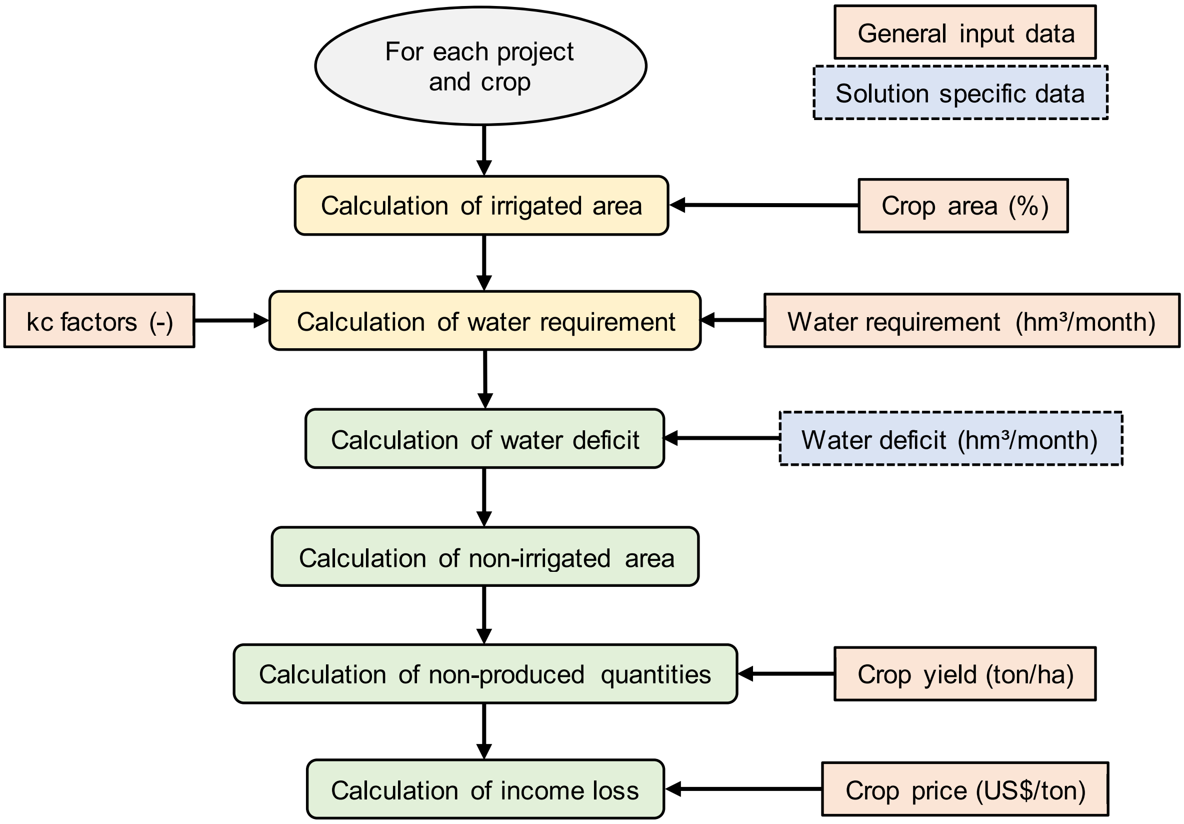

Figure 3.10 Flow chart for calculation of the cost of irrigation deficit in the IRIDE program

The general data include the following:

1. 25 files containing the percentage area (%) of all 25 crops for every one of the 7 cropping patterns (or irrigation project),
2. 25 files of the kc factors (-) of all 25 crops for every cropping pattern,

3. one file for all crops including their yields (tons of crop/ha of cultivated area) and prices (US$/ton),

4. one file containing the total net irrigated area (ha) and the cropping pattern (-) for all irrigation projects; it is noted that every irrigation project has only one irrigation pattern, and

5. one file with the required water quantities (hm^3/month) for all irrigation projects.

The scenario-specific data include an output file of Hydronomeas for each calculation scenario that contains the water deficit for each project and month (million m^3/month). Following the input of data, certain checks are performed for possible calculation errors.

The third step of IRIDE deals with the calculation of all required quantities and relevant checks that include (a) water-requirement calculations that are based on the general input data and (b) scenario-specific water-deficit calculations, which are performed as follows:

1. Calculation of irrigated areas (ha) for each project and crop and check of the total area for all projects and months.

2. Calculation of water needs (hm^3/month) for every project, month and crop and check of the total water needs for all projects and months.

3. Calculation of monthly water needs (hm^3/month), irrigated area (ha), and 'water needs/ha' for every crop (m^3/month ha) and subsequent check of the total water needs and areas for each crop.

4. Calculation of water deficit (hm^3/month) for every project, simulation month and crop, and check of the total water deficits for every simulation month (based on the output file of Hydronomeas).

5. Calculation of non-irrigated areas (ha) for each crop due to the calculated water deficit.

6. Calculation of non-produced quantities of each crop (1,000 tons) due to non-irrigated areas, based on the data given in the first step.

7. Calculation of the loss of income of each crop (million US$) due to non-production of crops irrigated areas, based on the data given in the first step.

8. Calculation of the total loss of income, i.e. the total cost of water deficit (million US$) due to the water deficit for the specific Pareto solution.

IRIDE was developed in a comprehensible way, so that it may be used for a wide range of hydro-systems with varying irrigation projects. By following the commands in the program code, inserting new data, and making small changes, for example to the number of projects or crops, users can calculate the economic cost of the irrigation deficit in any given case.

4 Scenario Definition and Preparation Steps

4.1 Investigated Scenarios

For the investigation of the water resources management in the UBNR basin four scenarios were developed, based on existing information (BCEOM et al. 1998, Kidanewold 2015), and were investigated in the present work. These scenarios that correspond to various development stages of the UBNR basin are shown in Table 4.1. Figure 4.1 summarizes the number of existing and proposed projects for each scenario, and Table 4.2 shows the total reservoir capacity, HPPs' installed capacity and net irrigated area for the four scenarios.

Table 4.1 Development scenarios for the UBNR basin

Name	Scenario	Description
S0	Natural conditions	No development of water resources. The "natural" system without any reservoirs, HPPs or irrigation project groups.
S1	Current conditions	Current development of water resources (2016) that includes five reservoirs, five HPPs and three irrigation project groups.
S2	Short- to medium- term development	Short- to medium-term planned development of water resources; it includes all projects that are existing or under construction and is anticipated to start operating in the short- to medium-term future (before approximately 2020).
S3	Full development	Long-term planned development of water resources that includes all projects that are likely to occur in the future (before approximately 2060).

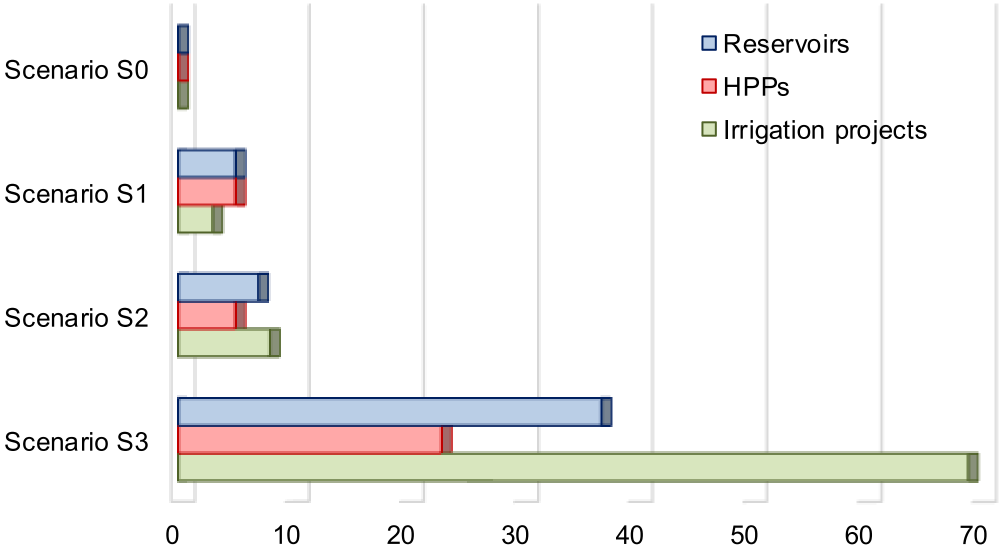

Figure 4.1 Number of reservoirs, HPPs and irrigation projects for all scenarios

Table 4.2 Total reservoir capacity (hm^3), HPPs' installed capacity (MW) and net irrigation area (ha) for all scenarios

Scenario	Reservoir capacity (hm^3)	HPP installed capacity (MW)	Net area (ha)
Natural (S0)	38,686	0	0
Current (S1)	40,192	776	18,522
Short- to Medium-term (S2)	40,669	776	124,210
Full development (S3)	221,452	14,214	584,110

4.1.1 Baseline Scenario: Natural-undisturbed Conditions

The baseline scenario represents the natural state of the UBNR without man-made changes, such as artificial reservoirs, HPPs or irrigation projects; it includes only the natural Lake Tana and all natural river flows. This scenario aims at verifying the simulations performed in Hydronomeas.

4.1.2 Scenario for the Current Conditions

Scenario S1 represents the currently operating reservoirs, HPPs and irrigation projects in the UBNR basin with the characteristics that are shown in Table 4.3 (see also Table 2.1) that include: (1) the number and capacity of the reservoirs, (2) the number and installed capacity of the HPPs, and (3) the number and irrigated net area of the irrigation project groups.

Table 4.3 Number and characteristics of reservoirs, HPPs and irrigation projects for the current conditions

Sub-basin	Reservoirs (No.)	Capacity (hm^3)	HPP (No.)	Installed capacity (MW)	Irrigation (No.)	Net area (ha)
Tana	2	38,769	3	545	1	5,100
Finchaa	3	1,423	2	231	2	13,422
Total	5	40,192	5	776	3	18,522

All projects, which are located in just two (Tana and Finchaa) of the 14 sub-basins, are the following:

I. Five reservoirs: Lake Tana (R1), Koga (R2), Finchaa (R16), Amerti (R17) and Neshe (R18). Lake Tana and Koga are located in the Tana sub-basin, while Finchaa, Amerti and Neshe in the Finchaa sub-basin.

II. Five HPPs: Tana-Beles (HP1), Tis Abbay I (HP2), Tis Abbay II (HP3), Finchaa (HP7) and Neshe (HP8). The HPPs Tana-Beles and Tis Abbay I/Tis Abbay II are located at the two different outlets of Lake Tana, while the HPPs Finchaa and

Neshe are located at the outlets of the Finchaa and Neshe reservoirs, respectively. The utilized water at Tana-Beles is released to the Beles River, the last tributary of the UBNR before the border with Sudan.

III. Three irrigation projects: Koga (IRG1), Finchaa (IRG31) and Neshe (part of IRG32) that are located at the Koga, Finchaa and Neshe reservoirs, respectively.

4.1.3 Short- to Medium-term Development

Scenario S2 represents a short- to medium-term development for the UBNR that includes the projects with the characteristics that are shown in Table 4.4; these are the following:

I. The projects of the current conditions (Scenario S1).

II. Two reservoirs that are Megech (R5) and Ribb (R6) and their corresponding irrigation projects Megech Gravity (IRG9) and Ribb (IRG8).

III. Three irrigation projects that are Megech Pump (IRG10), Didessa Pumping (IRG57) and Upper Beles (IRG67), which are located in the Tana, Didessa and Beles sub-basins, respectively.

It is noted that the difference between scenarios S1 and S2 are two additional reservoirs and four additional irrigation projects, without any HPPs. Therefore, the calculations are expected to show differences that are due to the additional irrigation projects that “compete” the HPPs.

Table 4.4 Number and characteristics of reservoirs, HPPs and irrigation projects for the short- to medium-term development

Sub-basin	Reservoirs (No.)	Capacity (hm³)	HPP (No.)	Installed capacity (MW)	Irrigation (No.)	Net area (ha)
Tana	4	39,246	3	545	4	48,329
Finchaa	3	1,423	2	231	2	17,358
Didessa	0	-	0	-	1	4,803
Beles	0	-	0	-	1	53,720
Total	7	40,669	5	776	8	124,210

4.1.4 Full Development

The full development includes the projects with the characteristics that are shown in Table 4.5; these are briefly 37 reservoirs, 23 HPPs, and 69 irrigation project groups.

Table 4.5 Number and characteristics of reservoirs, HPPs and irrigation projects for the full development scenario

Sub-basin	Reservoirs (No.)	Capacity (hm³)	HPP (No.)	Installed capacity (MW)	Irrigation (No.)	Net area (ha)
Tana	7	39,970	3	545	12	124,919
Welaka	0	-	0	-	1	1,080
Jemma	2	1,284	2	418	7	31,387
North Gojam	0	-	0	-	4	22,366
Muger	3	514	0	-	3	6,327
Guder	2	4,229	1	82	3	26,209
Finchaa	3	1,423	2	231	2	17,358
South Gojam	3	3,296	3	419	12	61,511
Wonbera	0	-	0	-	2	11,899
Anger	2	6,970	1	200	6	44,759
Didessa	7	17,953	3	385	9	73,631
Dabus	3	5,060	3	791	5	15,444
Beles	1	4,640	1	143	3	147,220
Main River	4	136,114	4	11,000	0	-
Total	37	221,452	23	14,214	69	584,110

4.2 Hydro-system Schematization

The schematization of the hydro-system for a given level of development according to the scenarios S0, S1, S2 and S3 was the first step before simulating and optimizing the UBNR hydro-system. The schematization process included the description of the river and the corresponding existing and proposed projects; it was performed using the collected data and Google Earth. During schematization, the physical system of the UBNR was transformed into a mathematical model, whose set-up had the form of a network and consisted of various components that are either autonomous or dependent. The main network components are shown in Table 4.6 and include: nodes, river segments/aqueducts, reservoirs, inflows, and targets. Nodes have two main functions in the network schematization; they are the principal component of the river segments defining their start and end, and are also used as demand areas, e.g. for assigning an irrigation target to a specific area. River segments/aqueducts refer to structures connecting two components in the hydro-system, e.g. reservoirs or nodes, and may represent channels, tunnels, pipelines etc. Reservoirs are important network components and require several input data, e.g. catchment area, spill level, level-volume-area curves, etc. Inflows correspond to water discharge time series in the hydro-system. Finally, targets can be set to the various components of the hydro-system; the most important targets are: hydropower production, irrigation, and the maximum, minimum, and constant flow of river segment/aqueducts. It is worth mentioning that HPPs are defined as units that transport water from one component to the other, generating hydropower. A code was assigned to each component in order to achieve a better overview of the hydro-system. Thus, nodes are noted with the code name RNi, river segments/aqueducts with RSi, reservoirs with Ri, inflows with INi, HPPs with HPi, and irrigation project groups with IRGi, where i the number of the corresponding node, river segment/aqueduct, reservoir, inflow, HPP and irrigation project group, respectively.

Table 4.6 Network components in Hydronomeas used for the schematization of the UBNR

Component	Code name	Autonomous/ dependent
Node	RN	Autonomous
River segment/aqueduct	RS	Dependent
Reservoir	R	Autonomous
Inflow	INi	Dependent
Target	HPi, IRGi	Dependent

4.3 Synthetic Time-Series Generation

Synthetic time-series were generated for the full development scenario using the Castalia tool. The time-series were generated for: river flows, reservoir inflows, rainfall and evaporation. Generally, synthetic time-series represent accurately the characteristics of the historical time-series, when their length is infinite. In the present work and in order to retain the statistical characteristics of the historical time-series, a length of 1,000 years, i.e. 12,000 simulation steps, was chosen for the synthetic time series, assuming this length is sufficient in order for the results to be impartial (Nikolopoulos 2015). Thus, stochastic simulation was used to generate the synthetic time-series, while the maximum allowed mean square error was set to 0.05, the maximum number of departures from several initial (random) values to 5, and the convergence criterion (optimization routine) to 10^{-5}. For the random number generation, the gamma distribution random numbers and the rejection method (three parameters) were applied. For the annual model parameters, the mean values symmetric model SMA was used, with the Fast Fourier Transform (FFT) for the estimation of the a-coefficients. For the monthly time series generation iterative algorithm, the convergence criterion was set to 0.25 and the maximum number of iterations to 100. For the annual auto-correlogram and the parameters fit criterion, the conservation of the coefficient R1 was applied. The persistence parameter β was set to 2.0 empirically, due to the relatively small length of the historical time-series.

4.4 Targets, Constraints and Priorities

The multi-dimensionality of the UBNR basin was taken into account in the present work, by assigning various targets and constraints in the hydro-system. To consider political issues, but also the protection of the river, tourism and the needs of people, minimum ecological flows were assigned downstream of reservoirs. At the southern outlet of Lake Tana, a minimum ecological flow was introduced in order to provide the Blue Nile falls that attract a lot of tourists every year, with a sufficient amount of water. Moreover, a minimum reservoir level was assigned to Lake Tana to ensure navigation that is important for the everyday life of people living in the area and for touristic purposes. Finally, targets were assigned to hydropower production and irrigation demand. Hydropower affects electricity production and thus the life quality of people in the region, while irrigation has an impact on food security (Stamou and Rutschmann 2017). Different priorities were assigned to the targets and constraints. Since agriculture plays a very important role in Ethiopia, it is assumed that irrigation has a higher priority than hydropower. The ecological flow is given a lower priority than hydropower and irrigation.

5 Calculations and Discussion

5.1 Calculations for Natural Conditions

The UBNR hydro-system was simulated in its natural-undisturbed conditions (Scenario S0) using a monthly time step and historical data of the period 1968-1992, i.e. for 25x12=300 simulation steps. In the natural situation of the UBNR hydro-system only Lake Tana (R1) and the 13 tributaries that are shown in Figure 5.1 are considered.

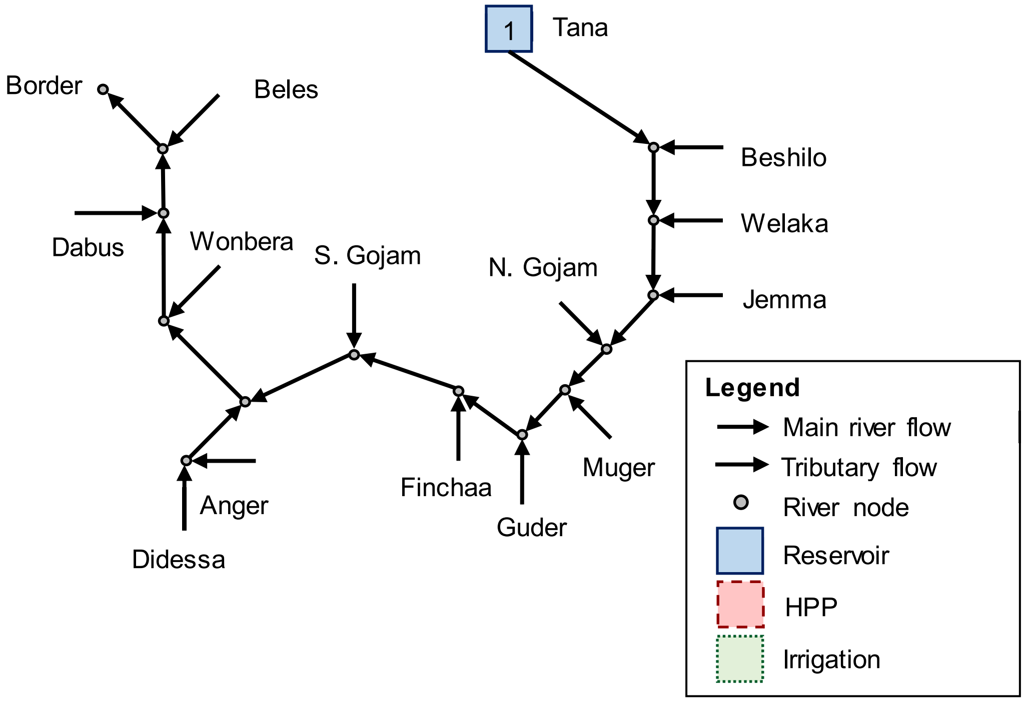

Figure 5.1 Schematization of the UBNR hydro-system for the natural conditions

The scope of the calculations was to determine the water mass balance in the natural UBNR hydro-system using water mass balance-continuity equations based on the collected input data.

5.1.1 Water Balance of Lake Tana

In Table 5.1 the average values of all water balance components of Lake Tana are presented, while in Figure 5.2 the monthly variation of the lake inflow and outflow are shown. Figure 5.3 shows, furthermore, the monthly variation of the water elevation of the lake; it is noted that the initial water elevation was taken equal to 1786.4 m based on the water elevation of December 1967 (last month before the simulation period). This value is 2.4 m higher than the intake level (1784.0 m), while the spill level is equal to 1789.0 m. The mean water elevation of Lake Tana was calculated to 1786.0 m that corresponds to a mean area of approximately 3,018 km², while the minimum and maximum values were calculated to 1785.1 m and 1787.3 m, respectively.

Table 5.1 Water balance components of Lake Tana

Component	km³/y	mm
Rainfall	3.89	1290
Evaporation	5.02	1664
Inflow	4.73	1568
Outflow	3.63	1203
Closure term	-0.03	

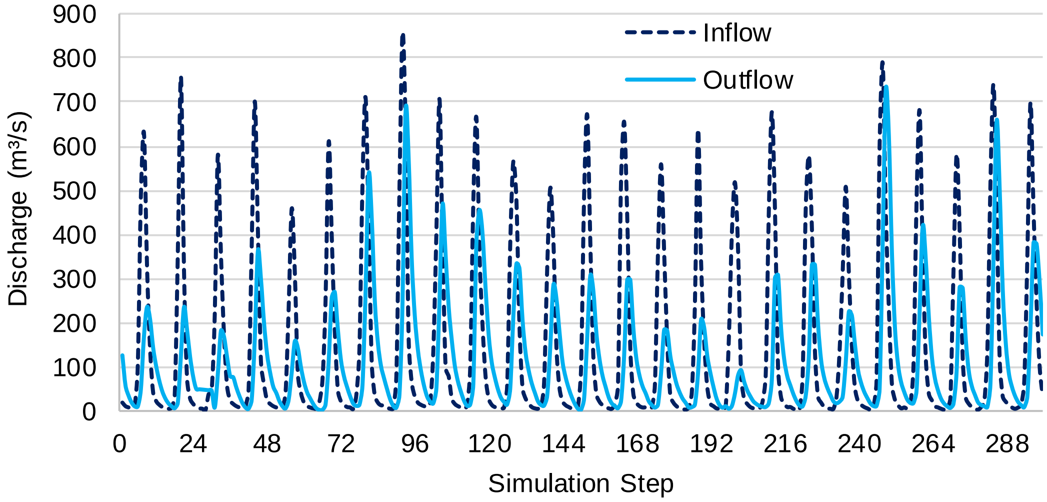

Figure 5.2 Inflow and outflow (m³/s) of Lake Tana in the period 1968-1992

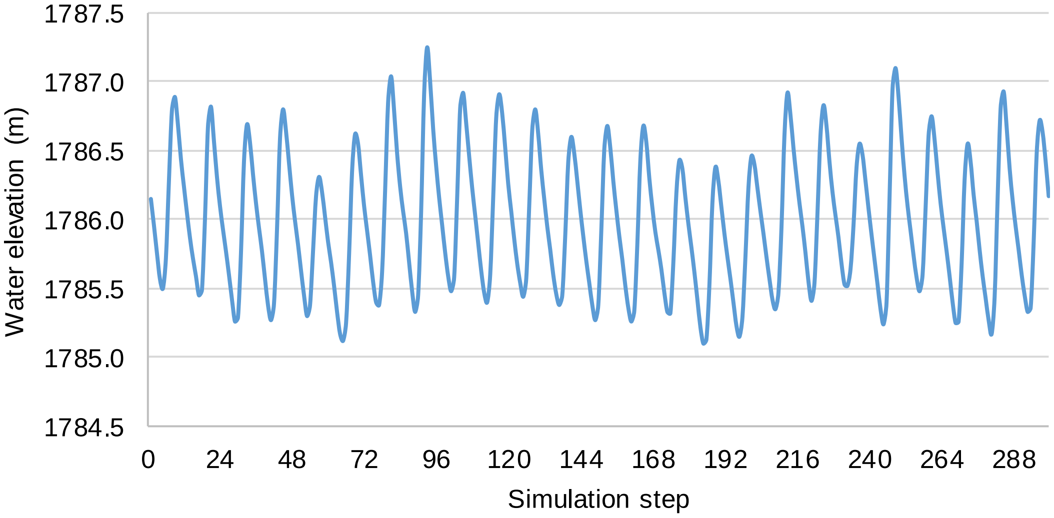

Figure 5.3 Water elevation (m) of Lake Tana in the period 1968-1992

5.1.2 Discharges of the Tributaries and Border

In Figures 5.4, 5.5 and 5.6 the monthly variation of the discharge of the six most important tributaries Jemma (A4), South Gojam (A9), Wonbera (A10), Dabus (A13), Anger (A11) and Didessa (A12) are shown. Figure 5.7 shows, furthermore, the percentage of each tributary in relation to the total discharge at the border between Ethiopia and Sudan. In Figure 5.8 the variation of the discharge at the border throughout the years is also shown, while the mean monthly discharge equals 1,562 m³/s.

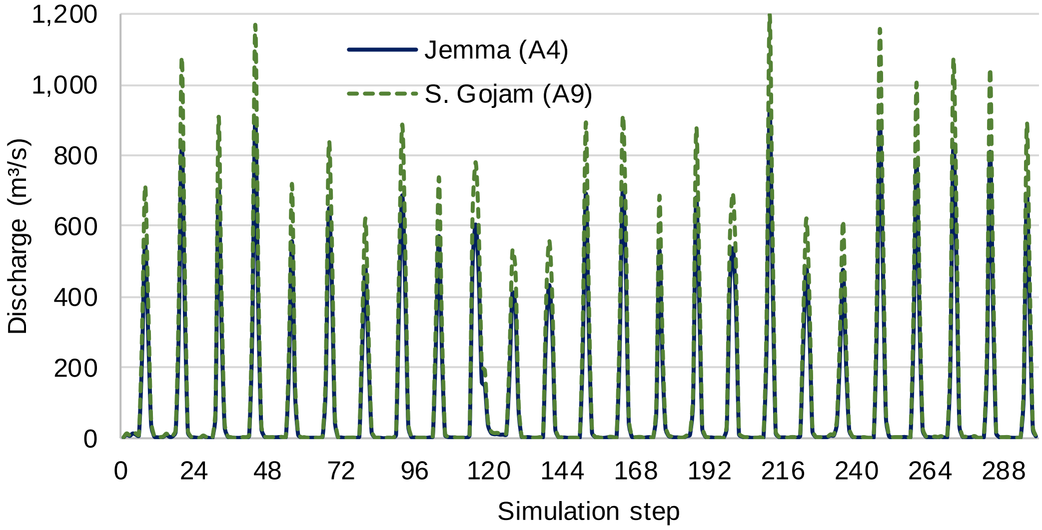

Figure 5.4 Discharge (m³/s) of the tributaries Jemma and South Gojam in the period 1968-1992

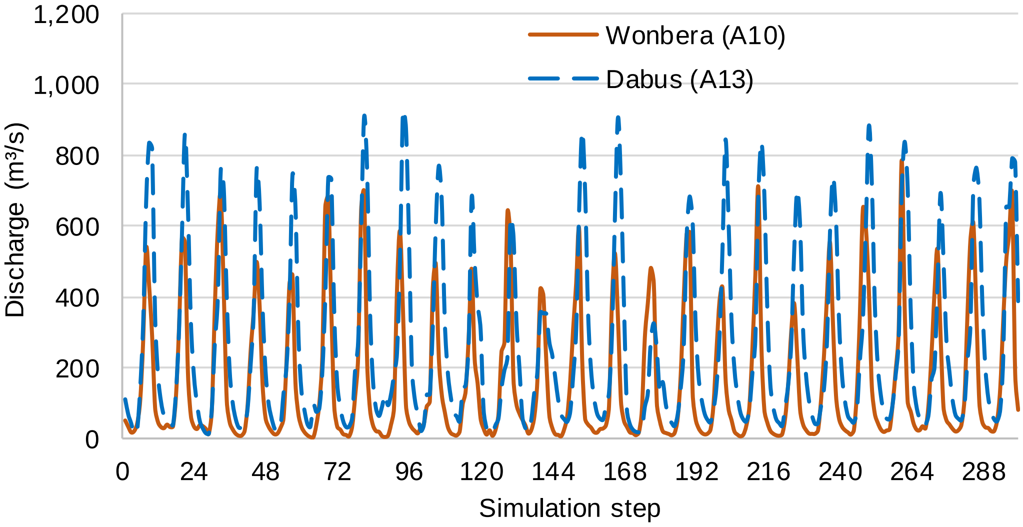

Figure 5.5 Discharge (m³/s) of the tributaries Wonbera and Dabus in the period 1968-1992

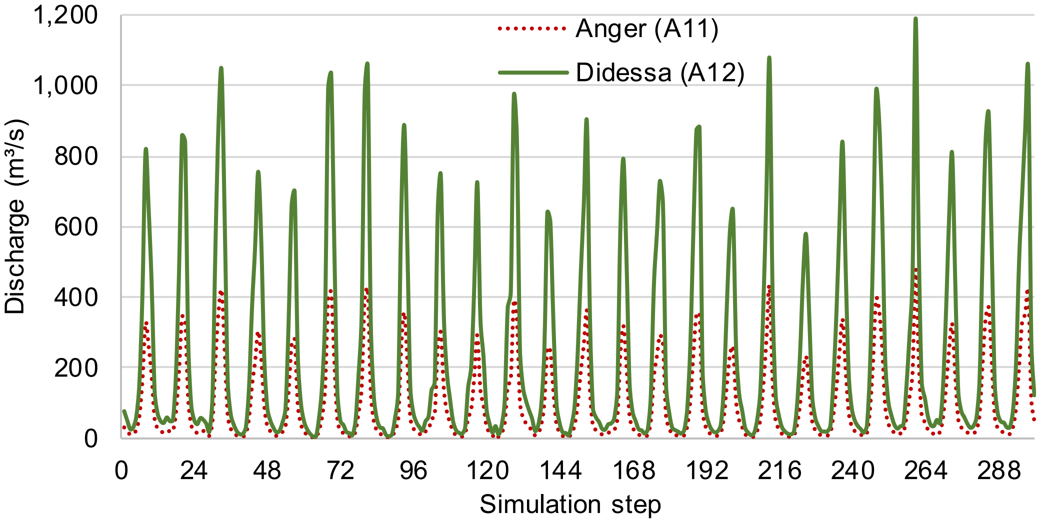

Figure 5.6 Discharge (m³/s) of the tributaries Anger and Didessa in the period 1968-1992

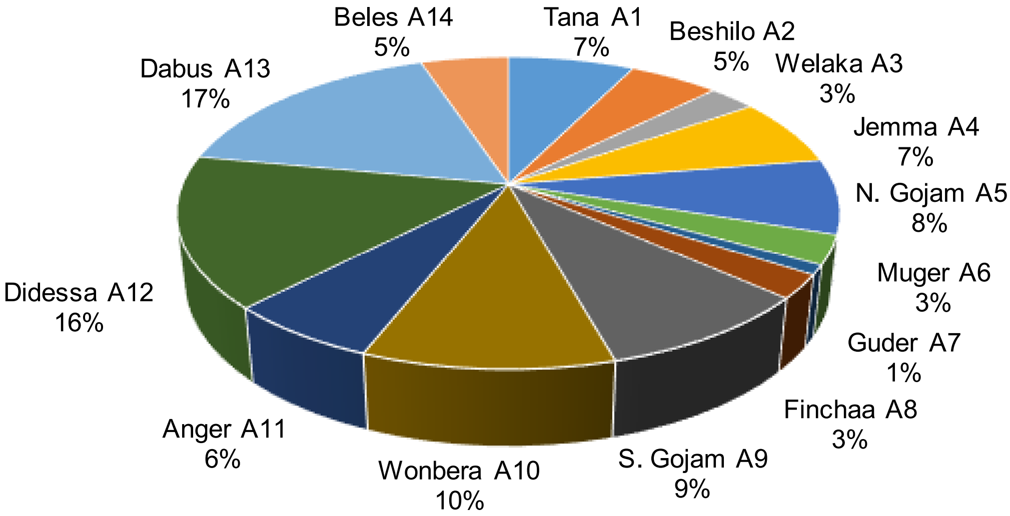

Figure 5.7 Percentage values (%) of the tributaries in the period 1968-1992

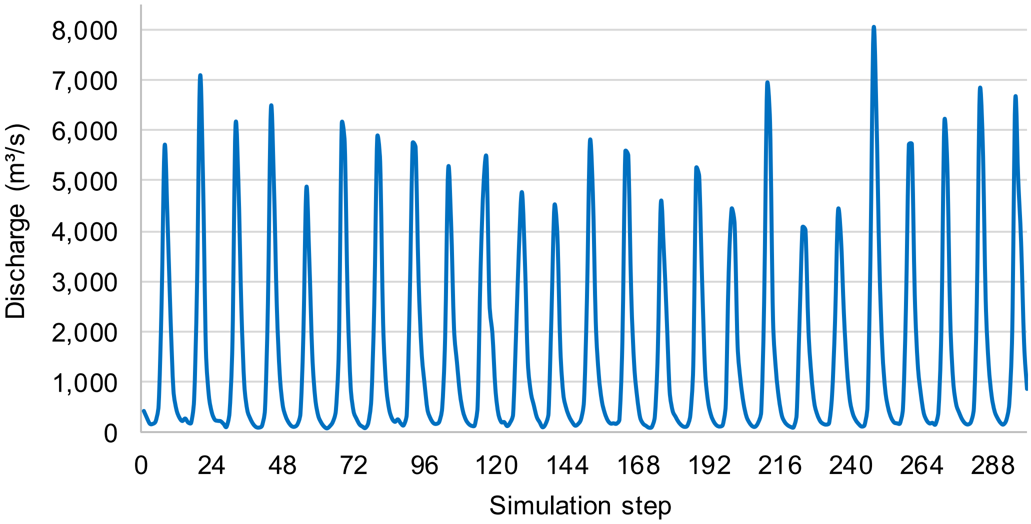

Figure 5.8 Discharge (m³/s) at the border in the period 1968-1992

5.2 Calculations for Current Conditions

5.2.1 Input Data and Simulations

For the current conditions, the simulated UBNR hydro-system that is shown in Figure 5.9 included five lakes/reservoirs, five hydropower projects (HPP) and three irrigation project groups (IRG). Two of the lakes/reservoirs, which are Tana (R1) and Koga (R2), are located in the Tana sub-basin, and three, which are Finchaa (R16), Amerti (R17) and Neshe (R18), in the Finchaa sub-basin. The five HPPs are Tana-Beles (HP1), Tis Abbay I (HP2), Tis Abbay II (HP3), Finchaa (HP7) and Neshe (HP8), while the three irrigation projects are Koga (IRG1), Finchaa (IRG31) and Neshe (IRG32’, part of IRG32); these receive water by the reservoirs Koga, Finchaa and Neshe, respectively. The HPPs Tana-Beles and Tis Abbay I/Tis Abbay II are located at the two different outlets of Lake Tana, while the HPPs Finchaa and Neshe are located at the outlets of the reservoirs Finchaa and Neshe, respectively. The utilized water at Tana-Beles is released to the Beles River, the last tributary of the UBNR before the border of Ethiopia with Sudan. The HPPs Tis Abbay I and Tis Abbay II are considered as stand-by stations for the current conditions (SMEC 2008).

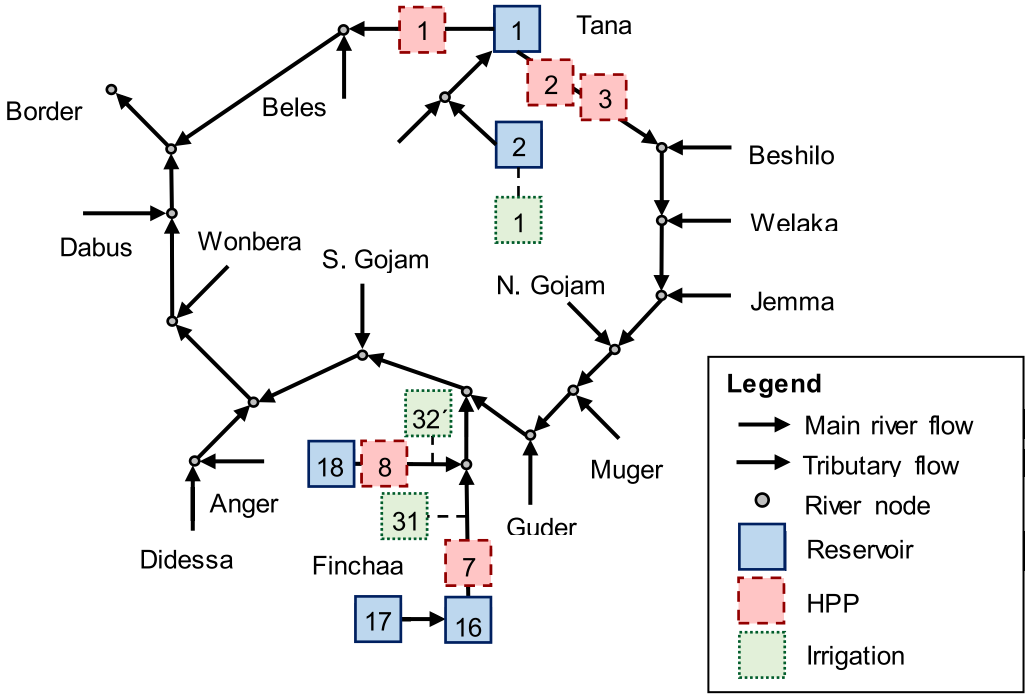

Figure 5.9 Schematization of the UBNR hydro-system for the current conditions

The input data included the following:

1. the characteristics of the rivers and their tributaries (discharges),

2. the reservoirs (inflows, outflows, rainfall, evaporation, catchment area, spill-initial-intake elevation, elevation-volume and elevation-area curves),
3. the HPPs (discharge and installed capacity, head, efficiency),
4. the irrigation projects and the associated targets (irrigation demand target), and
5. constraints imposed by environmental and social aspects (maximum and minimum reservoir operating levels, ecological flows that were assumed equal to a percentage of the reservoir inflow).

Mean monthly values for river discharges have been used. Priorities were introduced for the targets and constraints; with “priority of level 1” representing the most important. Agriculture has a very important role in Ethiopia; thus, irrigation projects are given a higher priority than HHPs. Moreover, reservoir ecological flow is given a lower priority than HPPs and irrigation. Table 5.2 summarizes the basic model input data of the reservoirs, HPPs and irrigation projects.

Table 5.2 Basic model input data of the reservoirs, HHPs and irrigation projects for the current conditions

Sub-basin	Reservoir	Net irrigation area (ha)	Irrigation demand (hm^3/y)	Installed capacity (MW)
Tana (A1)	Lake Tana (R1)	-	-	460 (HP1), 12 (HP2), 73 (HP3)
	Koga (R2)	5,100 (IRG1)	50 (IRG1)	-
Finchaa (A8)	Finchaa (R16)	6,205 (IRG31)	47 (IRG31)	134 (HP7)
	Amerti (R17)	-	-	-
	Neshe (R18)	7,217 (IRG32’)	67 (IRG32’)	97 (HP8)
Total		18,522	164	776

The calculations of main interest are (1) hydropower production, (2) irrigation demand and deficit and (3) discharge at the border.

5.2.2 Hydropower Production

The variation of the monthly hydropower production of the HPPs Tana-Beles, Finchaa and Neshe is shown in Figure 5.10, while the total annual production was calculated equal to 3,251 GWh/y. The individual values of the HPPs are: Tana-Beles = 2,405 GWh/y, Finchaa = 634 GWh/y, and Neshe = 212 GWh/y. The hydropower amount is produced by only three currently existing HPPs, since it is assumed that Tis Abbay I and Tis Abbay II are only operating as stand-by stations.

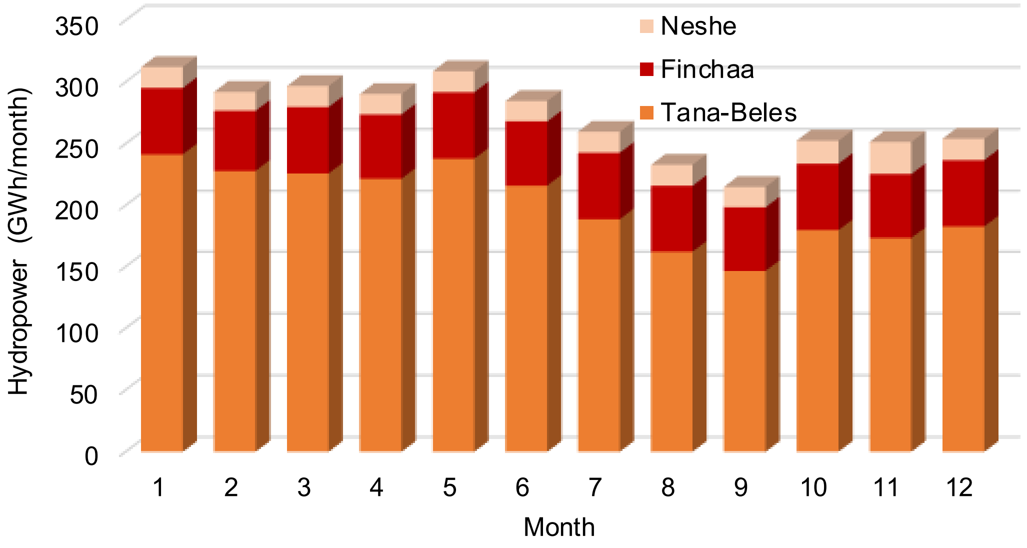

Figure 5.10 Monthly hydropower production (GWh/month) for the current conditions

5.2.3 Irrigation Demand and Deficit

The variation of the total monthly irrigation demand is shown in Figure 5.11. The annual irrigation demand is determined equal to 164 hm³/y. No irrigation deficit is observed for the current conditions; thus, the target of irrigation is met.

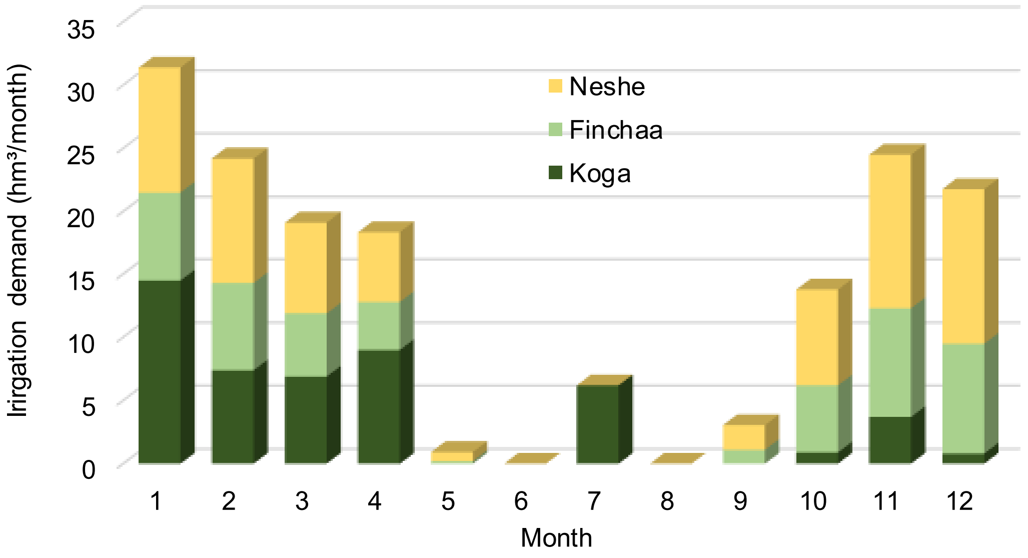

Figure 5.11 Monthly irrigation demand (hm³/month) for the current conditions

5.2.4 Discharges of the Tributaries and Border

The variation of the discharge throughout the year for the six most important tributaries Jemma (A4), S. Gojam (A9), Wonbera (A10), Anger (A11), Didessa (A12) and Dabus (A13) is presented in Figure 5.12. In Figure 5.13 the discharge at the border to Sudan is shown, while the mean monthly discharge equals 1,551 m³/s.

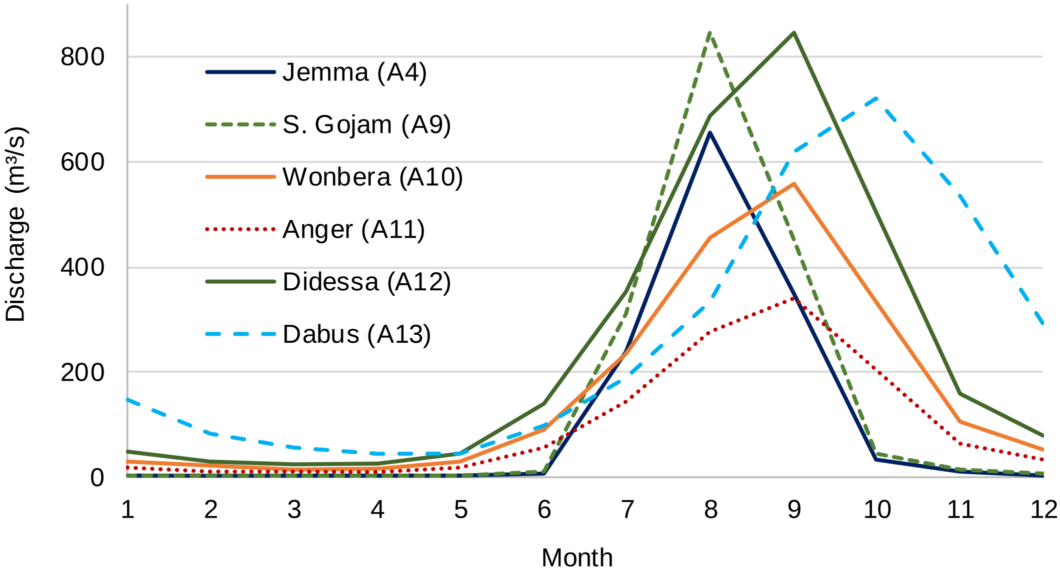

Figure 5.12 Discharge (m³/s) of important tributaries for the current conditions

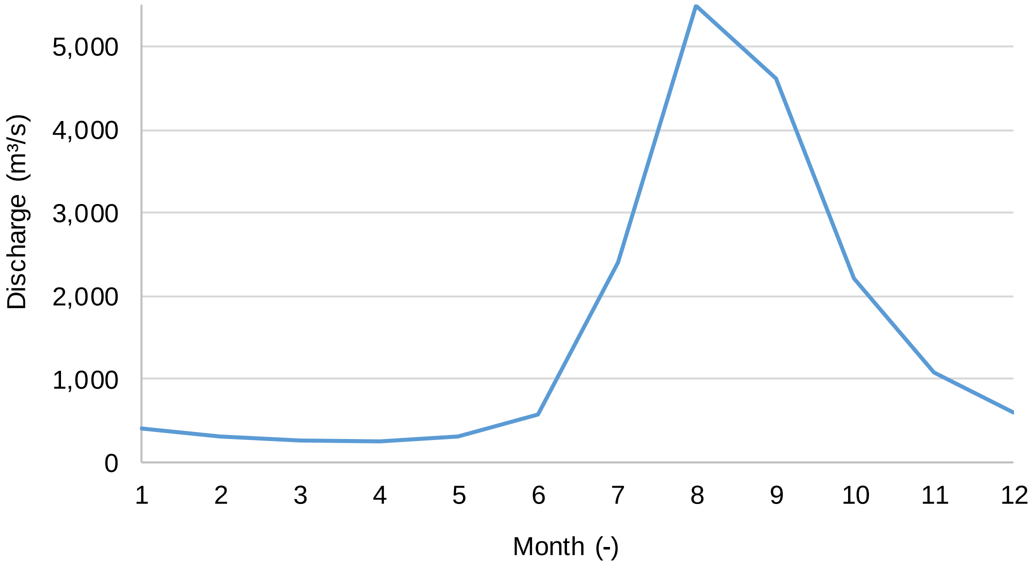

Figure 5.13 Discharge (m³/s) at the border for the current conditions

5.3 Calculations for the Short- to Medium-term Development

5.3.1 Input Data and Simulations

The short- to medium-term development included the currently constructing reservoirs, HPPs and irrigation project groups that are anticipated to start operating in the short- to medium-term future (before approximately 2020). These include the reservoirs Megech (R5) and Ribb (R6) and their corresponding irrigation projects Megech Gravity (IRG9) and Ribb (IRG8), respectively, as well as the irrigation projects Megech Pump (IRG10', part of IRG10), Didessa Pumping (IRG57) and Upper Beles (IRG67) that are located in the Tana, Didessa and Beles sub-basins, respectively, as shown in Figure 5.14. The Megech Pump project receives water from Lake Tana, while Didessa Pumping and Upper Beles receive water from the Didessa and Beles Rivers, respectively. Table 5.3 summarizes the basic model input data of the reservoirs, HPPs and irrigation project groups for the short- to medium-term development.

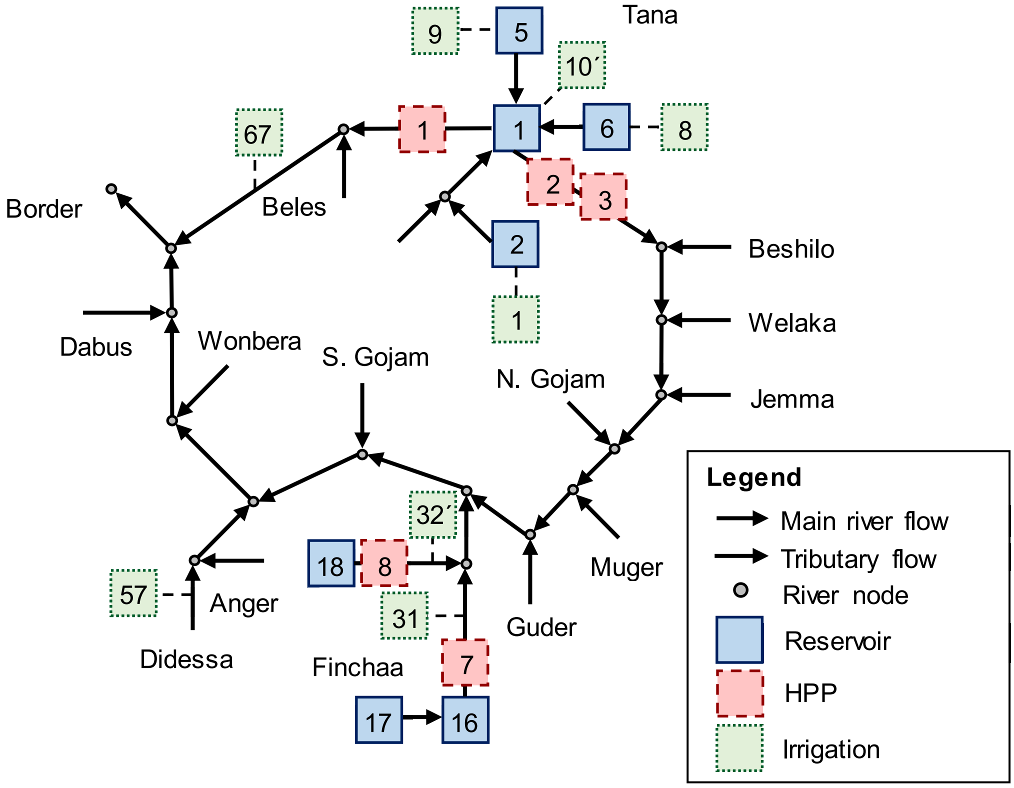

Figure 5.14 Schematization of the UBNR hydro-system for the short- to medium-term development

Table 5.3 Basic model input data of the reservoirs, HHPs and irrigation projects for the short- to medium-term development

Sub-basin	Reservoir	Net irrigation area (ha)	Irrigation demand (hm³/y)	Installed capacity (MW)
Tana (A1)	Lake Tana (R1)	15,993 (IRG10’)	128 (IRG10’)	460 (HP1), 12 (HP2), 73 (HP3)
	Koga (R2)	5,100 (IRG1)	50 (IRG1)	-
	Megech (R5)	7,311 (IRG9)	58 (IRG9)	
	Ribb (R6)	19,925 (IRG8)	197 (IRG8)	
Finchaa (A8)	Finchaa (R16)	6,205 (IRG31)	47 (IRG31)	134 (HP7)
	Amerti (R17)	-	-	-
	Neshe (R18)	11,153 (IRG32)	104 (IRG32)	97 (HP8)
Didessa (A12)		4,803 (IRG57)	30 (IRG58)	
Beles (A14)		53,720 (IRG67)	530 (IRG67)	
Total		124,210	1,144	776

5.3.2 Hydropower Production

Calculations showed that total annual hydropower production is equal to 2,777 GWh/y. The variation of the total mean monthly hydropower prodcution is shown in Figure 5.15, while the individual values of the HPPs are: Tana-Beles = 1,719 GWh/y, Tis Abbay I = 24 GWh/y, Tis Abbay II = 79 GWh/y, Finchaa = 723 GWh/y, and Neshe = 232 GWh/y. The duration curve of the monthly hydropower production is shown in Figure 5.16.

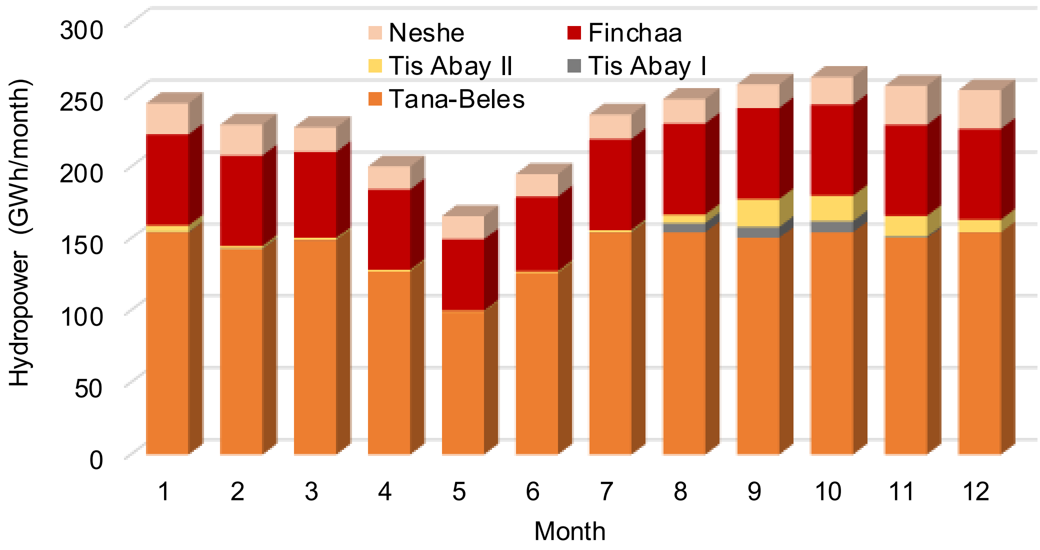

Figure 5.15 Mean monthly hydropower production (GWh/month) for the short- to medium-term development

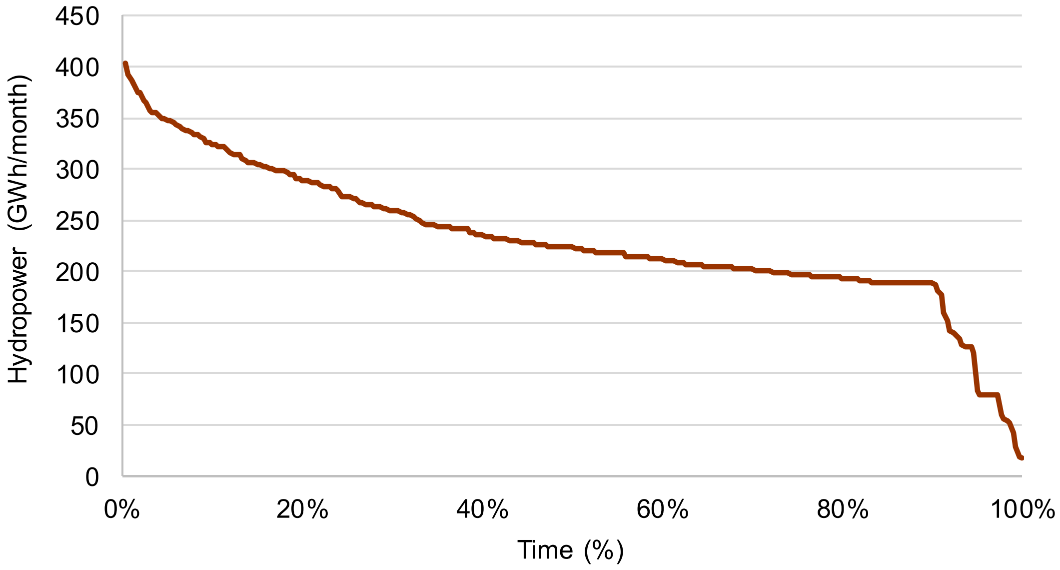

Figure 5.16 Duration curve (%) of the monthly hydropower production for the short- to medium-term development

5.3.3 Irrigation Demand and Deficit

The annual irrigation demand was estimated to 1,144 hm³/y, while the actual annual irrigation amount was calculated to 1,045 hm³/y. The variation of the total actual irrigation amount throughout the year is shown in Figure 5.17, while the resulting irrigation deficit was calculated at approximately 98 hm³/y and is shown in Figure 5.18 for every irrigation project group.

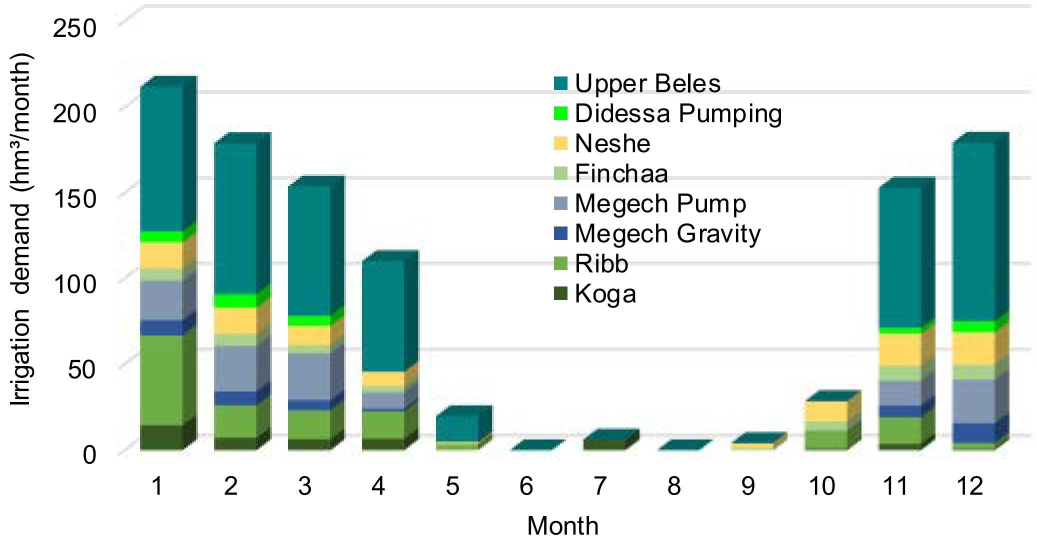

Figure 5.17 Mean monthly actual irrigation amount (hm³/month) for the short- to medium-term development

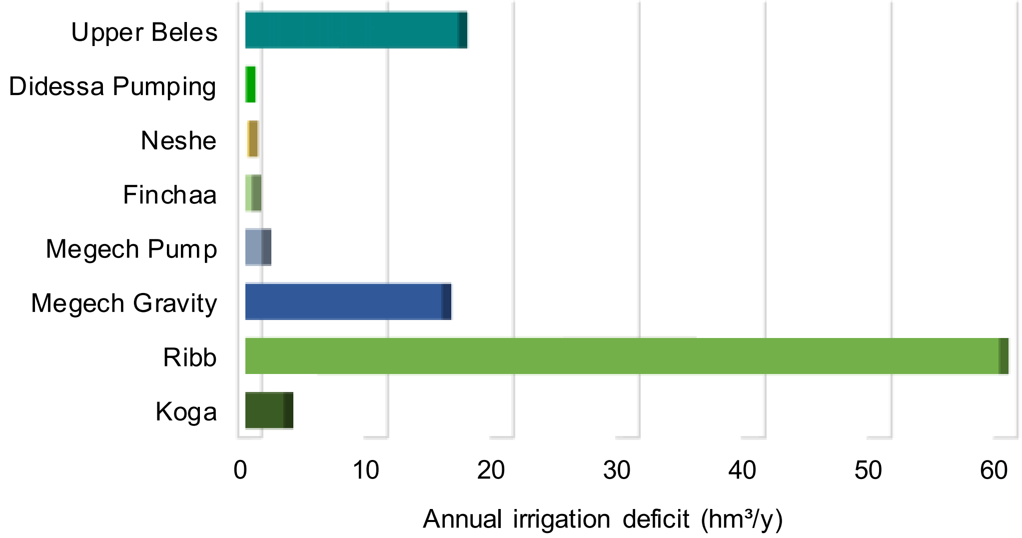

Figure 5.18 Mean annual irrigation deficit (hm³/y) for the short- to medium-term development

5.3.4 Discharges of the Tributaries and Border

In Figure 5.19 the variation of the discharge of the tributaries Didessa (A12) and Beles (A14), at which projects were implemented, is shown. Figure 5.20 shows, furthermore, the variation of the discharge at the border, while the mean monthly discharge equals 1,501 m³/s.

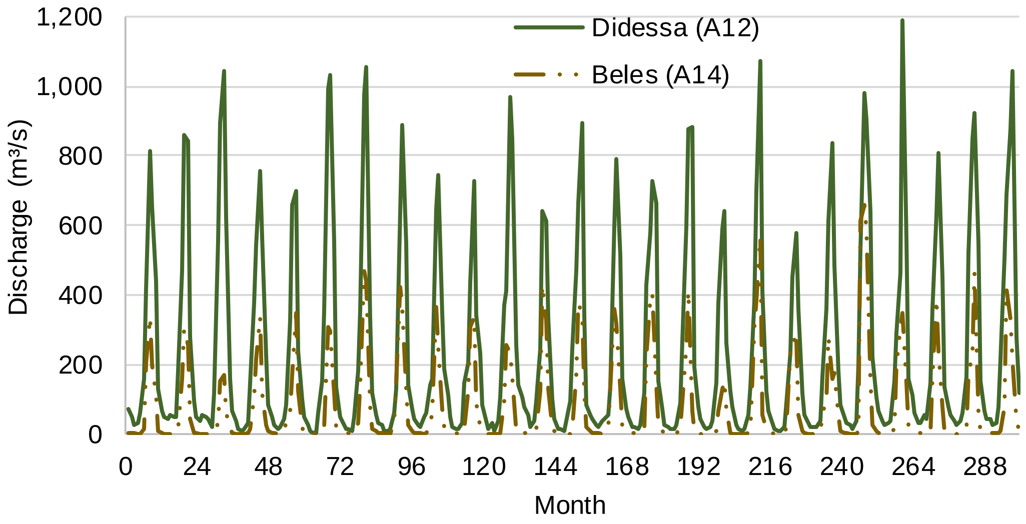

Figure 5.19 Discharges (m³/s) of the tributaries Didessa (A12) and Beles (A14) for the short- to medium-term development

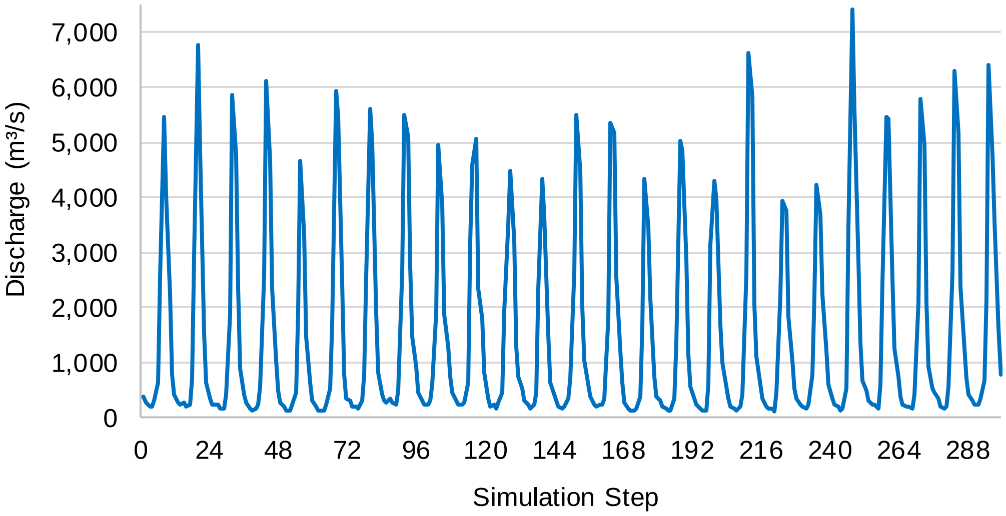

Figure 5.20 Discharge (m³/s) at the border for the short- to medium-term development

5.4 Calculations for the Full Development

5.4.1 Input Data and Simulations

The full development (Scenario S3) included all reservoirs, HPPs and irrigation project groups that are likely to occur in the future (before approximately 2060). These include 37 reservoirs, 23 HPPs and 69 irrigation project groups, as shown in Figure 5.21. Table 5.4 summarizes the basic model input data of the reservoirs, HPPs and irrigation project groups for the full development. Synthetic time series of 1,000 years have been used for the river discharges based on historical data of the years 1968-1992; the simulation steps are equal to 1,000x12=12,000.

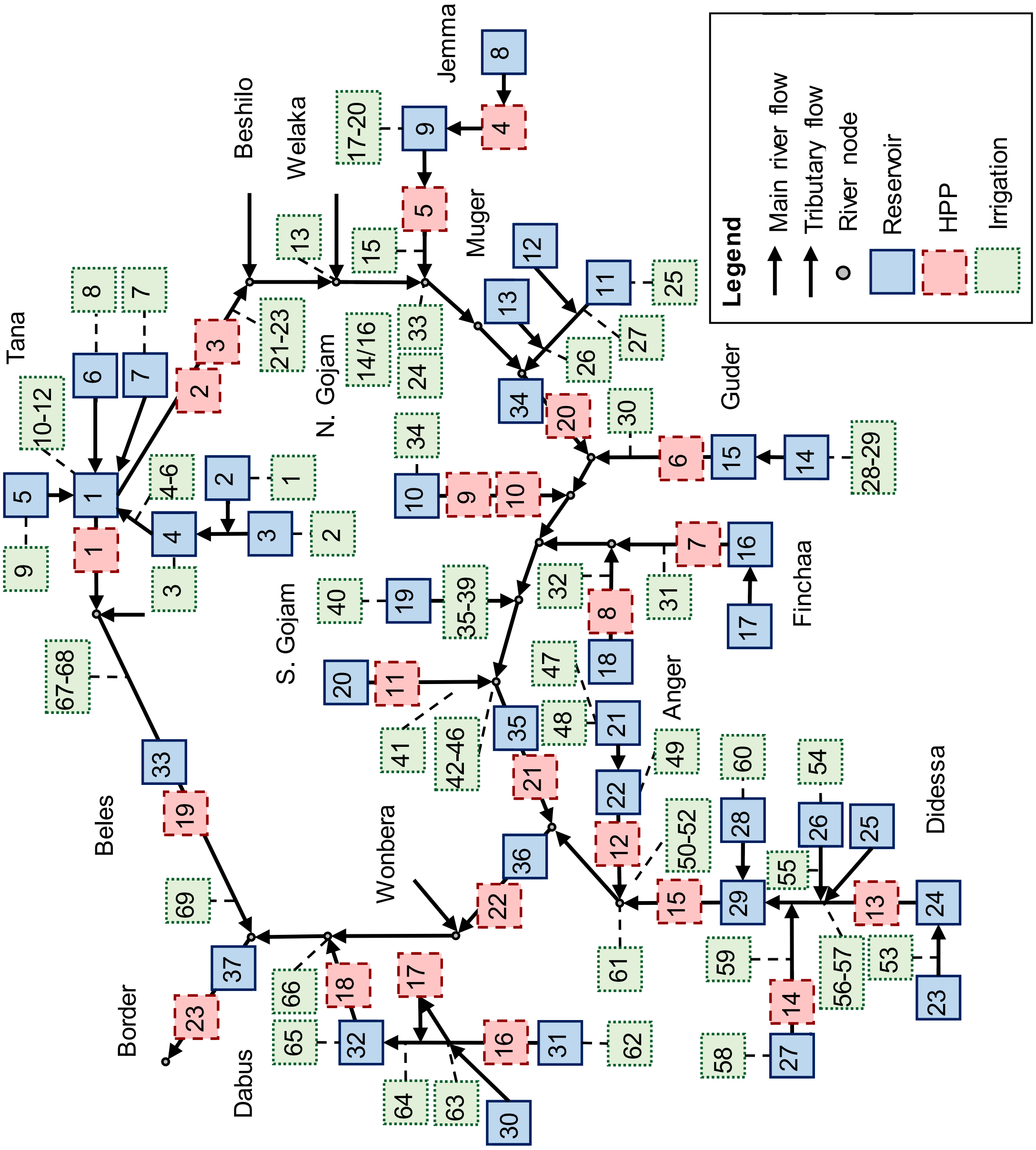

Figure 5.21 Schematization of the UBNR hydro-system for the full development

Table 5.4 Basic model input data of the reservoirs, HHPs and irrigation project groups for the full development scenario

Sub-basin	Reservoir	Net irrigation area (ha)	Demand (hm^3/y)	Installed capacity (MW)
Tana (A1)	Lake Tana (R1)	48,337 (IRG10-12)	391	545 (HP1-3)
	Koga (R2)	5,100 (IRG1)	50	-
	Jema (R3)	7,786 (IRG2)	57	-
	Gilgel Abbay (R4)	12,687 (IRG3)	96	-
	Megech (R5)	7,311 (IRG9)	58	-
	Ribb (R6)	19,925 (IRG8)	197	-
	Gumara (R7)	13,976 (IRG7)	113	-
	-	9,797 (IRG4-6)	80	-
Welaka (A3)	-	1,080 (IRG13)	7	-
Jemma (A4)	Aleltu East (R8)	2,224 (IRG17-18)	12	418 (HP4-5)
	Aleltu West (R9)	-	-	-
	-	29,163 (IRG14-16,19-20)	141	-
N. Gojam (A5)	-	22,366 (IRG21-24)	152	-
Muger (A6)	Homecho (R11)	4,420 (IRG25)	17	-
	Gerbi (R12)	-	-	-
	Siblu (R13)	-	-	-
	-	1,907 (IRG26-27)	9	
Guder (A7)	Upper Guder (R14)	4,896 (IRG28)	27	-
	Lower Guder (R15)	-	-	82 (HP6)
	-	21,313 (IRG29-30)	138	
Finchaa (A8)	Finchaa (R16)	6,205 (IRG31)	47	134 (HP7)
	Amerti (R17)	-	-	-
	Neshe (R18)	11,153 (IRG32)	104	97 (HP8)
S. Gojam (A9)	Chemoga (R10)	-	-	280 (HP9-10)
	Middle Birr (R19)	8,500 (IRG40)	61	-
	Fettam (R20)	1,845 (IRG41)	10	139 (HP11)
	-	51,166 (IRG33-39,42-44)	373	-
Wonbera (A10)	-	11,899 (IRG45-46)	101	-
Anger (A11)	Anger (R21)	14,450 (IRG47)	92	-
	Nekemte (R22)	11,220 (IRG49)	71	200 (HP12)
	-	19,089 (IRG48, 50-52)	148	-
Didessa (A12)	Hida (R23)	1,190 (IRG53)	7	-
	Upper Didessa (R24)	-	-	40 (HP13)
	Urgesa (R25)	6,170 (IRG55)	39	-
	Negeso (R26)	22,815 (IRG54)	121	-
	Dabana (R27)	1,105 (IRG58)	7	100 (HP14)
	Digida (R28)	4,633 (IRG60)	28	-
	Lower Didessa (R29)	-	-	245 (HP15)
	-	37,718 (IRG56-57,59,61)	231	-
Dabus (A13)	Upper Dila (R30)	3,469 (IRG63)	21	-
	Upper Dabus (R31)	-	-	551 (HP16-17)
	Lower Dabus (R32)	4,590 (IRG65)	46	240 (HP18)

	-	7,385 (IRG62,64,66)	52	-
Beles (A14)	Dangur (R33)	85,000 (IRG69)	851	143 (HP19)
	-	62,220 (IRG67-68)	614	-
Main River	Karadobi (R34)	-	-	1,600 (HP20)
	Mabil (R35)	-	-	1,400 (HP21)
	Mendaia (R36)	-	-	2,000 (HP22)
	GERD (R37)	-	-	6,000 (HP23)
Total		584,110	4,568	14,214

5.4.2 Hydropower Production

Calculations showed that total annual hydropower production is equal to 46,620 GWh/y. The variation of the mean monthly hydropower production of all HPPs is shown in Figure 5.22, while the individual mean annual values of each HPP are shown in Table 5.5. The duration curve of the monthly hydropower production is shown in Figure 5.23.

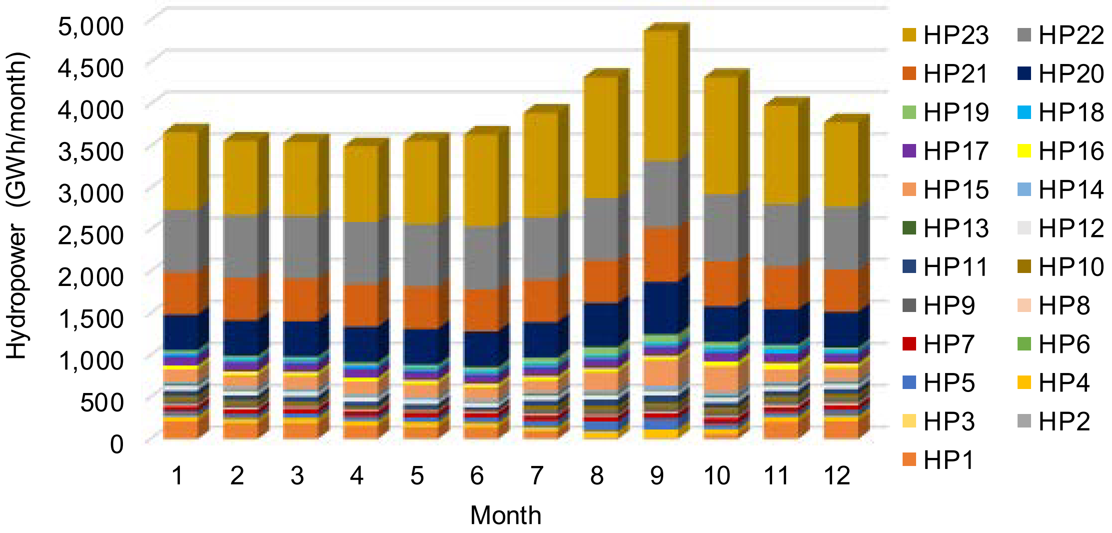

Figure 5.22 Mean monthly hydropower production of the 23 HHPs of the full development

Table 5.5 Annual hydropower production (GWh/y) for the full development

Sub-basin	HPP	Hydropower production (GWh/y)
Tana (A1)	Tana Beles (HP1)	1,585
	Tis Abbay I (HP2)	10
	Tis Abbay II (HP3)	6
Jemma (A4)	Aleltu East (HP4)	785
	Aleltu West (HP5)	817
Guder (A7)	Lower Guder (HP6)	33
Finchaa (A8)	Finchaa (HP7)	722
	Neshe (HP8)	233
South Gojam (A9)	Chemoga I (HP9)	485
	Chemoga II (HP10)	485

	Fetam (HP11)	737
Anger (A11)	Nekemte (HP12)	683
Didessa (A12)	Upper Didessa (HP13)	152
	Dabana (HP14)	373
	Lower Didessa (HP15)	2,165
Dabus (A13)	Upper Dabus I (HP16)	619
	Upper Dabus II (HP17)	1,312
	Lower Dabus (HP18)	543
Beles (A14)	Lower Beles (HP19)	635
Main River	Karadobi (HP20)	5,387
	Mabil (HP21)	6,238
	Mendaia (HP22)	9,127
	GERD (HP23)	13,491
Total		46,620

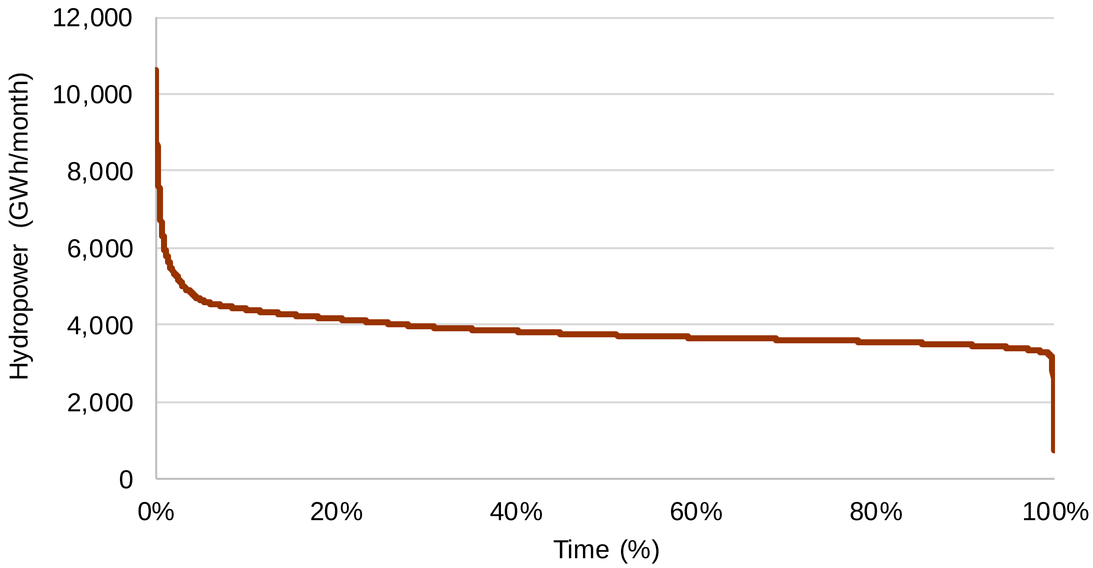

Figure 5.23 Duration curve (%) of the monthly hydropower production of the full development scenario

5.4.3 Irrigation Demand and Deficit

The annual irrigation demand was estimated equal to 4,568 hm³/y, while the actual annual irrigation amount was calculated equal to 4,332 hm³/y. This results to an annual irrigation deficit of 236 hm³/y; the variation of the mean monthly deficit throughout the year is shown in Figure 5.24 for all non-irrigated irrigation project groups, while the individual mean annual values are shown in Table 5.6.

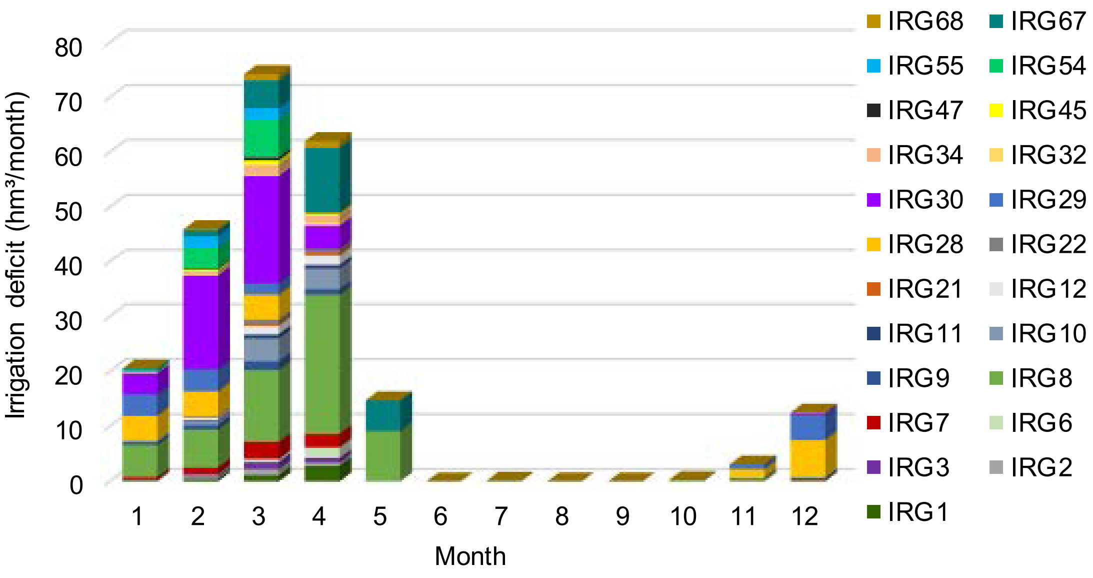

Figure 5.24 Mean monthly irrigation deficit (hm³/month) for the full development scenario

Table 5.6 Mean annual irrigation deficit (hm³/y) for the full development scenario

Sub-basin	IRG	Mean annual irrigation deficit (hm³/y)
Tana (A1)	IRG1	5
	IRG2	2
	IRG3	3
	IRG6	3
	IRG7	7
	IRG8	61
	IRG9	5
	IRG10	9
	IRG11	2
	IRG12	4
N. Gojam (A5)	IRG21	1
	IRG22	2
Guder (A7)	IRG28	22
	IRG29	15
	IRG30	45
Finchaa (A8)	IRG32	1
S. Gojam (A9)	IRG34	4
Wonbera (A10)	IRG45	2
Anger (A11)	IRG47	1
Didessa (A12)	IRG54	11
	IRG55	5
Beles (A14)	IRG67	24
	IRG68	3
Total		236

5.4.4 Discharges of the Tributaries and Border

In Figure 5.25 the variation of the discharge of the six most important tributaries Jemma (A4), South Gojam (A9), Wonbera (A10), Dabus (A13), Anger (A11) and Didessa (A12) is shown throughout the year. In Figure 5.26 the variation of the discharge at the border is shown, while the mean monthly discharge equals 1,339 m³/s.

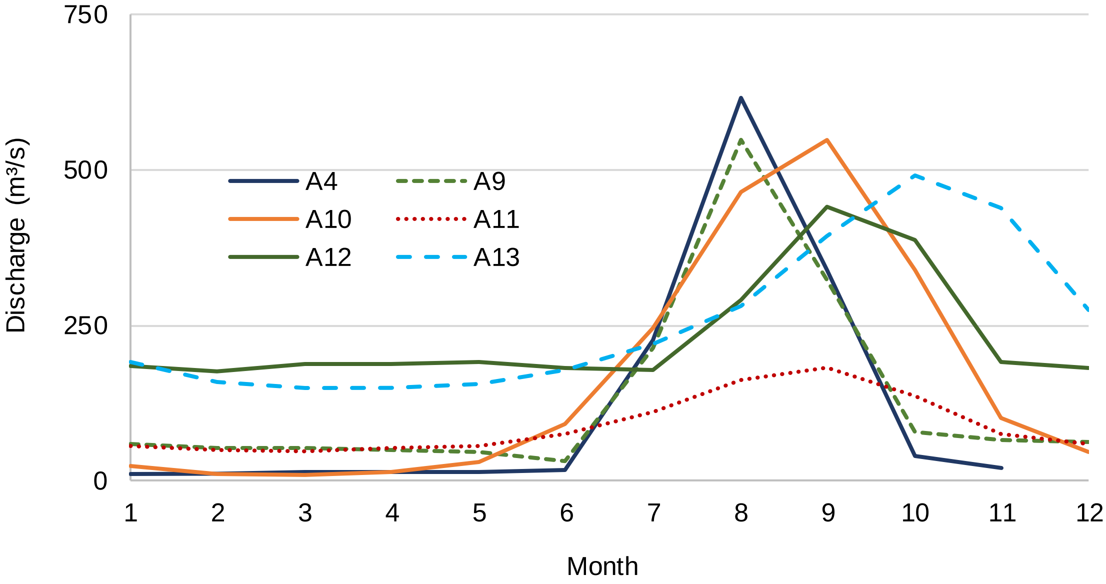

Figure 5.25 Mean monthly discharge (m³/s) of tributaries for the full development

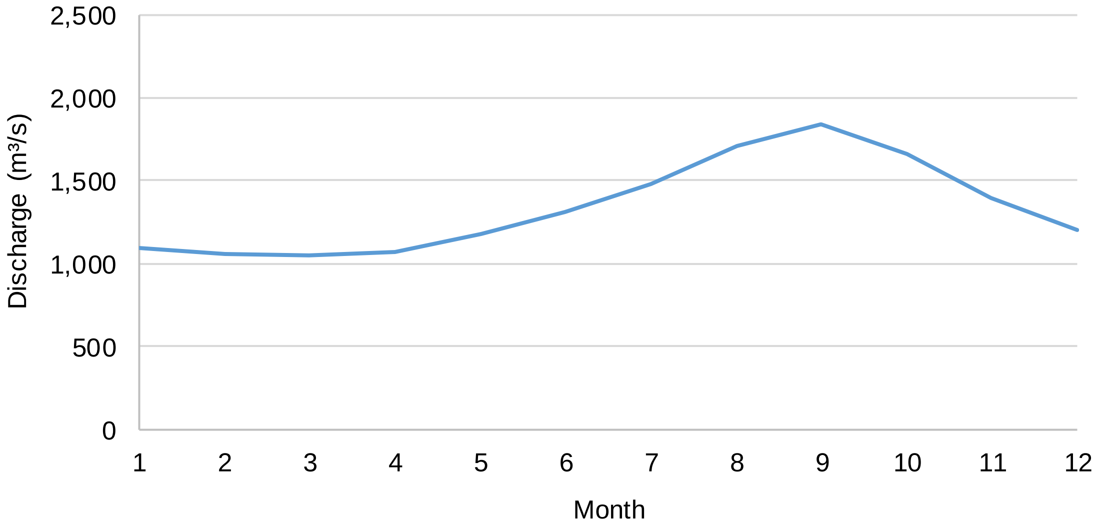

Figure 5.26 Mean monthly discharge (m³/s) at the border for the full development

5.5 Discussion on the Calculations of Hydronomeas

5.5.1 General

The main characteristics and results of the calculations in Hydronomeas are summarized for the four scenarios in Table 5.7.

Table 5.7 Main characteristics of the four scenarios

Scenario	Natural (S0)	Current (S1)	Short-medium-term (S2)	Full development (S3)
Reservoirs (No.)	1	5	7	37
Capacity (km³)	38.69	40.19	40.67	221.45
HPPs (No.)	0	5	5	23
Installed Capacity (MW)	0	776	776	14,214
Hydropower (GWh/y)	0	3,251	2,777	46,620
IRGs (No.)	0	3	8	69
Net Area (ha)	0	18,522	124,210	584,110
Irrigation (km³/y)	0	0.16	1.05	4.33
Discharge at border (km³/y)	49.30	49.00	47.40	42.3

5.5.2 Hydropower Production

For the current conditions that included five HPPs, the annual hydropower production was calculated equal to 3,251 GWh/y. Goor et al. (2010) calculated the annual hydropower production equal to approximately 2,500 GWh/y (taken from figure); a value that is lower than the one from the present work, since it neglects the Finchaa and Neshe HPPs with an installed capacity of 231 MW. Furthermore, McCartney et al. (2012) calculated the annual hydropower production equal to 1,383 GWh/y, a value that is lower than the one from the present work, since it neglects the Tana-Beles, Finchaa and Neshe HPPs and accounts for only 218 MW total installed capacity (year 2008), in comparison to the present study that includes all existing HPPs and accounts for a total installed capacity of 776 MW (year 2016).

For the full development scenario that included 23 HPPs, the hydropower production was calculated equal to 46,620 GWh/y. Goor et al. (2010) calculated an annual hydropower production equal to approximately 42,500 GWh/y (taken from figure); a value than is lower compared to the one of the present work, since they investigate only Tis Abbay I, Tis Abbay II, Tana-Beles, and four large HPPs on the main river of the UBNR. McCartney et al. (2012) calculated the annual hydropower production equal to 31,297 GWh/y, a value that is lower than the one from the present work, since it includes HHPs with an installed capacity of 6,426 MW, compared to the 14,214 MW of the present study.

In the following, a comparison is presented between (1) the current conditions and (2) the short- to medium-term and (3) full development, in order to further investigate the hydropower development. The annual hydropower production for the current conditions, short- to medium-term and full development is shown in Figure 5.27, while Figure 5.28 shows the variation of the hydropower production throughout the year.

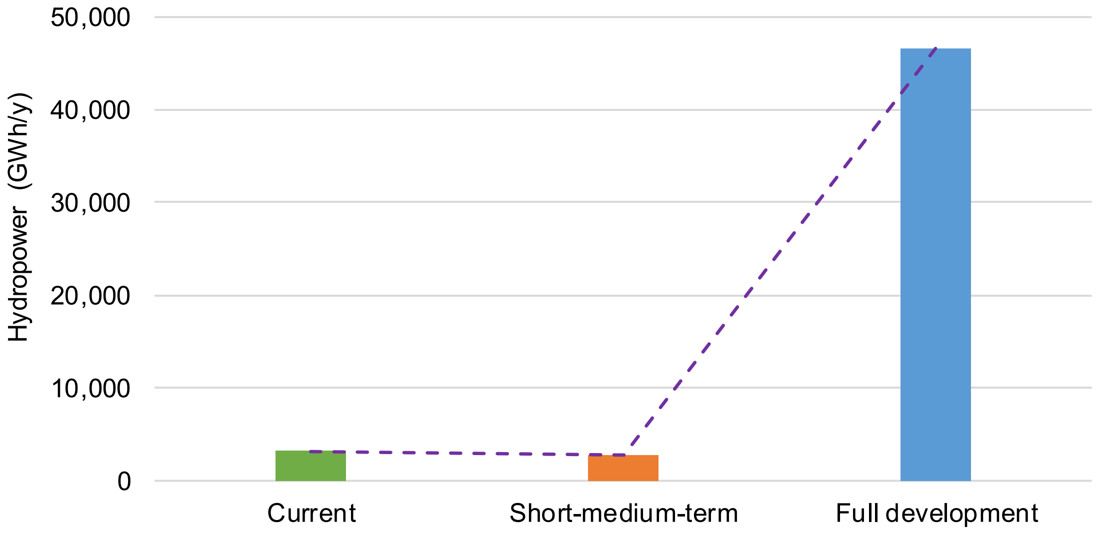

Figure 5.27 Comparison of annual hydropower production (GWh/y) for the three scenarios

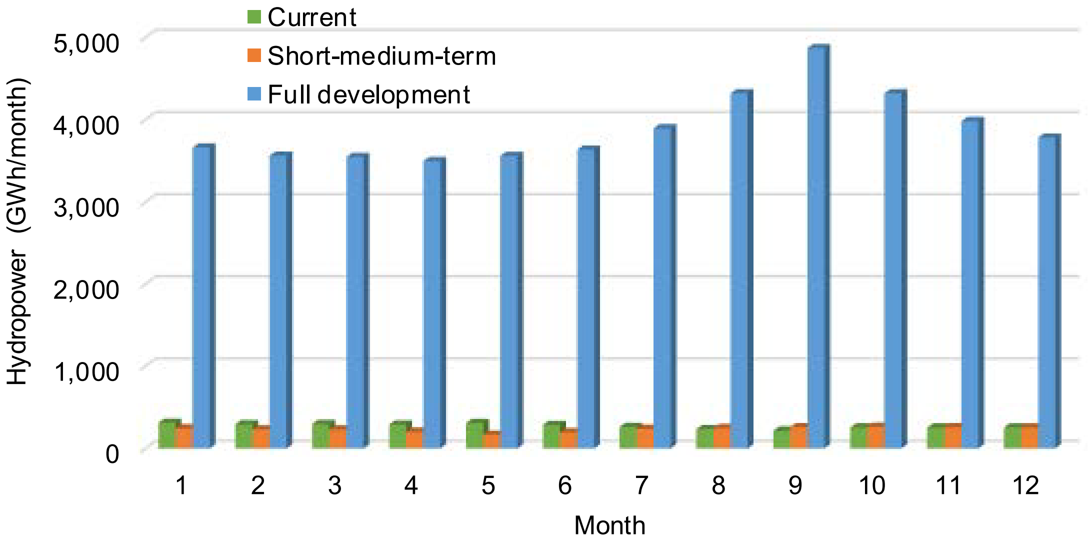

Figure 5.28 Variation of monthly hydropower production (GWh/month) for the three scenarios

From the current conditions to the short- to medium-term development, a decrease of 14.6 % was observed in the hydropower production that arises because two reservoirs and five irrigation projects groups were added to the hydro-system in the short- to medium-term development, without, however, an expansion in the existing HPPs. In the full development, the hydropower production was calculated equal to 14 times the hydropower production of the current conditions.

5.5.3 Irrigation Demand and Deficit

For the current conditions, the actual irrigation amount for the irrigated area of 18,522 ha of the three irrigation projects was calculated equal to 164 hm³/y. McCartney et al. (2012) calculated the annual irrigation demand for their irrigated area of 15,345 ha equal to 260 hm³/y; thus, accounting for an irrigation demand of approximately 1,700 mm (17,000 m³/ha), a value that is relatively high for the UBNR region. McCartney and Girma (2012) calculated the annual irrigation demand for their irrigated area of 15,345 ha, equal to 128 hm³/y.

For the full development scenario, the annual irrigation requirement for the 584,110 ha of irrigated area was estimated equal to 4,568 hm³/y, while the annual actual irrigation amount was calculated equal to 4,332 hm³/y. McCartney et al. (2012) calculated the annual irrigation demand for their irrigated area of 461,000 ha, equal to 3,810 hm³/y. McCartney and Girma (2012) calculated the annual irrigation demand for their irrigated area of 364,355 ha, equal to 2,787 hm³/y.

In the following, a comparison is presented between (1) the current conditions and (2) the short- to medium-term and (3) full development, in order to further investigate the irrigation development. The annual actual irrigation amount for the current conditions, short- to medium-term and full development are shown in Figure 5.29. In the current conditions, no irrigation deficit is observed, since only three irrigation projects exist; the irrigation demand of the three projects was calculated equal to 164 hm³/y that corresponds to less than under 1% of the total UBNR discharge. An almost seven- and 26-fold increase was observed in the actual irrigation amount of the short- to medium-term and full development, respectively, compared to the actual irrigation amount of the current conditions. Furthermore, for the short- to medium-term and full development, an irrigation deficit of approximately 98 and 236 hm³/y was observed; figures that correspond to 8.6 and 5.2% of the irrigation demand of 1,144 hm³/y and 4,568 hm³/y, respectively. McCartney and Girma (2012) calculated an unmet demand of 363 hm³/y for their irrigated area of 364,355 ha. Figure 5.30 shows the variation of the irrigation deficit throughout the year for the short- to medium-term and full development.

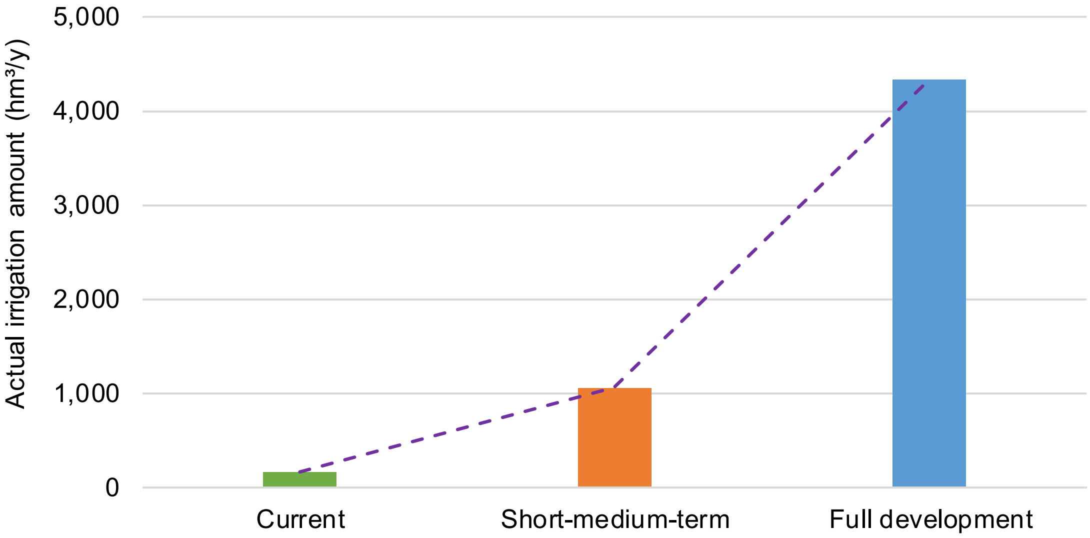

Figure 5.29 Comparison of the annual actual irrigation amount (hm³/y) for the three scenarios

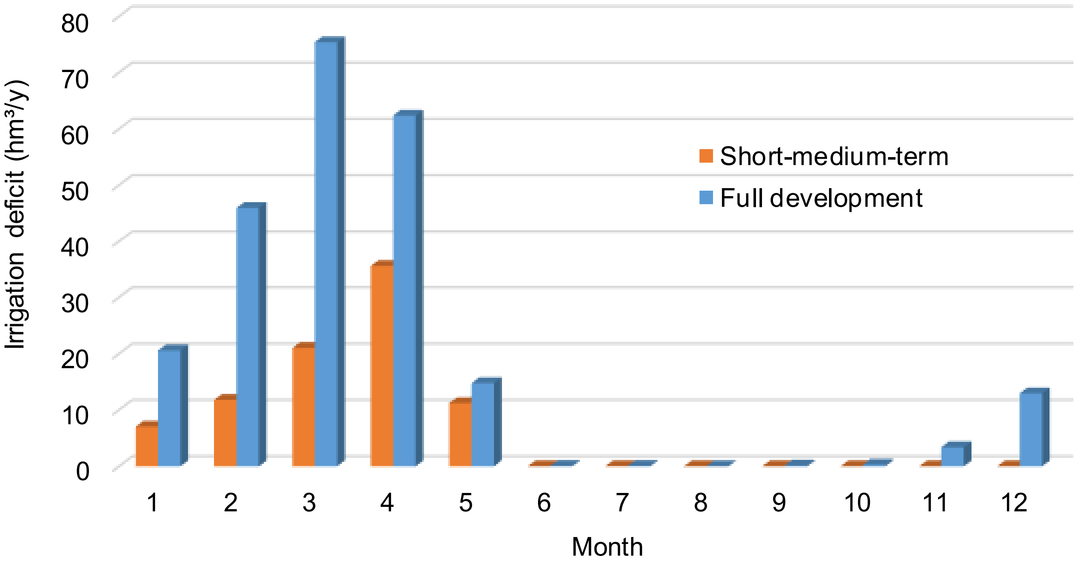

Figure 5.30 Variation of the monthly irrigation deficit (hm³/month) for the two scenarios

5.5.4 Discharge at the Border

The calculations of Section 5.1 (see Figure 5.8) for the natural conditions (absence of infrastructure to impound or consume water) showed the following regarding the discharge at the border:

1. The discharge at the border is equal to 49.3 km^3/y (1,562 m^3/s). This value is in agreement with the values presented in other studies that are given in the following. According to Kim and Kaluarachchi (2008) observed discharge data at Roseires/El Deim produced a mean annual discharge of 49 km^3/y (1921-1990, monthly discharge data from the National Center for Atmospheric Research -

NCAR). Other studies presented the mean annual discharge as 46–54 km^3/y (Conway 1997, 2000; Sutcliffe and Parks, 1999; National Meteorological Service Agency (NMSA), 2001; UNESCO, 2004; Conway, 2005). According to Mulat and Moges (2014), the annual run-off amounts to more than 48 km^3/y (about half of Ethiopia's total run-off). According to Bastawesy et al. (2015), the long-term mean annual flow of at Rosaires/El Deim equals 48.7 km^3/y. Wheeler et al. (2016) gives the average annual flow at GERD equal 49.4 km^3/y. Guariso and Whittington (1987) state that the annual mean flow of the Blue Nile at the Sudanese-Ethiopian border is about 50 km^3/y. According to Conway (2000), the UBNR has a mean annual discharge of 48.5 km^3/y (1912-1997). Shamseldin and O'Connor (2003) give the average annual flow at Roseries/Eldeim equal to 48.75 km^3/y (1976-1994). Mishra and Hata (2006) also give an average annual flow of about 50 km^3/y, measured at the basin outlet at ElDeim station near the Sudan-Ethiopia border. According to Shamseldin (2010), the mean annual flow of the Blue Nile River at Eldeim is about 50 km^3/y. McCartney et al. (2012) show a mean annual discharge of 45.1 km^3/y for the natural conditions. Elsanabary and Gan (2015) give a mean annual streamflow volume of 48.5 km^3/y.

2. Discharges vary from 37.2 km^3/y (1,179 m^3/s) to 67.0 km^3/y (2,123 m^3/s). The corresponding ranges values of McCartney and Girma (2012) are 44.5 to 61.9 km^3/y (1,410 to 1,961 m^3/s). According to Kim and Kaluarachchi (2008) the annual discharge ranged from a minimum of 31 km^3/y in 1972 and 1984 to a maximum of 70 km^3/y in 1929 from observed discharge data at Roseires/El Deim (data from the National Center for Atmospheric Research - NCAR). According to Bastawesy et al. (2015) records show a considerable variation from low annual totals of 20.69 km^3/y in 1913 and 29.65 km^3/y in 1984, to high totals of 69.67 km^3/y in 1917 and 69.85 km^3/y in 1929. According to Shamseldin and O'Connor (2003) the annual flow varies between 28.68 and 69.80 km^3/y (1976-1994), while according to Shamseldin (2010) the annual flow varies between 70 km^3 during flood years and 30 km^3/y during drought years.

3. The seasonal distribution of flows is very marked, 40.6 km^3/y that is 82.4% of the annual discharge is concentrated during July–October due to the summer Monsoon, while only 3.6% of the flow occurs during the dry season (February to May). This agrees with Shamseldin and O'Connor (2003), who state that the Blue Nile is a very seasonal river with the peak flow occurring in late August, while the total flow during the flood season (June-October) constitutes, on average, 80% of the total annual flow in the river. Mishra and Hata (2006) also state that more than

> 80% of the flow occurs during the flood season between July and September, while only 4% of that flow occurs during the driest period from January to April. According to Kim and Kaluarachchi (2008) more than 80% of the flow occurs during the wet season (July to October). McCartney and Girma (2012) state that mean monthly flow varies considerably with more than 80% of the flow occurring during the wet season (July to October), while only 4% of the flow occurs during the dry season (February to May) (Awulachew et al. 2008). Bastawesy et al. (2015) argue that bulk of the runoff (84% on average) occurs between June and October.

Furthermore, the calculations of Section 5.2 (see Figure 5.13) for the current conditions showed the following regarding the discharge at the border. The discharge at the border is equal to 49.0 km³/y (i.e. 1,551 m³/s). McCartney et al. (2012) calculated a mean annual discharge of 45.2 km³/y for their current conditions, stating that their estimate is closer to the Sudanese estimate of 45.5 km³/y at the border rather than the one measured by Ethiopia that equals 50.6 km³/y. McCartney and Girma (2012) calculated a discharge of 1,655 m³/s (i.e. 52.2 km³/y) for their current conditions. Molden et al. (2009) calculated a mean annual flow of 48.2 km³/y for their current conditions. Goor et al. (2010) state that for their current conditions 50% of the time, the annual discharge at the border will be greater than 49.5 km³/y.

The calculations of Section 5.3 (see Figure 5.20) for the short- to medium-term development showed the following regarding the discharge at the border. The discharge at the border is equal to 47.4 km³/y (i.e. 1,501 m³/s), which corresponds to a decrease of 4% compared to the natural conditions. McCartney et al. (2012) calculated a mean annual discharge of 43.2 km³/y for their medium-term development that corresponds to a 5% decrease compared to their natural situation.

Finally, the calculations of Section 5.4 (see Figure 5.26) for the full development scenario showed the following regarding the discharge at the border. The discharge at the border is equal to 42.3 km³/y (i.e. 1,339 m³/s), which corresponds to a decrease of 14% compared to the natural conditions. McCartney et al. (2012) calculated an annual run-off at the border of 42.7 km³/y, which corresponds to a 6% decrease compared to their natural conditions; their study does not include all proposed reservoirs and most importantly GERD, and thus accounts for smaller evaporation losses.

In the following, a comparison is presented between the discharge at the border of (1) the natural conditions, (2) the current conditions, (3) the short- to medium-term, and (4) the full development, in order to further investigate the water resources development of the three scenarios. Figure 5.31 shows the mean monthly discharge at the border; from the natural to the current conditions, almost no decrease was observed, while for the short- to medium-term and full development, a decrease of 4 and 14% s observed, respectively. The discharge decrease at border is a result of two main aspects: (1) irrigation water and (2) net reservoir evaporation. A total amount of 4,332 hm³/y is withdrawn from the hydro-system for irrigation purposes in the full development, while due to the construction of 37 reservoirs a total amount of 12,700 hm³/y is evaporating, which results to a total water loss of 3,912 hm³/y (rainfall-evaporation). Compared to the natural conditions, where only Lake Tana exists, this corresponds to a 3-fold increase in water lost due to reservoir evaporation.

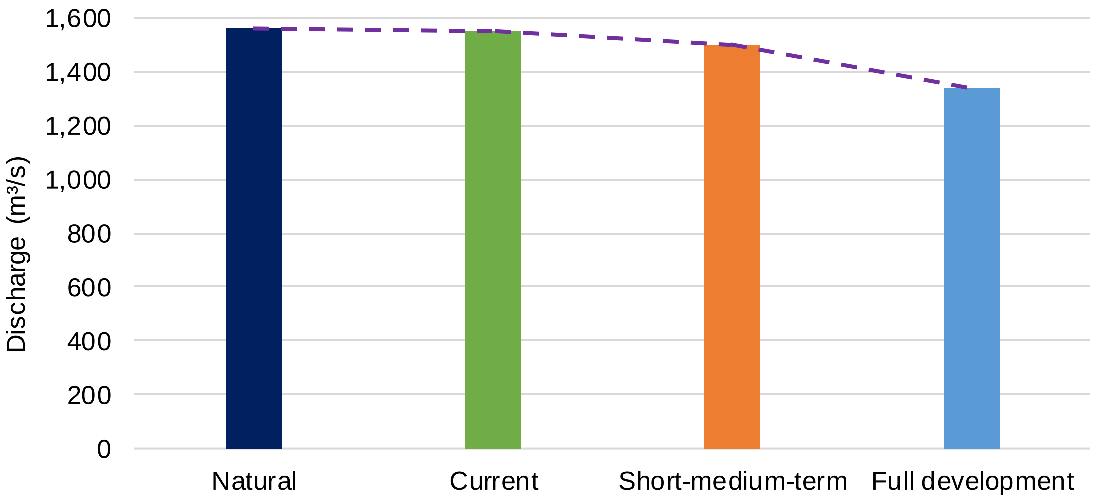

Figure 5.31 Comparison of the mean monthly discharge (m³/s) at the border for the four scenarios

Figure 5.32 shows, furthermore, the monthly variation of the discharge at the border throughout the year for the four scenarios. The flow pattern of the natural conditions, the current conditions and the short- to medium-term development are similar. However, a significant change is observed in the flow pattern of the full development. Due to the construction of the 32 new reservoirs and 18 new HPPs, the discharge in the full development is more evenly distributed throughout the year, while water is transferred from the wet to the dry period and flood picks are reduced. This change in the flow pattern was also observed by other researchers (Goor at al. 2010, Arjoon et al. 2014). Figure 5.33 depicts the change in discharge from the natural conditions to (A) current conditions, (B) short- to medium-term and (C) full development.

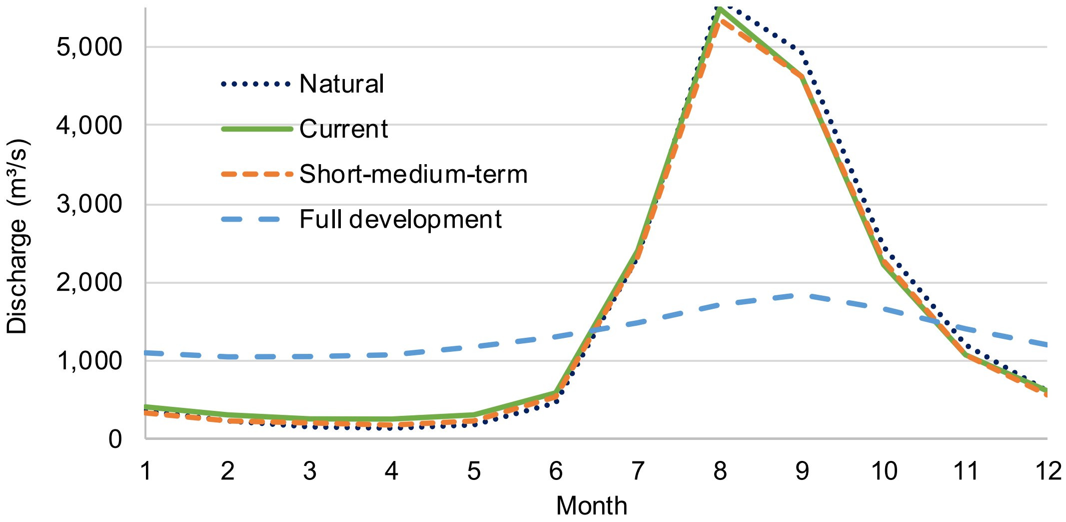

Figure 5.32 Comparison of the monthly discharge (m³/s) at the border for the four scenarios

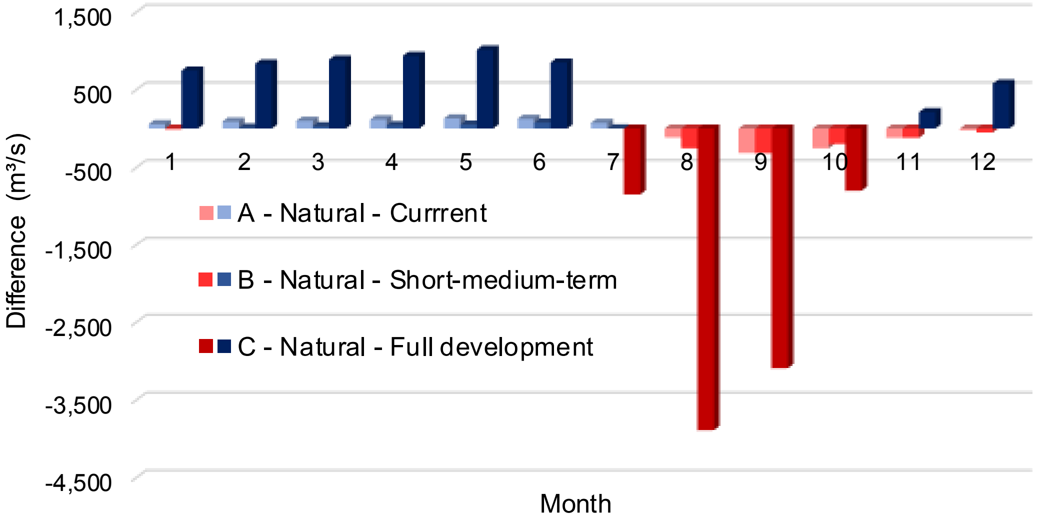

Figure 5.33 Discharge difference (m³/s) between the natural conditions and the three development scenarios

Furthermore, Table 5.8 presents the percentage of each tributary in relation to the total discharge at the border for the four scenarios; thus, showing the significance of each tributary.

Table 5.8 Percentage of each tributary (%) related to the total discharge for the four scenarios

Sub-basin	Natural	Current	Short-medium-term	Full development
Tana (A1)	7	7	6	3
Beshilo (A2)	5	5	5	6
Welaka (A3)	3	3	3	3
Jemma (A4)	7	7	7	8

N. Gojam (A5)	8	8	8	9
Muger (A6)	3	3	3	3
Guder (A7)	1	1	1	1
Finchaa (A8)	3	3	2	2
S. Gojam (A9)	9	9	8	9
Wonbera (A10)	10	10	11	12
Anger (A11)	6	6	7	7
Didessa (A12)	16	16	16	17
Dabus (A13)	17	17	18	19
Beles (A14)	5	5	5	1
Total	100	100	100	100

5.6 Pareto calculations

5.6.1 Pareto Calculations for the Short- to Medium-term Development

The Pareto front that is shown in Figure 5.34 was generated for the short- to medium-term development of the UBNR hydro-system. The optimization procedure was performed 11 times for different sets of weights and six Pareto optimal solutions (points M1 to M6) were gained. The extreme Pareto points M1 (162.6 GWh/month, 86.7 hm³/y) and M6 (194.2 GWh/month, 111.0 hm³/y) represent management policies, in which irrigation and hydropower are more important, respectively. Points M2, M3, M4 and M5 represent intermediate cases with different weighting of the two objectives. Thus, point M1 represents the "worst" situation for hydropower production and the "best" situation for irrigation deficit. For a relatively small increase in the irrigation deficit (from 86.7 to 86.9 hm³/y) close to point M1, a relatively large increase in hydropower production is observed (from 162.6 to 167.0 GWh/month). Point M6 represents the opposite case; for a relatively small decrease in hydropower production (from 194.2 to 193.8 GWh/month) close to point M6, a relatively large decrease in irrigation deficit (from 111.0 to 108.8 hm³/y) is observed. The theoretical "utopian solution", for which hydropower production and irrigation deficit would be optimized simultaneously, would result to a hydropower production of 194.2 GWh/month and an irrigation deficit of 86.7 hm³/y.

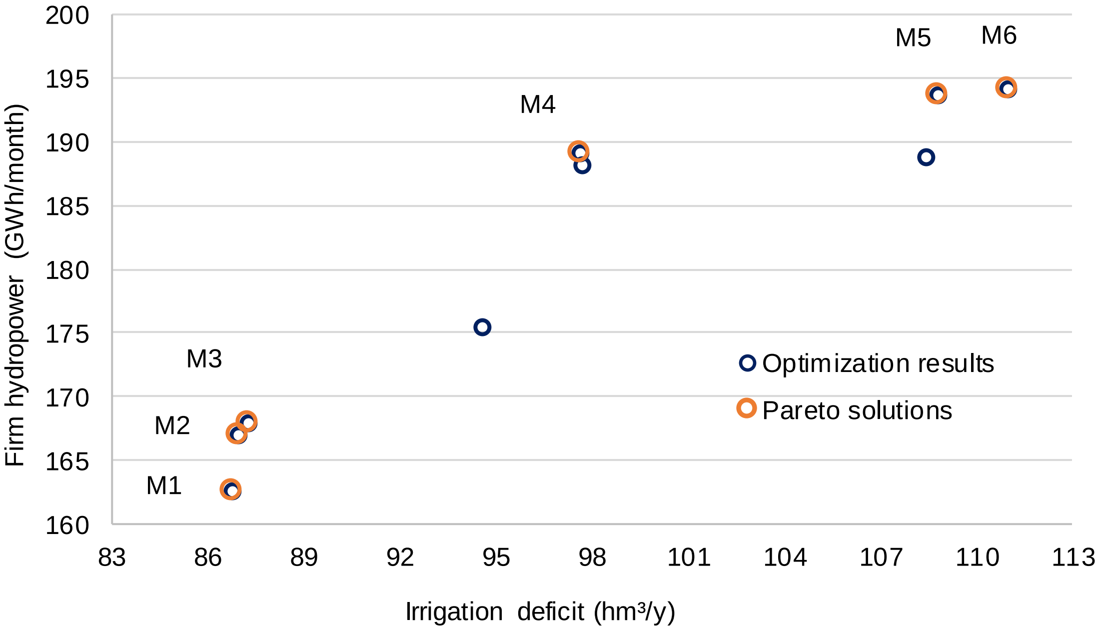

Figure 5.34 Pareto front of the UBNR hydro-system for the short- to medium-term development

Calculations showed that mean annual hydropower production of the Pareto solutions M1 to M6 varies from 2,704 to 2,777 GWh/y as shown in Figure 5.35, while the mean annual values of the individual HPPs are shown in Table 5.9. Furthermore, the monthly variation of the hydropower production throughout the year is shown in Figures 5.36 and 5.37 while Figure 5.38 shows the duration curve of the monthly hydropower production.

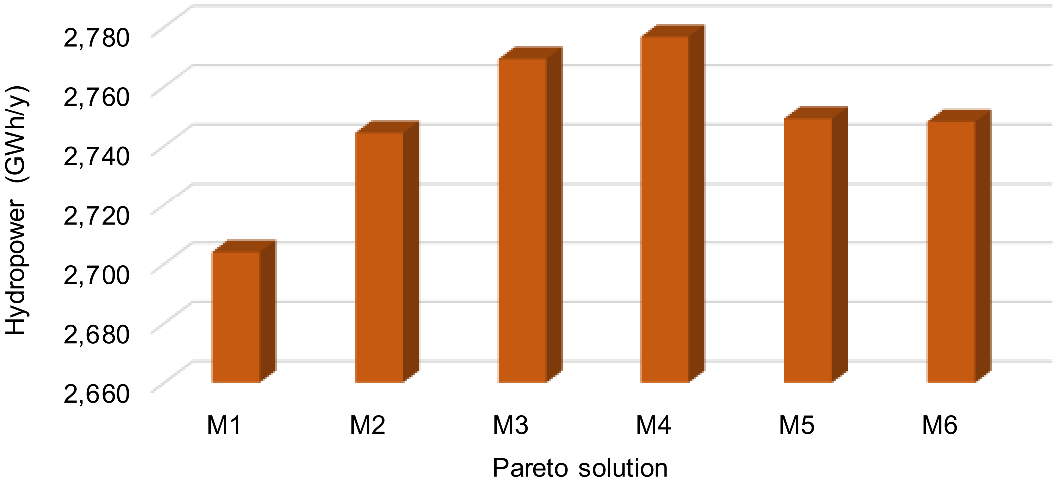

Figure 5.35 Mean annual hydropower production of the Pareto solutions M1 to M6

Table 5.9 Mean annual hydropower production per HPP (GWh/y) for the Pareto solutions M1 to M6

HPP	M1	M2	M3	M4	M5	M6
HP1	1,708	1,708	1,708	1,719	1,729	1,730
HP2	23	23	23	24	25	26
HP3	83	83	83	79	74	71
HP7	658	699	723	723	690	690
HP8	232	232	232	232	232	232
	2,704	2,744	2,769	2,777	2,749	2,748

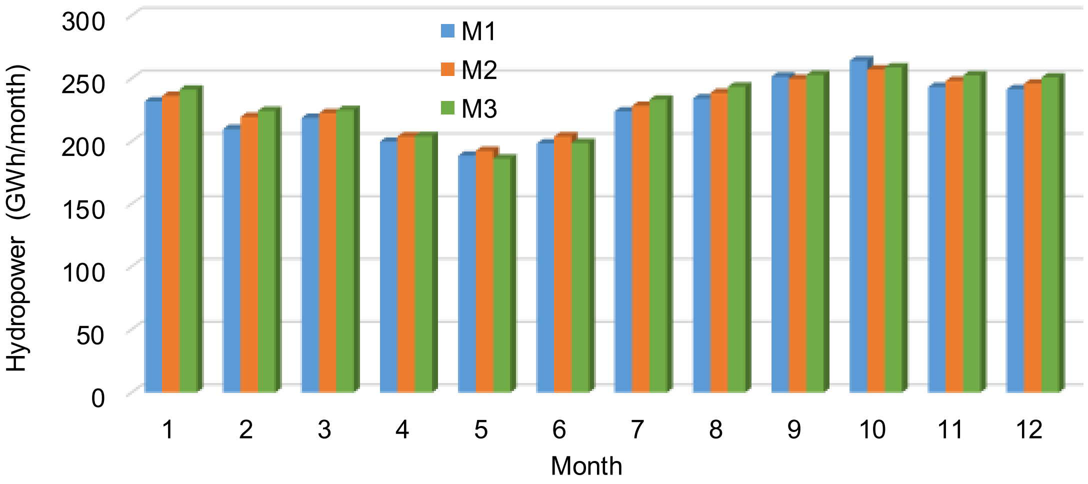

Figure 5.36 Variation of the hydropower production (GWh/month) of the Pareto solutions M1, M2 and M3

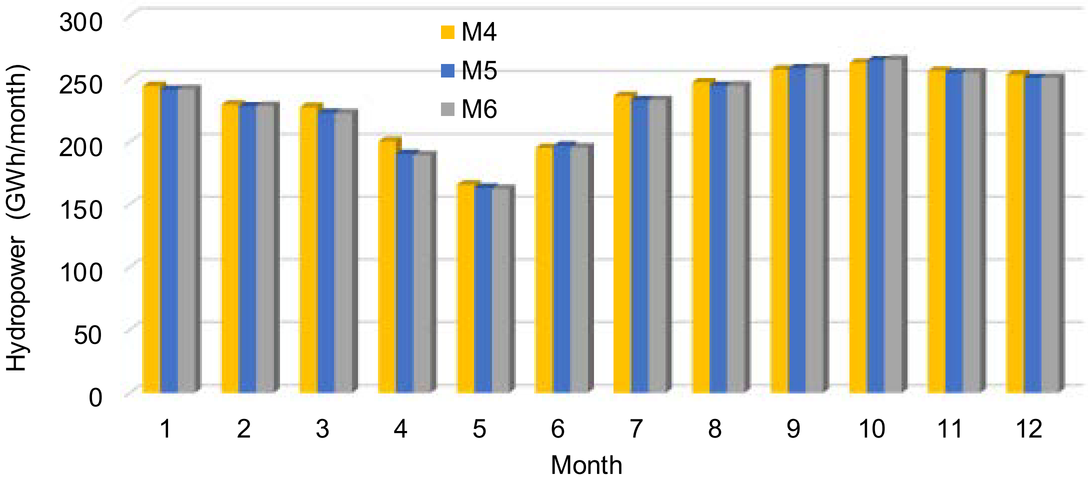

Figure 5.37 Variation of the hydropower production (GWh/month) of the Pareto solutions M4, M5 and M6

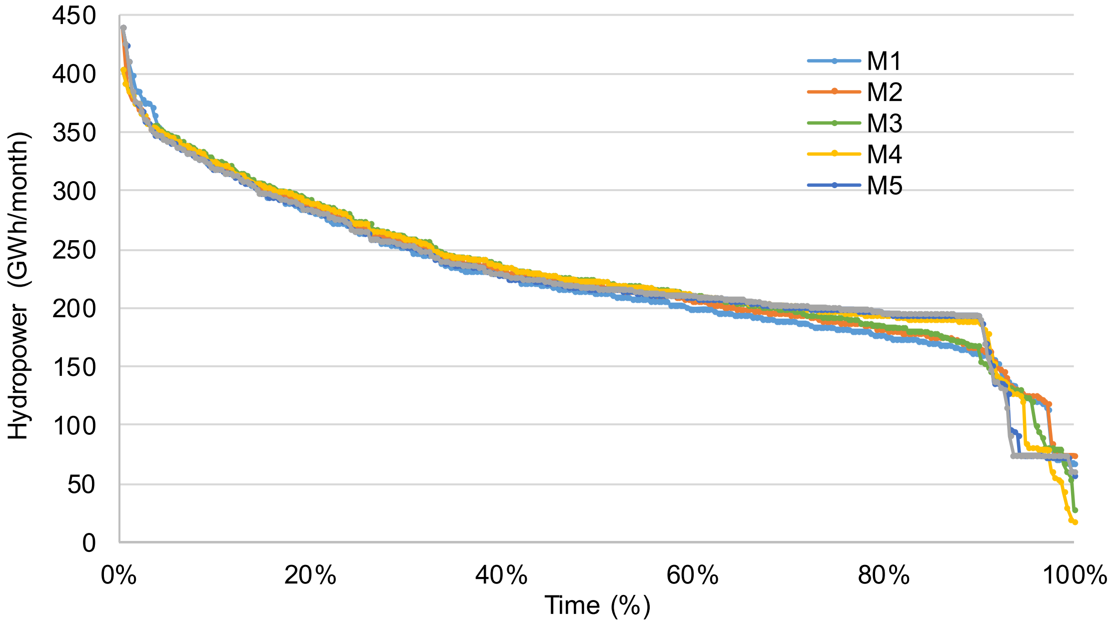

Figure 5.38 Duration curve of the monthly hydropower production (GWh/month) of the Pareto solutions M1 to M6

Calculations showed, moreover, that the actual irrigation amount of the Pareto solutions M1 to F6 varies from 1,031.8 to 1,056.1 hm³/y, while the monthly variation of the actual irrigation amount is shown in Figures 5.39 and 5.40. Compared to the estimated annual irrigation demand of 1,144 hm³/y that leads to the annual irrigation deficit of 86.7 to 111.0 hm³/y for the Pareto solutions M1 to M6. Figure 5.41 shows, furthermore, the irrigation deficit/demand ratio of the Pareto solutions M1 to M6, while the individual mean annual irrigation deficit of each irrigation project is shown in Table 5.10.

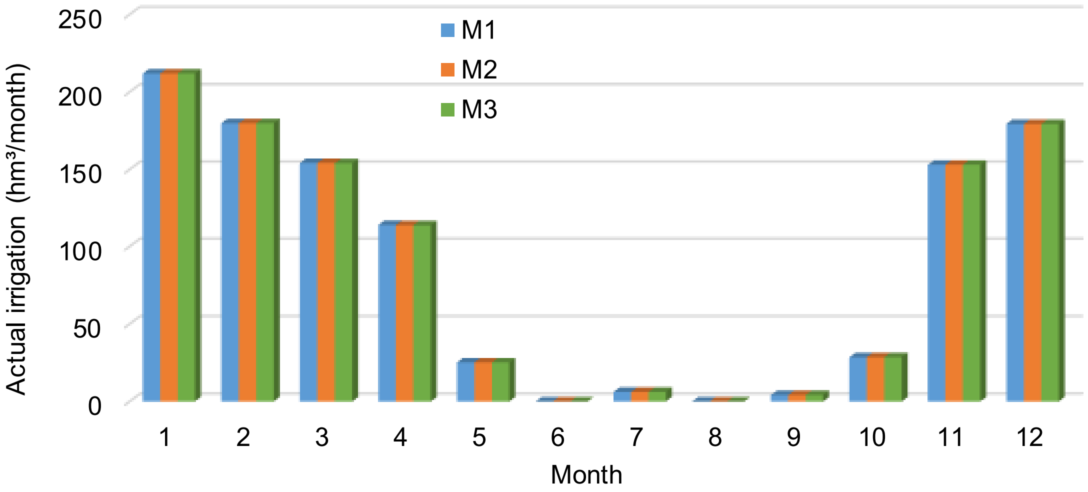

Figure 5.39 Variation of the irrigation amount (hm³/month) of the Pareto solutions M1, M2 and M3

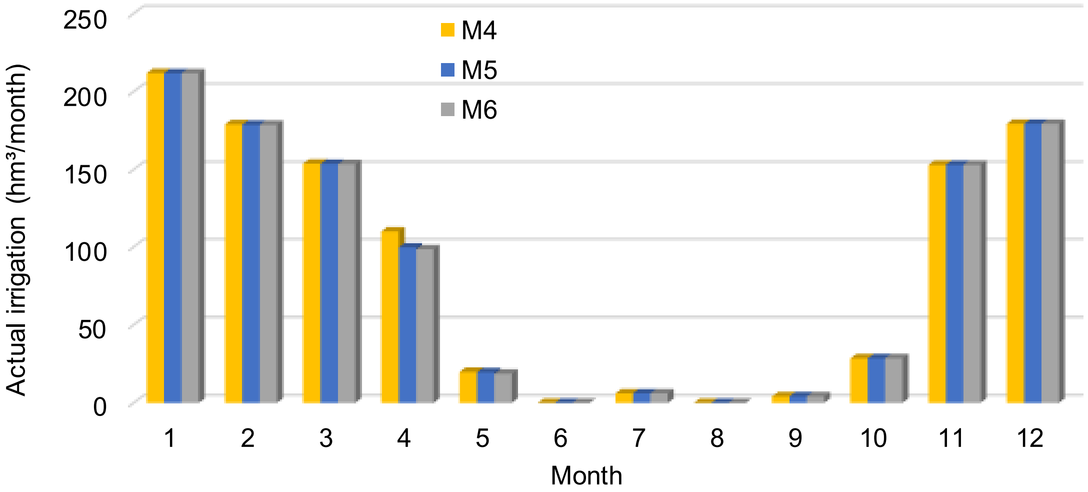

Figure 5.40 Variation of the mean irrigation amount (hm³/month) of the Pareto solutions M4, M5 and M6

Table 5.10 Mean annual irrigation deficit (hm³/y) for the Pareto solutions M1 to M6

IRG	M1	M2	M3	M4	M5	M6
IRG1	2.8	2.8	2.8	3.1	4.9	5.0
IRG8	58.4	58.4	58.4	59.8	60.0	60.0
IRG9	15.3	15.3	15.3	15.6	15.6	15.6
IRG10	0.9	0.9	0.9	1.3	3.1	3.2
IRG31	0	0.2	0.5	0.5	0.2	0.2
IRG32	0.3	0.3	0.3	0.3	0.3	0.3
IRG57	0.1	0.1	0.1	0.1	0.1	0.1
IRG67	9.1	9.1	9.1	16.9	24.6	26.6
Total	86.7	86.9	87.2	97.6	108.8	111.0

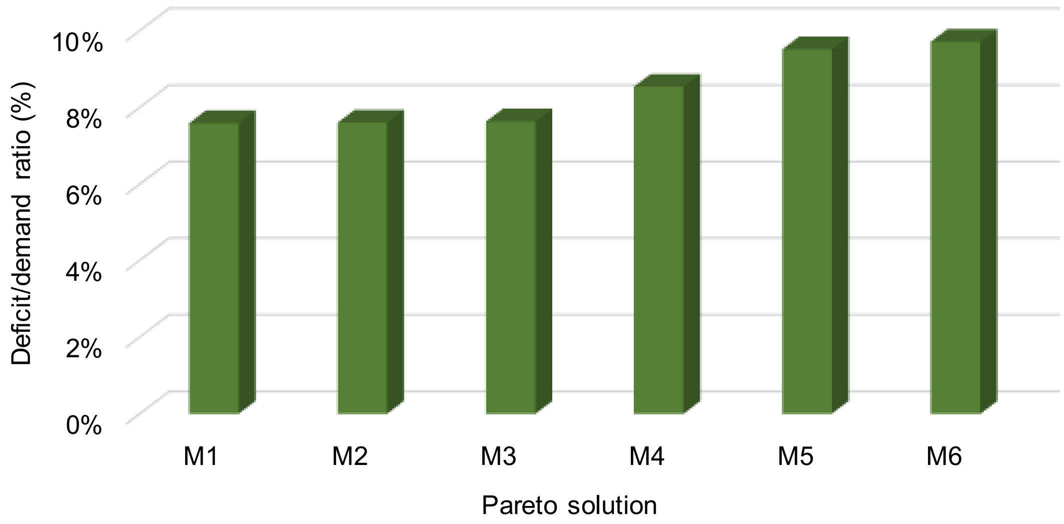

Figure 5.41 Irrigation deficit/demand ratio (%) of Pareto solutions M1 to M6

The mean monthly discharge at the border between Ethiopia and Sudan that is shown in Figure 5.42 is practically the same (1,500 to 1,501 m³/s) for all the Pareto solutions. Moreover, Figure 5.43 depicts that the variation of discharge throughout the year is also nearly the same for all solutions.

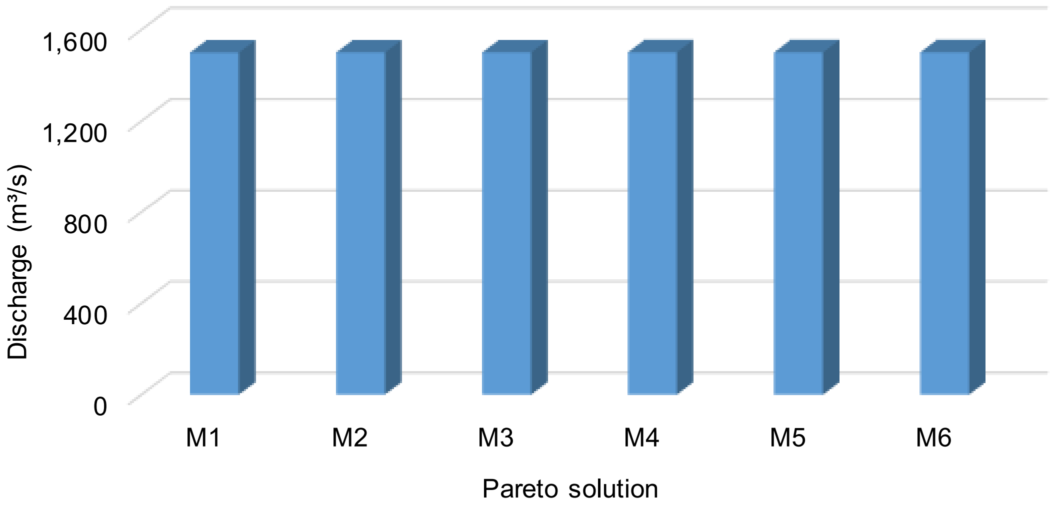

Figure 5.42 Mean monthly discharge (m³/s) of Pareto solutions M1 to M6

The irrigation projects Koga, Megech Pump and Upper Beles, and the HPPs Tana-Beles, Tis Abbay I, Tis Abbay II and Finchaa are the most sensitive to changes in the Parrto solutions and thus, management policies. The main reason for that sensitivity is that the irrigation projects Koga, Megech Pump and Upper Beles and the HPPs Tana-Beles, Tis Abbay I and Tis Abbay II are located upstream and downstream of Lake Tana.

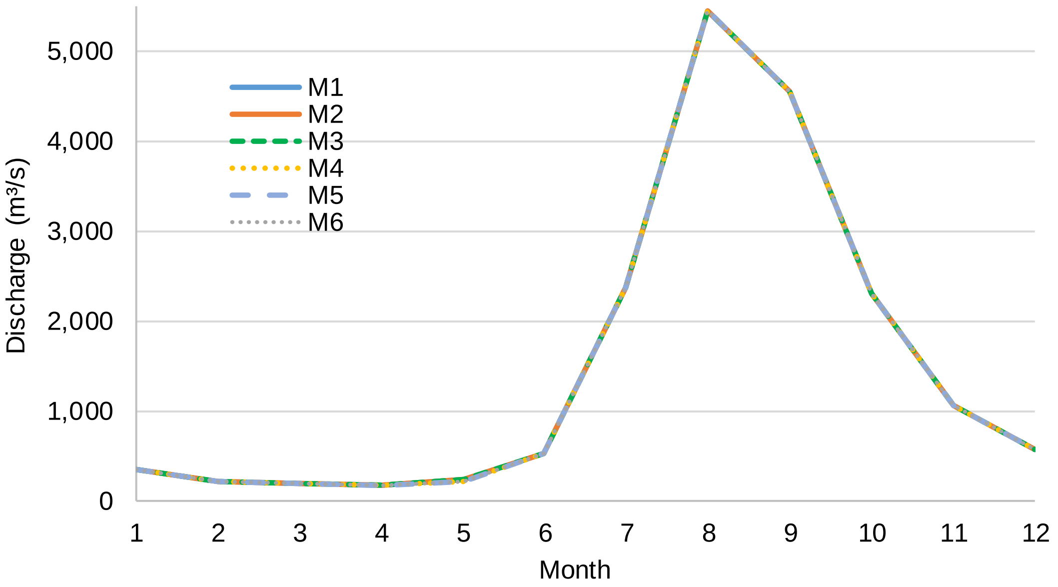

Figure 5.43 Variation of monthly discharge (m³/s) at the border of the Pareto solutions M1 to M6

5.6.2 Pareto Calculations for the Full Development

The Pareto front that is shown in Figure 5.44 was generated for the full development of the UBNR hydro-system. The optimization procedure was performed 101 times for different sets of weights, while each optimization run lasted for approximately 80 hours. The nine Pareto solutions, points F1 to F9, gained from the optimization procedure represent feasible cases. Points F1 (1966.9 GWh/month, 162.0 hm³/y,) and F9 (3479.6 GWh/month, 1069.0 hm³/y) represent management policies, in which irrigation and hydropower are more important, respectively. Points F2 to F8 represent intermediate cases with different weighting of the two objectives. Thus, point F1 represents the “worst” situation for hydropower production and the “best” situation for irrigation deficit. For a relatively small increase in the irrigation deficit (from 162.0 to 181.3 hm³/y) close to point F1, a relatively large increase in hydropower production is observed (from 1966.9 to 2972.0 GWh/month); thus the gradient of the Pareto front is very steep. Point F9 represents the opposite case. For a relatively small decrease in hydropower production (from 3479.6 to 3426.3 GWh/month) close to point F9, a relatively large decrease in irrigation deficit (from 1069.0 to 635.4 hm³/y) is observed; thus, the gradient of the Pareto front is very flat. The theoretical “utopian solution”, for which hydropower production and irrigation deficit would be optimized simultaneously, would result to a hydropower production of 3479.6 GWh/month and an irrigation deficit of 162.0 hm³/y.

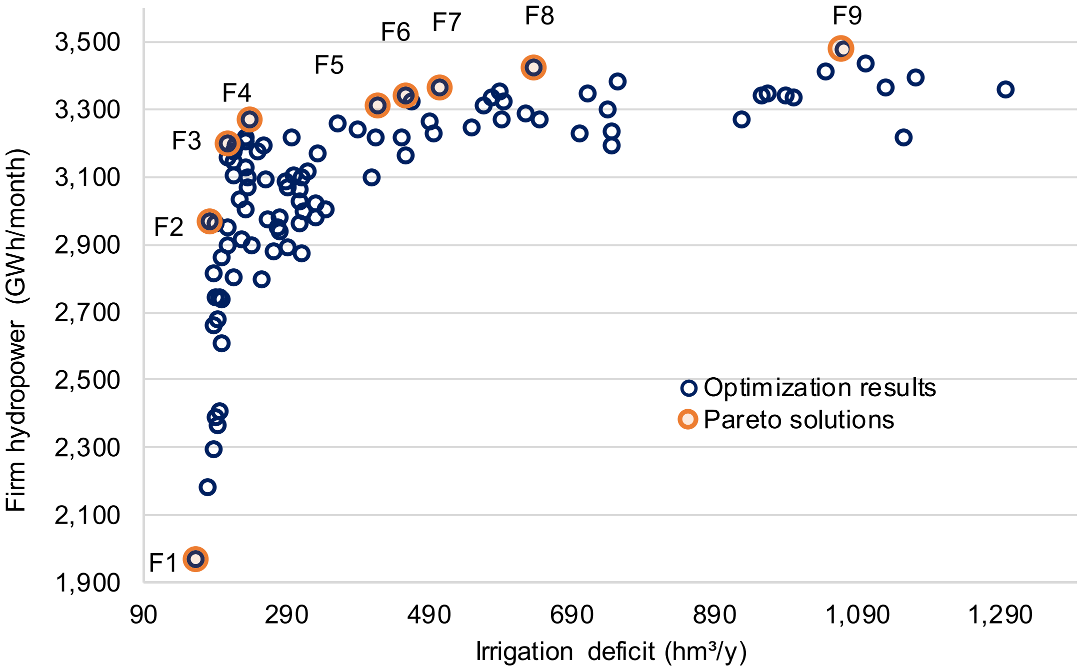

Figure 5.44 Pareto front of the UBNR hydro-system for the full development

Calculations showed that mean annual hydropower production of the Pareto solutions F1 to F9 varies from 43,711 to 47,749 GWh/y (Figure 5.45), while the individual mean annual values of each HPP for all Pareto solutions are shown in Table 5.11. Furthermore, the variation of the hydropower production throughout the year is shown in Figures 5.46, 5.47 and 5.48 for the Pareto solutions F1 to F9, while Figure 5.49 shows the duration curve of the monthly hydropower production.

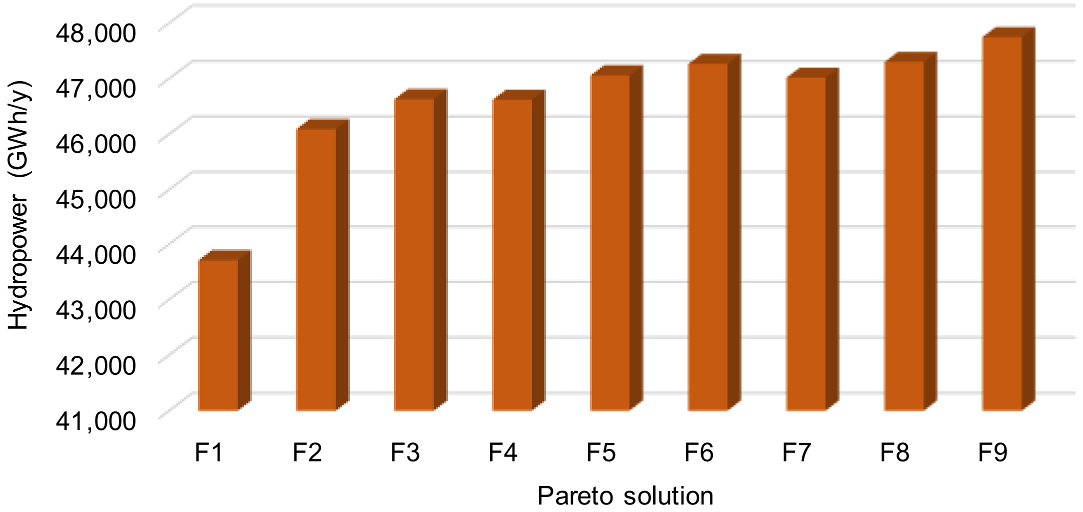

Figure 5.45 Mean annual hydropower production of the Pareto solutions F1 to F9

Table 5.11 Mean annual hydropower production (GWh/y) for the 23 HPPs of the Pareto solutions F1 to F9

HPP	F1	F2	F3	F4	F5	F6	F7	F8	F9
HP1	1,632	1,583	1,577	1,585	1,769	1,786	1,587	1,652	1,386
HP2	1	1	32	10	27	25	50	54	27
HP3	10	6	5	6	1	1	1	1	113
HP4	857	773	864	785	858	802	785	843	852
HP5	863	804	903	817	897	834	817	845	890
HP6	33	33	33	33	33	33	36	36	36
HP7	631	672	731	722	682	679	722	715	696
HP8	234	233	233	233	233	233	236	233	236
HP9	415	466	482	485	445	493	513	460	507
HP10	415	466	482	485	445	493	513	460	507
HP11	747	732	747	737	738	738	749	758	750
HP12	653	661	676	683	665	670	678	680	677
HP13	149	151	142	152	151	151	153	152	153
HP14	374	370	383	373	379	373	372	382	373
HP15	2,116	2,143	2,143	2,165	2,170	2,191	2,166	2,191	2,178
HP16	630	619	619	619	622	630	619	627	618
HP17	1,461	1,336	1,290	1,312	1,443	1,460	1,267	1,126	788
HP18	552	543	543	543	544	550	544	552	543
HP19	634	625	624	635	770	779	703	756	734
HP20	3,485	5,328	5,314	5,387	5,336	5,357	5,411	5,433	5,706
HP21	6,033	6,215	6,227	6,238	6,200	6,206	6,305	6,290	6,484
HP22	8,371	8,905	9,109	9,127	9,006	9,044	9,201	9,186	9,387
HP23	13,416	13,426	13,471	13,491	13,644	13,738	13,592	13,866	14,108
Total	43,711	46,090	46,630	46,620	47,060	47,264	47,017	47,301	47,749

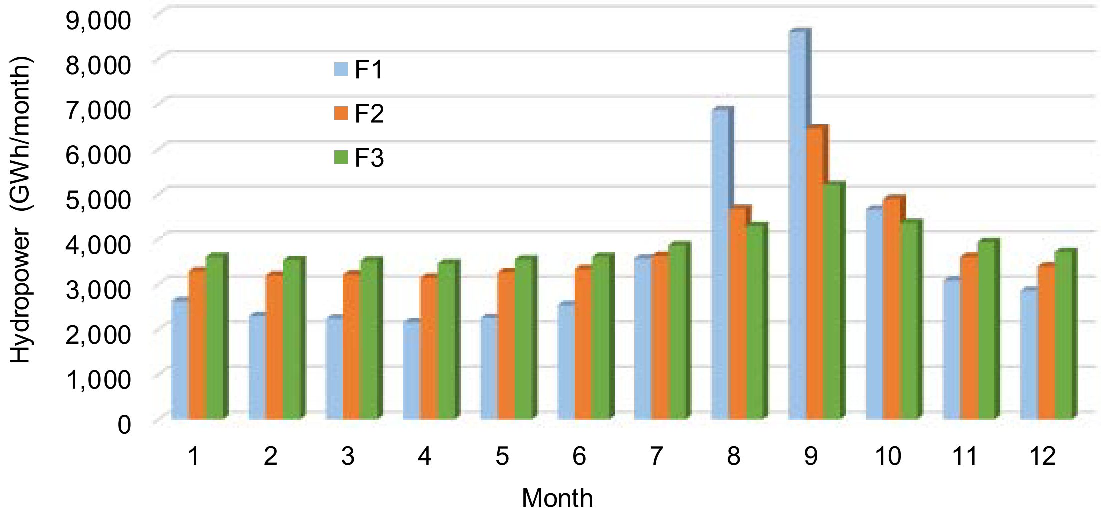

Figure 5.46 Monthly variation of the hydropower production (GWh/month) of the Pareto solutions F1, F2 and F3

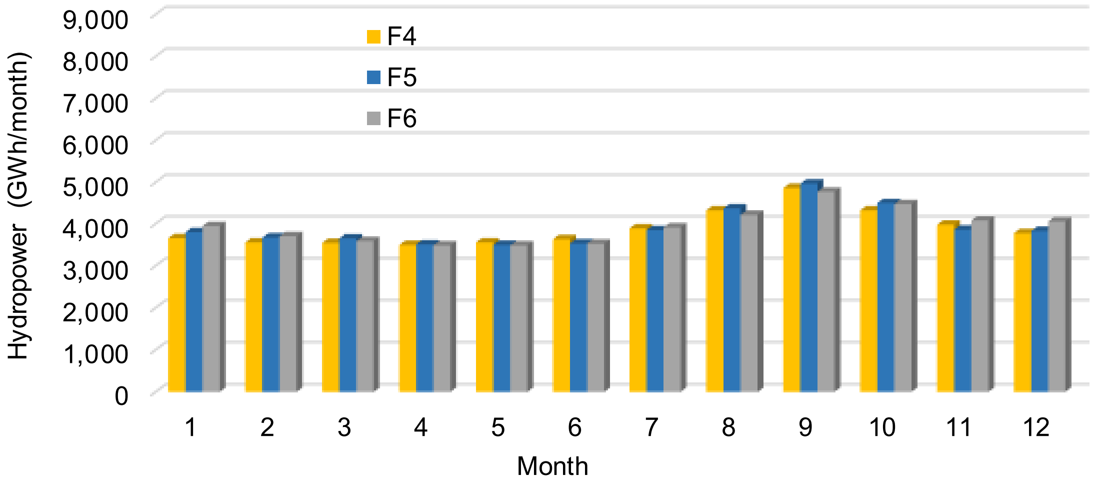

Figure 5.47 Monthly variation of the hydropower production (GWh/month) of the Pareto solutions F4, F5 and F6

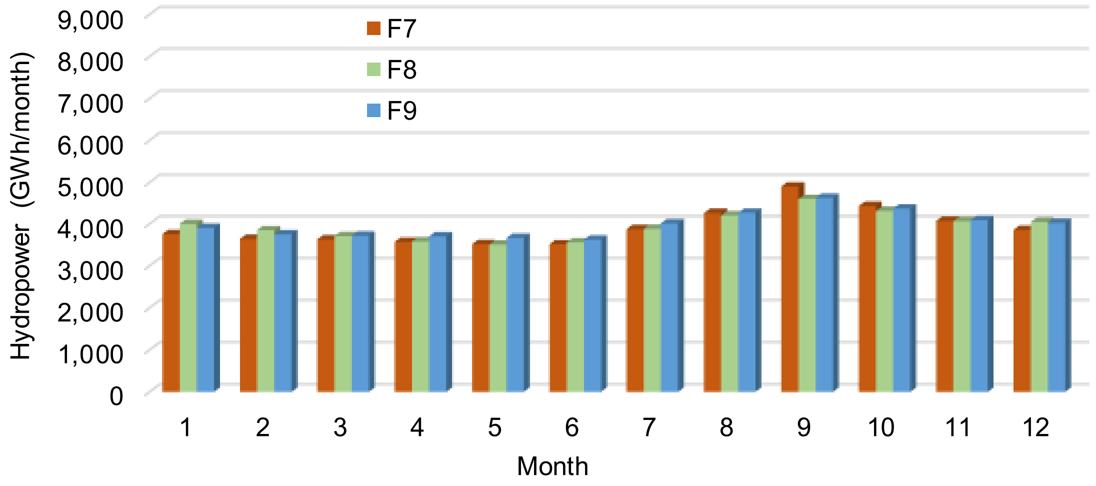

Figure 5.48 Monthly variation of the hydropower production (GWh/month) of the Pareto solutions F7, F8 and F9

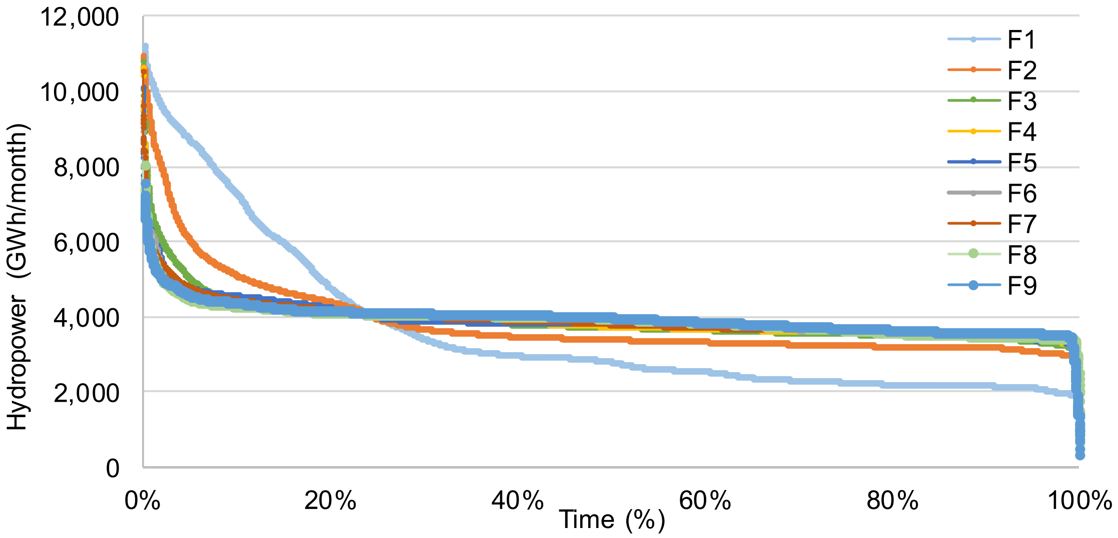

Figure 5.49 Duration curve of the monthly hydropower production (GWh/month) of the Pareto solutions F1 to F9

Calculations showed, moreover, that the actual irrigation amount of the Pareto solutions F1 to F9 varies from 3,499 to 4,406 hm³/y, while the variation throughout the year is shown in Figures 5.50, 5.51 and 5.52. Compared to the estimated annual irrigation demand of 4,568 hm³/y that leads to the annual irrigation deficit of 162 to 1069 hm³/y for the Pareto solutions F1 to F9. Figure 5.53 shows the deficit/demand ratio of all Pareto solutions, while the individual mean annual irrigation deficit of each irrigation project is shown in Table 5.12.

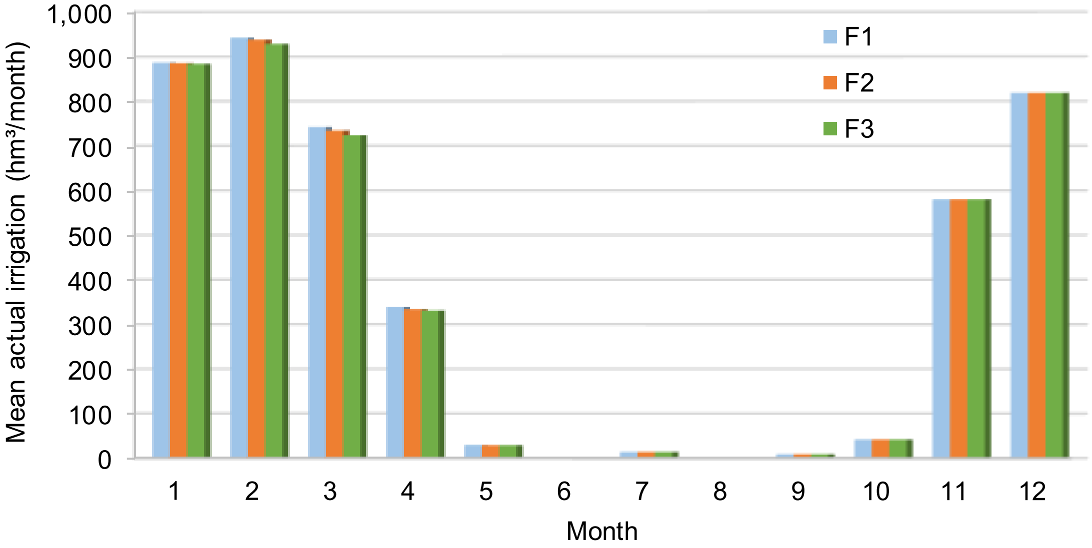

Figure 5.50 Variation of the mean irrigation amount (hm³/month) of Pareto solutions F1, F2 and F3

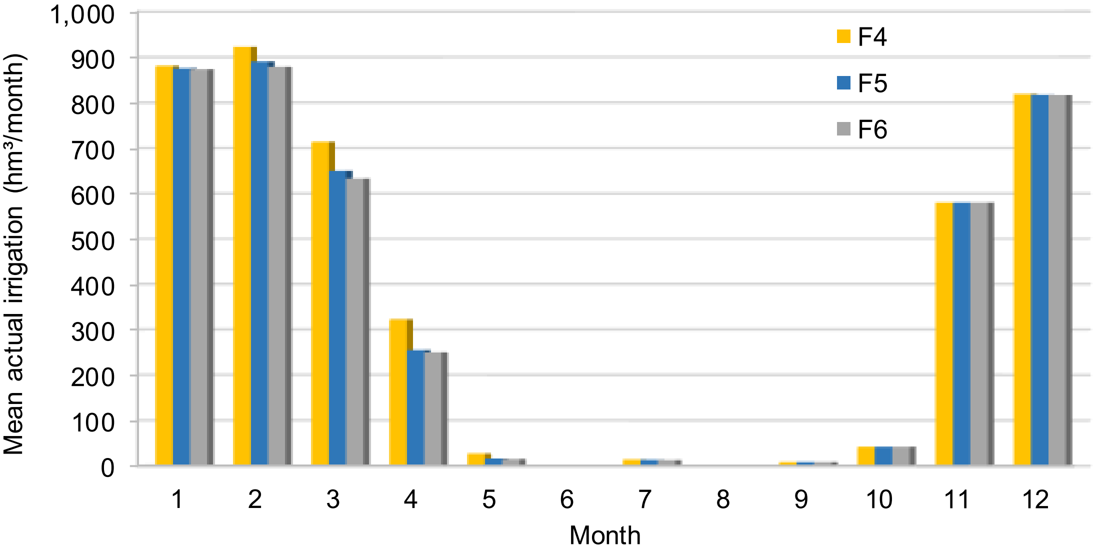

Figure 5.51 Variation of the mean irrigation amount (hm³/month) of Pareto solutions F4, F5 and F6

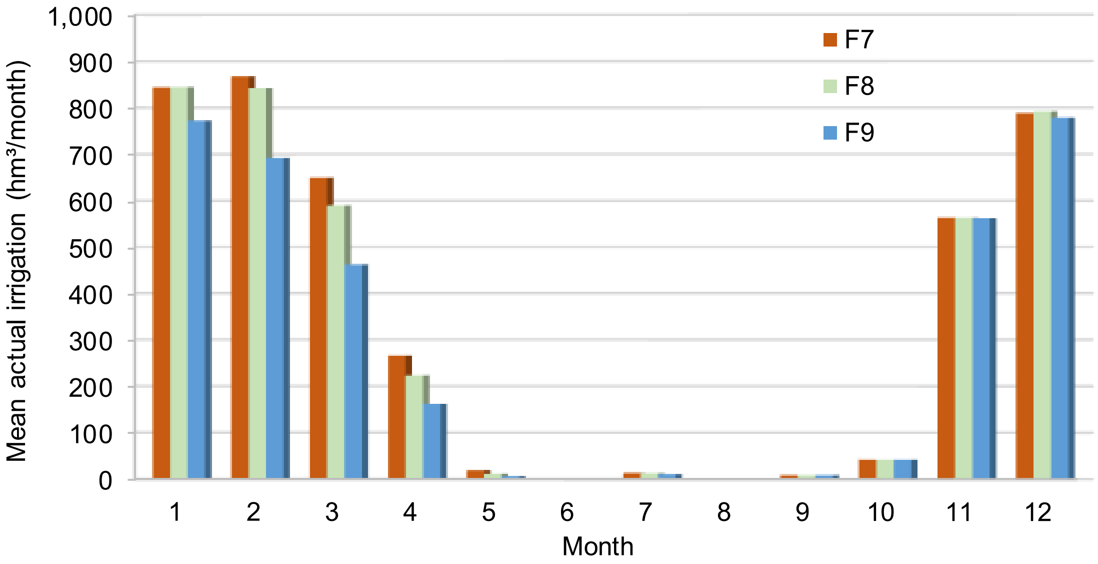

Figure 5.52 Variation of the mean irrigation amount (hm³/month) of Pareto solutions F7, F8 and F9

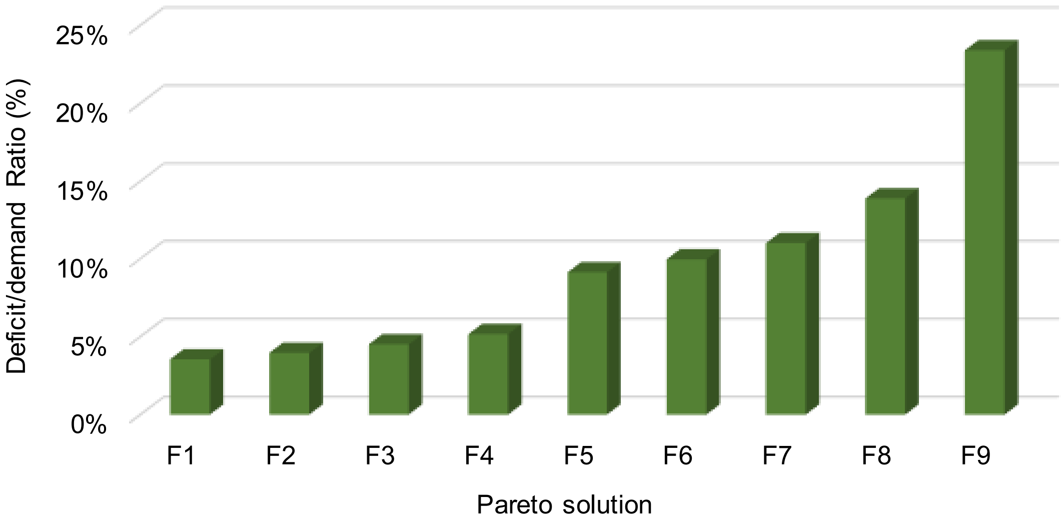

Figure 5.53 Irrigation deficit/demand ratio (%) of the Pareto solutions F1 to F9

Table 5.12 Mean annual irrigation deficit (hm³/y) for the Pareto solutions F1 to F9

IRG	F1	F2	F3	F4	F5	F6	F7	F8	F9
IRG1	3	4	4	5	10	11	8	14	24
IRG2	1	1	1	2	8	9	6	12	24
IRG3	1	1	2	3	12	13	8	19	41
IRG4	0	0	0	0	0	0	0	1	1
IRG5	0	0	0	0	2	2	1	3	7
IRG6	1	2	2	3	11	12	8	16	30
IRG7	5	6	6	7	20	21	15	28	53
IRG8	57	59	59	61	75	77	70	86	116
IRG9	3	3	4	5	12	13	10	17	28
IRG10	4	6	6	9	39	42	30	59	117

IRG11	1	1	1	2	7	8	5	11	22
IRG12	2	2	3	4	16	18	12	25	48
IRG21	0	1	1	1	5	5	3	7	15
IRG22	1	1	1	2	6	7	5	10	21
IRG23	0	0	0	0	1	1	1	2	4
IRG28	22	22	22	22	22	22	26	26	26
IRG29	15	15	15	15	15	15	18	18	17
IRG30	23	29	38	45	47	46	116	117	116
IRG32	0	1	0	1	4	0	45	0	42
IRG34	0	0	3	4	0	7	16	0	13
IRG45	2	2	2	2	2	2	2	2	2
IRG47	0	0	1	1	0	0	0	1	1
IRG54	3	5	11	11	3	12	11	11	12
IRG55	1	2	5	5	1	5	5	5	5
IRG67	13	16	17	24	86	93	72	127	232
IRG68	1	2	2	3	11	12	9	18	37
IRG69	0	0	0	0	0	0	0	0	12
Total	162	181	206	236	417	455	503	635	1,069

The mean monthly discharge at the border varies from 1,333 to 1,401 m³/s for the Pareto solutions F1 to F9 and is shown in Figure 5.54. The variation of the discharge at the border throughout the year for the Pareto solutions F1 to F9 is, furthermore, shown in Figure 5.55. The Pareto solution F1, for which irrigation is more important than hydropower, follows more the natural flow pattern of the UBNR. As the solution, however, approaches to the Pareto solution F9, for which hydropower is more important compared to irrigation, the flow pattern changes completely; water is transferred from the wet to the dry period and flood picks are reduced.

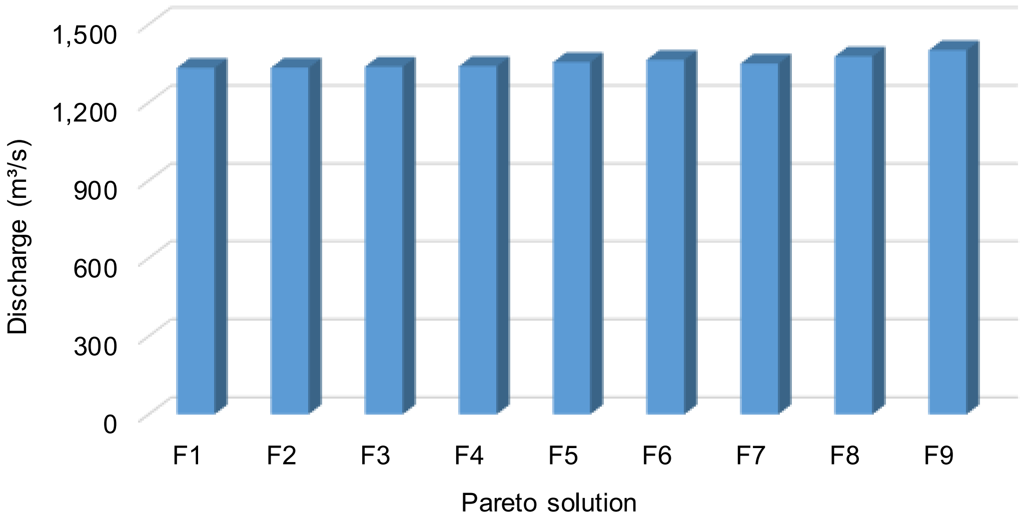

Figure 5.54 Mean monthly discharge (m³/s) of Pareto solutions F1 to F9

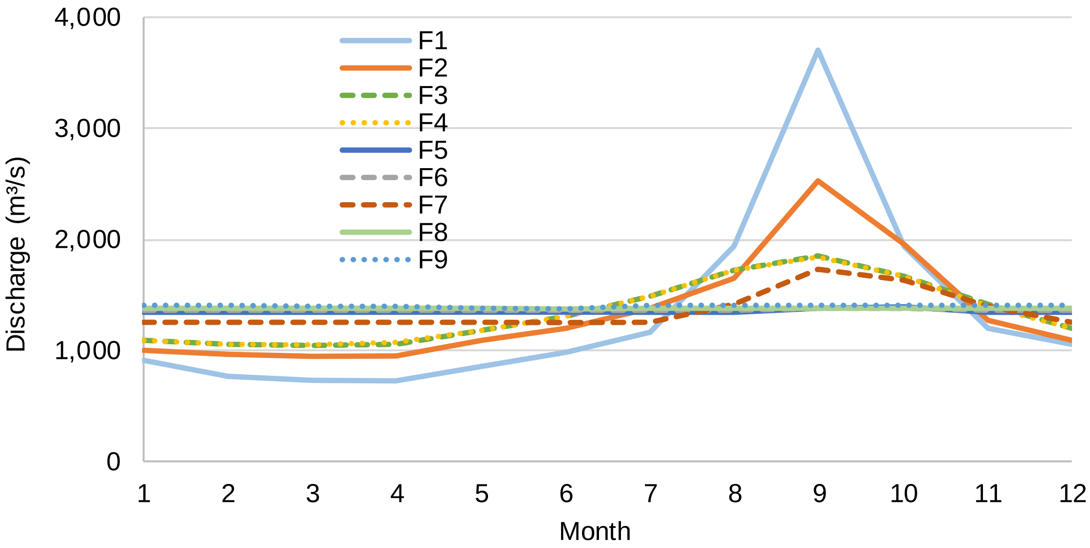

Figure 5.55 Variation of monthly discharge (m³/s) at the border for the Pareto solutions F1 to F9

Furthermore, the results of the Pareto calculations of the full development are discussed in the following, in order to further investigate the effect of different management policies. Table 5.13 summarizes the categorization of the HPPs according to their sensitivity to changes in the management policies, while Figure 5.56 shows the ratio of generated hydropower of every HPP in relation to its maximum value for the Pareto solutions F1 to F9. The HHPs HP6, HP8, HP11-HP16, HP18, HP21 and HP23 yield a hydropower value that ranges from 90 to 100% of their maximum value for all Pareto solutions. Thus, these HHPs operate almost equal for all solutions and are, therefore, not sensitive to changes in the Pareto solutions, which translates to changes in the management policies. The seven HPPs HP4, HP5, HP7, HP9, HP10, HP19 and HP22 yield a hydropower value that ranges from 80 to 100% of their maximum value for the nine Pareto solutions F1 to F9 and thus, show a greater difference in hydropower production between the solutions than the first group. Furthermore, the three HPPs HP1, HP17 and HP20 yield a hydropower value that ranges from 50 to 100% of their maximum value, and are, therefore, more sensitive to changes in the management policies. Finally, the two HPPs HP1 and HP2 yield a hydropower value that ranges from 2 and 1%, respectively, to 100% of their maximum value, which shows that these are the most sensitive HPPs to changes in the management policies.

Table 5.13 Categorization of HPPs according to their sensitivity to management policies

Sensitivity level	HPP
not sensitive	6, 8, 11, 12, 13, 14, 15, 16, 18, 21, 23
little sensitive	4, 5, 7, 9, 10, 19, 22
sensitive	1, 17, 20
very sensitive	1, 2

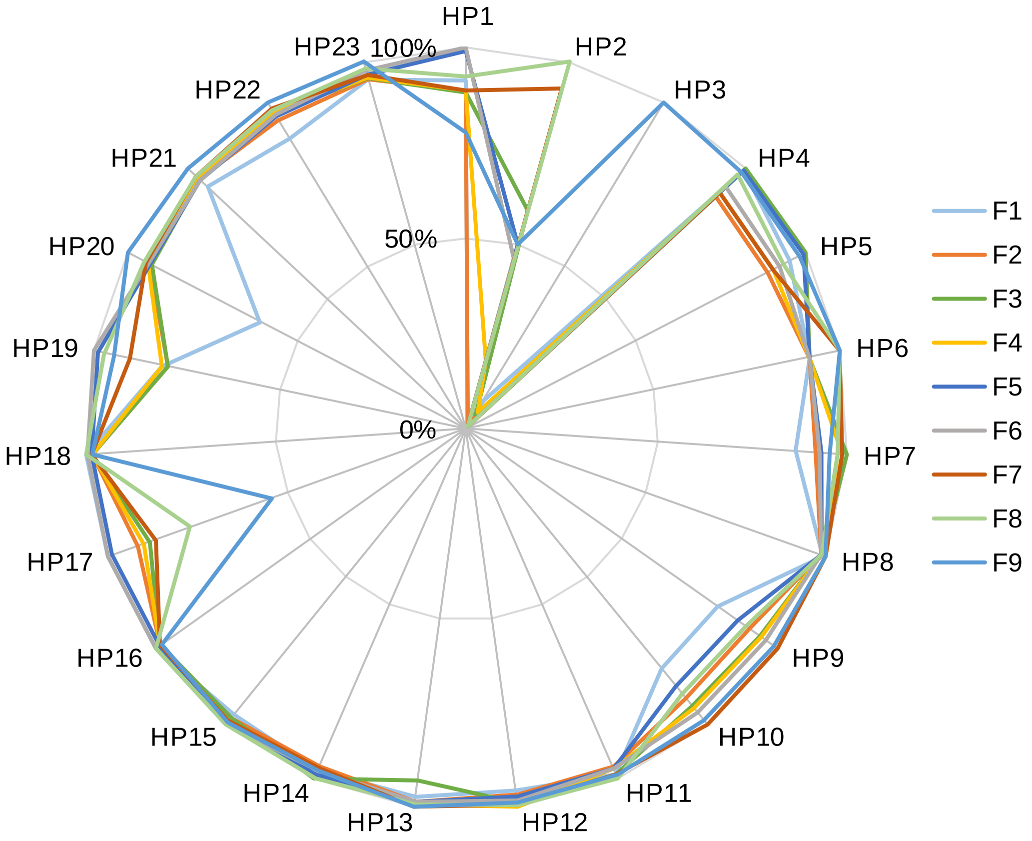

Figure 5.56 Ratio of generated to maximum hydropower of the 23 HPPs for the Pareto solutions F1 to F9

Moreover, from the 69 irrigation project groups, 41 IRGs show no or very little irrigation deficit for all Pareto solutions F1 to F9 and are thus, not sensitive changes in the management policies. These are: IRG4, IRG13-20, IRG24-27, IRG31, IRG33, IR35-44, IRG46, IRG48-53, IRG56-64 and IRG66. Furthermore, the irrigation project groups IRG45, IRG47, IRG65 and IRG69 show an irrigation deficit that is very small compared to their annual irrigation demand, and the projects IRG8, IRG28, IRG29, IRG54 and IRG55 show a similar irrigation deficit for all Pareto solutions. From the remaining irrigation project groups, the IRG2, IRG3, IRG5, IRG22, IRG23, IRG32, IRG34, IRG67 and IRG68 show an irrigation deficit that ranges from 0 to 40% of their irrigation demand and are, therefore, categorized as sensitive to changes in the management policies. The irrigation project groups IRG1, IRG6, IRG7, IRG9, IRG10, IRG11, IRG12 and IRG21 show, furthermore, an irrigation deficit that ranges from 0 to 50% of their irrigation demand and are categorized as very sensitive. Finally, IRG30 shows an irrigation deficit that ranges from 20 to 100% of its annual irrigation demand and shows, thus, the greatest variation to changes in the management policies. Table 5.14 summarizes the categorization of the IRGs according to their sensitivity to changes in the management policies.

Table 5.14 Categorization of IRGs according to their sensitivity to management policies

Sensitivity level	IRG
not sensitive	4, 13, 14, 15, 16, 17, 18, 19, 20, 24, 25, 26, 27, 31, 33, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 46, 48, 49, 50, 51, 52, 53, 56, 57, 58, 59, 60, 61, 62, 63, 64, 66
little sensitive	45, 47, 65, 69, 8, 28, 29, 54, 55
sensitive	2, 3, 5, 22, 23, 32, 34, 67,68
very sensitive	1, 6, 7, 9, 10, 11, 12, 21
most sensitive	30

5.7 Social Cost-Benefit Analysis for the Full Development

5.7.1 Introduction

All Pareto solutions presented in Section 5.6 are considered equally good without additional subjective preference information (Cheikh et al. 2010). Absent known preferences of the decision makers, additional factors can influence the selection of the best compromise among them. In order to suggest one Pareto optimal solution as the best compromise for the UBNR basin, a social cost-benefit analysis was performed for the full development. The net social benefits of the Pareto optimal solutions were calculated by assigning monetary values to hydropower and irrigation in order to quantify them.

The following assumptions were made:

1. The average export price of hydropower is equal to 0.08 US$/kWh (2.2 ETB/kWh); this value is consistent with international experience (Whittington et al. 2005, Block and Strzepek 2010).

2. The unit cost of a HPP ranges from 800 to 4,000 US$/kWh depending on its size; the larger the HPP, the lower the unit cost (Chen and Swain 2014, IRENA 2012). The calculated capital cost of a HPP ranged from to 50 to 4,800 million US$.

3. The operating and maintenance (O&M) cost of a HPP ranges from 1 to 4% of the capital cost, depending on its size; the larger the HPP the lower the percentage (IRENA 2012). The calculated O&M cost of a HPP varied from to 2 to 48 million US$/y.

4. The unit cost of an irrigation project is equal to 14,455 US$/ha and includes all irrigation-related costs (Inocencio et al. 2007). The calculated capital cost of an irrigation project ranged from 20 to 388 million US$.

5. For multi-purpose projects, where the capital cost of the dam is already considered, and irrigation projects, where no dam construction is needed, the unit cost of an irrigation project is equal to 1,000 US$/ha (You 2008). The calculated capital cost of such projects ranged from 1 to 100 million US$.

6. The O&M cost of an irrigation project is equal to 0.003 US$/m^3 for the canals and 4 US$/ha for the on-farm systems per year (You 2008). The calculated O&M cost of an irrigation project varied from 20.000 to 2.5 million US$/y.

7. The equivalent annual capital (EAC) cost of a HPP (Au and Au 1992) is calculated using a discount rate equal to 10% (Block and Strzepek 2010, IRENA 2012), an economic lifetime of the HPP that ranges from 30 to 40 years depending on the size of the HPP (Beleke et al. 2007, IRENA 2012), and the capital cost. The calculated EAC cost of the HPPs ranged from 12 to 491 million US$/y.

8. The EAC cost of an irrigation project (Au and Au 1992) is calculated using a discount rate equal to 10% (Block and Strzepek 2010, IRENA 2012), an economic lifetime of the irrigation project equal to 40 years, and the capital cost of the project. The EAC cost of the HPPs ranged from 130,000 US$/y to 40 million US$/y.

9. Current prices are used in the analysis.

5.7.2 Social Cost-Benefit Analysis – Selection of the Proposed Solution

The cost of the irrigation deficit is calculated using the program IRIDE that is described in section 3.6.3; the result is shown in Table 5.15 together with the basic characteristics of the calculations. The outcome of the cost-benefit analysis is shown in Table 5.16 and Figure 5.58, while Table 5.16 includes some basic characteristics; Pareto solution F9 that maximizes the net benefit is obviously the proposed solution, according to the chosen socio-economic criteria.

Table 5.15 Cost of irrigation deficit (million US$/y)

Pareto solution	Non-irrigated area (ha/y)	Non-produced quantities of crops (ton/y)	Cost of irrigation deficit (million US$/y)
F1	8,533	72,200	11.8
F2	9,676	86,410	13.8
F3	11,227	94,350	15.6
F4	12,769	117,270	18.4
F5	21,787	292,910	38.1
F6	24,104	306,950	40.9
F7	21,942	279,830	37.3
F8	29,907	386,560	50.8
F9	45,602	573,140	75.3

Table 5.16 Cost of irrigation deficit, EAC and O&M cost of irrigation, EAC and O&M cost of HPPs, benefit from HPPs and net benefit (million US$/y) of the Pareto solutions F1 to F9 (IRIDE approach)

Pareto solution	Cost of irrigation deficit (million US$/y)	EAC cost-Irrigation (million US$/y)	O&M cost-Irrigation (million US$/y)	EAC cost-HPPs (million US$/y)	O&M cost-HPPs (million US$/y)	Benefit of HPPs (million US$/y)	Net benefit (million US$/y)
F1	11.8	282	108	1,647	285	1,888	-444

F2	13.8	282	108	1,647	285	2,853	519
F3	15.6	282	108	1,647	285	3,075	739
F4	18.4	282	108	1,647	285	3,143	804
F5	38.1	282	108	1,647	285	3,180	821
F6	40.9	282	108	1,647	285	3,209	848
F7	37.3	282	108	1,647	285	3,231	873
F8	50.8	282	108	1,647	285	3,289	918
F9	75.3	282	108	1,647	285	3,340	944

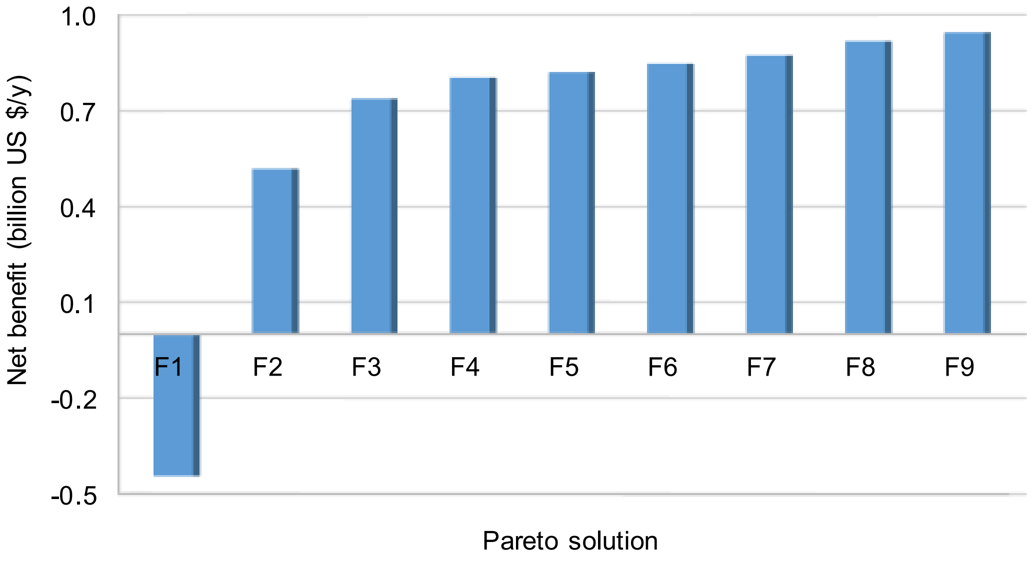

Figure 5.57 Net benefit (billion US$/y) for the Pareto solutions F1 to F9 (IRIDE approach)

5.7.3 Simplified Approach

For comparison purposes, a simpler approach was also employed, in which the Willingness-To-Pay (WTP) or the Net Return (NR) are used as indicators to quantify the irrigation deficit.

The following assumptions were made:

1. The WTP is equal to 0.003 US$/m³ (0.07 ETB/m³) (Kassahun et al. 2016).
2. The NR is equal to 0.05 US$/m³ (1.4 ETB/m³); this value is consistent with international experience (Whittington et al. 2005, Goor et al. 2010).

The cost of the irrigation deficit is calculated by multiplying the WTP and NR by the irrigation deficit. The outcome of the simplified cost-benefit analysis for the WTP and NR is shown in Tables 5.17 and 5.18, and in Figures 5.58 and 5.59, respectively, while Tables 5.17 and 5.18 include some basic characteristics; Pareto solution F9 that maximizes the net benefit is obviously the proposed solution, according to the chosen criteria.

Table 5.17 Cost of irrigation deficit, EAC and O&M cost of irrigation, EAC and O&M cost of HPPs, benefit from HPPs and net benefit (million US$/y) of the Pareto solutions F1 to F9 (WTP approach)

Pareto solution	Cost of irrigation deficit (million US$/y)	EAC cost-irrigation (million US$/y)	O&M cost-irrigation (million US$/y)	EAC cost-HPPs (million US$/y)	O&M cost-HPPs (million US$/y)	Benefit of HPPs (million US$/y)	Net benefit (million US$/y)
F1	0.4	282	108	1,647	285	1,888	-433
F2	0.5	282	108	1,647	285	2,853	532
F3	0.5	282	108	1,647	285	3,075	754
F4	0.6	282	108	1,647	285	3,143	822
F5	1.1	282	108	1,647	285	3,180	858
F6	1.2	282	108	1,647	285	3,209	887
F7	1.3	282	108	1,647	285	3,231	909
F8	1.6	282	108	1,647	285	3,289	967
F9	2.7	282	108	1,647	285	3,340	1,017

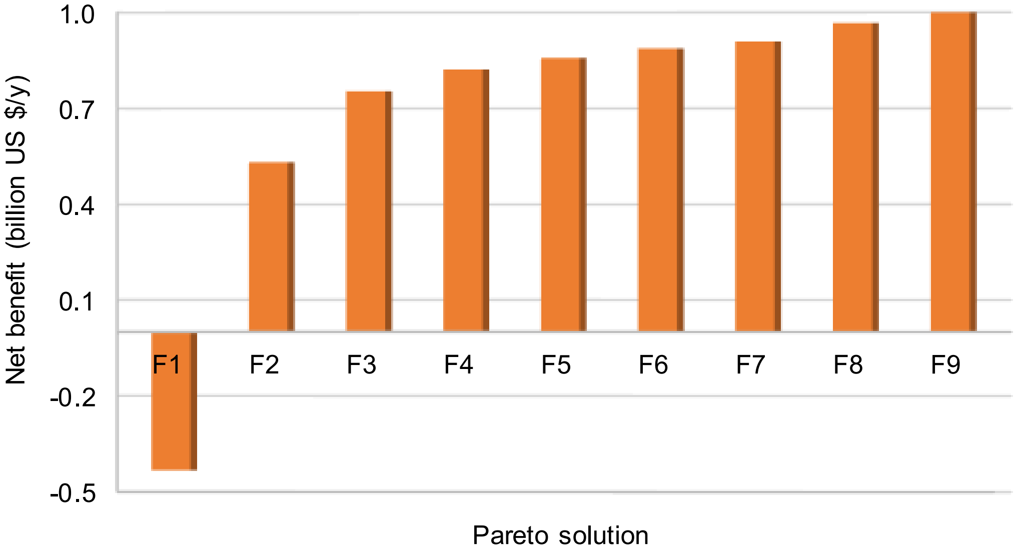

Figure 5.58 Net benefit (billion US$/y) for the Pareto solutions F1 to F9 (WTP approach)

Table 5.18 Cost of irrigation deficit, EAC and O&M cost of irrigation, EAC and O&M cost of HPPs, benefit from HPPs and net benefit (million US$/y) of the Pareto solutions F1 to F9 (NR approach)

Pareto solution	Cost of irrigation deficit (million US$/y)	EAC cost-irrigation (million US$/y)	O&M cost-irrigation (million US$/y)	EAC cost-HPPs (million US$/y)	O&M cost-HPPs (million US$/y)	Benefit of HPPs (million US$/y)	Net benefit (million US$/y)
F1	8.1	282	108	1,647	285	1,888	-441
F2	9.1	282	108	1,647	285	2,853	523
F3	10.3	282	108	1,647	285	3,075	744
F4	11.8	282	108	1,647	285	3,143	810
F5	20.8	282	108	1,647	285	3,180	838

F6	22.8	282	108	1,647	285	3,209	866
F7	25.2	282	108	1,647	285	3,231	885
F8	31.8	282	108	1,647	285	3,289	937
F9	53.4	282	108	1,647	285	3,340	966

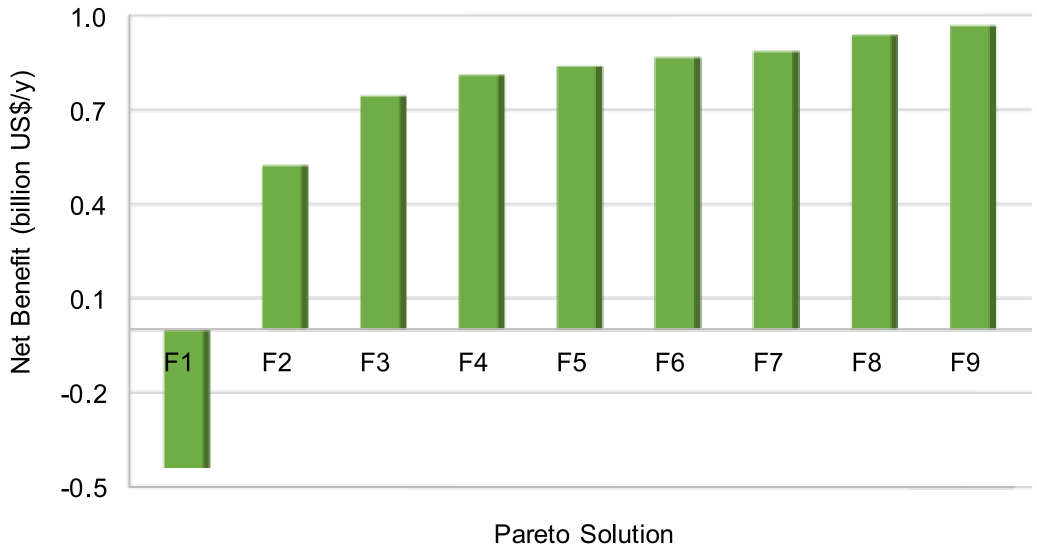

Figure 5.59 Net benefit (billion US$/y) for the Pareto solutions F1 to F9 (NR approach)

Regardless the approach that is used to calculate the cost of the irrigation deficit, Pareto solution F9 is the solution that yields the highest net benefit according to the chosen socio-economic criteria, i.e. 944, 1,017 and 966 million US$/y for the IRIDE, WTP and NR approach, respectively. Pareto solution F9 is the solution with the highest firm hydropower production (3479.6 GWh/month, which correspond to an annual hydropower production of 47,749 GWh/y) and the highest irrigation deficit (1,069 hm^3/y); thus, hydropower is prevailing.

5.7.4 Discount Rate – Sensitivity Analysis

A sensitivity analysis was performed for the discount rate using the following values: 5, 7.5, 10 and 12%. The new EAC cost ranges from 939 to 1,953 million US$/y for the HPPs, and 160 to 334 million US$/y for irrigation projects, and is shown in Table 5.19. Furthermore, the discount rate, for which the net benefit would be negative for all solutions, was calculated equal to 16%.

Table 5.19 EAC cost (million US$/y) for the discount rates 5, 7.5, 10 and 12%

Discount rate (%)	5%	7.5%	10%	12%
Irrigation EAC (million US$/y)	160	219	282	334

HPP EAC (million US$/y)	939	1,279	1,647	1,953

The results of the social cost benefit analysis for the various discount rates are shown in Figures 5.60, 5.61 and 5.62 for the IRIDE, WTP and NR approach, respectively. It is shown that although the absolute value of the equivalent annual capital costs of the HPPs and irrigation projects changes for the different values of discount rate as expected, Pareto solution F9 still maximizes the net benefit, and is the proposed solution for all cases, according to the chosen socio-economic criteria.

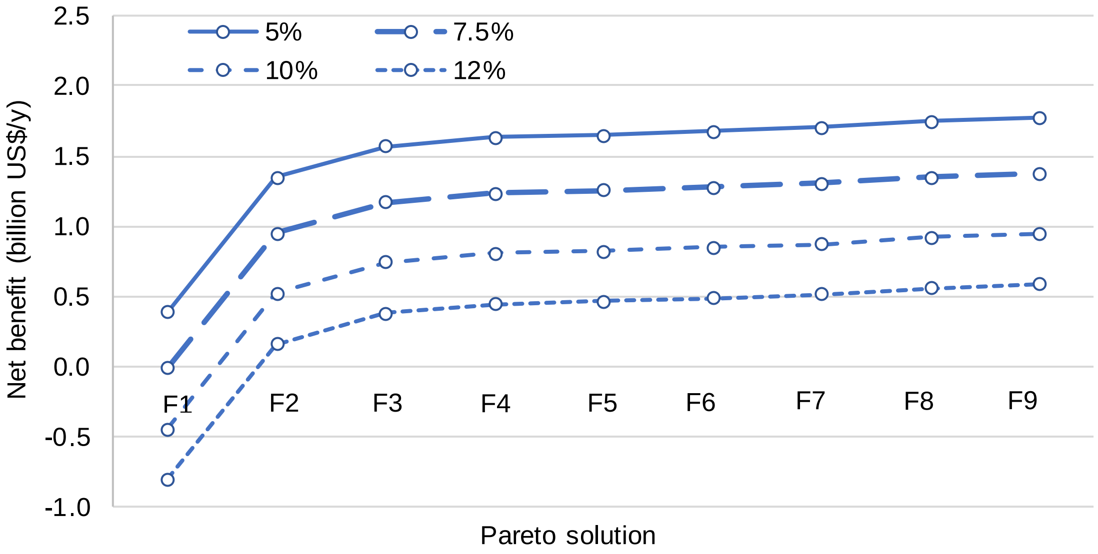

Figure 5.60 Net benefit (billion US$/y) for discount rate 5, 7.5, 10 and 12% for the Pareto solutions F1 to F9 (IRIDE approach)

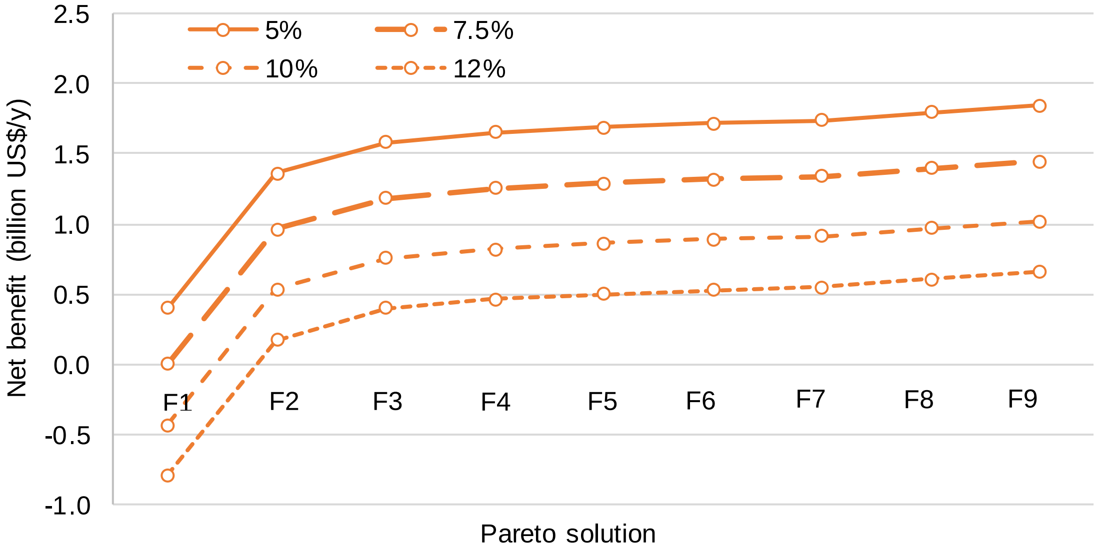

Figure 5.61 Net benefit (billion US$/y) for discount rate 5, 7.5, 10 and 12% for the Pareto solutions F1 to F9 (WTP approach)

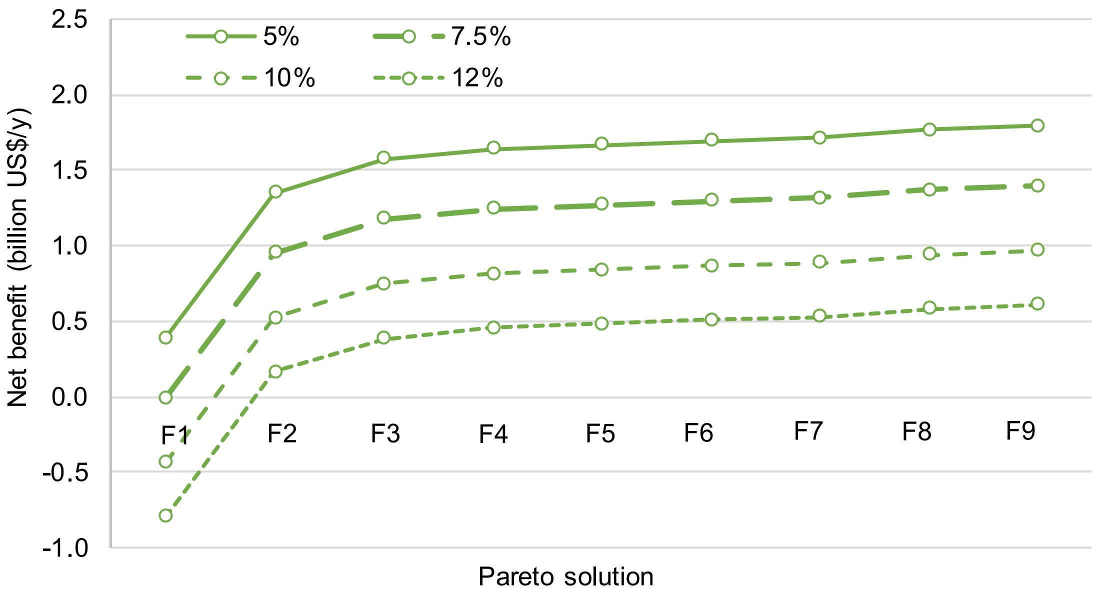

Figure 5.62 Net benefit (billion US$/y) for discount rate 5, 7.5, 10 and 12% for the Pareto solutions F1 to F9 (NR approach)

5.7.5 Main Characteristics of the Proposed Solution

The proposed Pareto solution F9 that yields the highest net benefit for the UBNR basin includes 37 reservoirs of a total volume equal to 221,452 hm³, 23 HPPs with an installed total capacity of 14,214 MW and 69 irrigation project groups of a total net area equal to 584,110 ha. Its main characteristics are the following:

1. The hydropower production was calculated equal to 47,749 GWh/y, i.e. almost 15 times higher than the amount produced in the current conditions, while Figure 5.63 shows the variation of the hydropower production throughout the year.

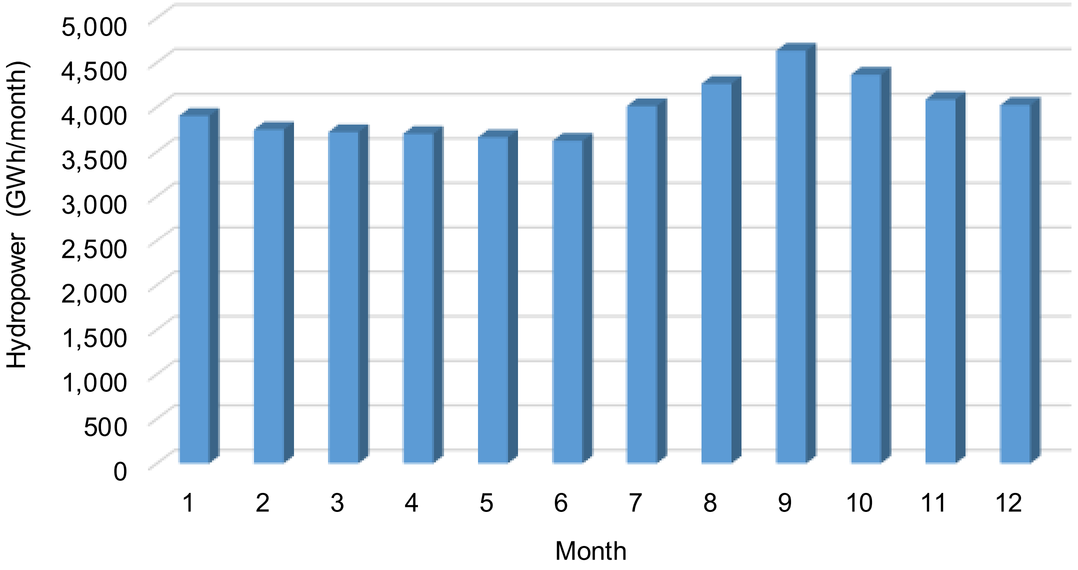

Figure 5.63 Variation of the hydropower production (GWh/month) for Pareto solution F9

2. The annual irrigation demand was determined equal to 4,568 hm³/y; this value is equal to 9.3% of the average river discharge of the natural conditions (49.3 km³/y). However, the actual irrigation amount was calculated equal to 3,499 hm³/y, i.e. the irrigation deficit is equal to 1,069 hm³/y that is 23% of the annual irrigation demand. Figures 5.64 and 5.65 show the variation of the actual irrigation amount and the irrigation deficit throughout the year, respectively.

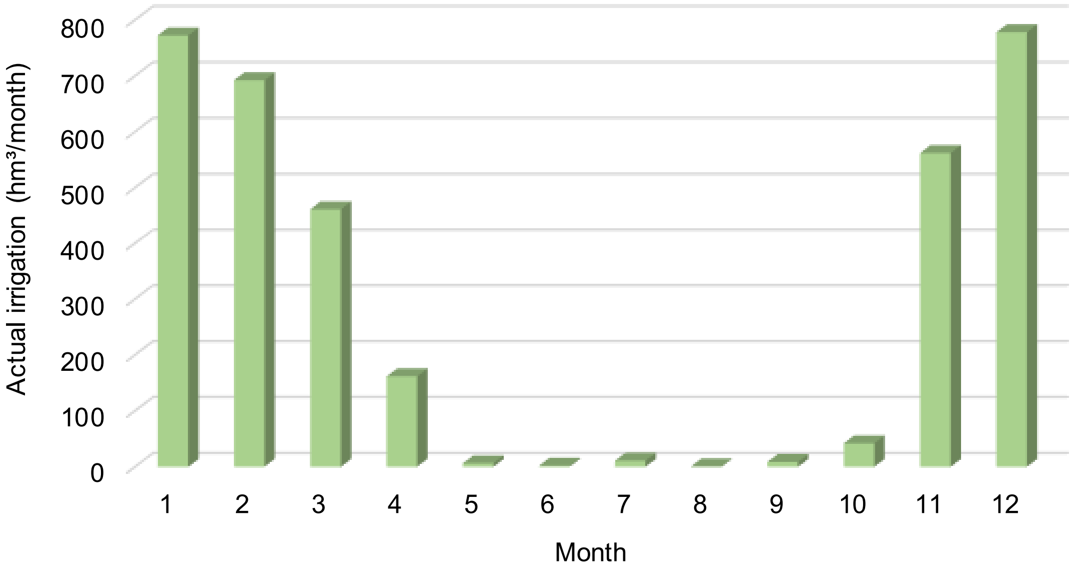

Figure 5.64 Variation of the actual irrigation amount (hm³/month) for Pareto solution F9

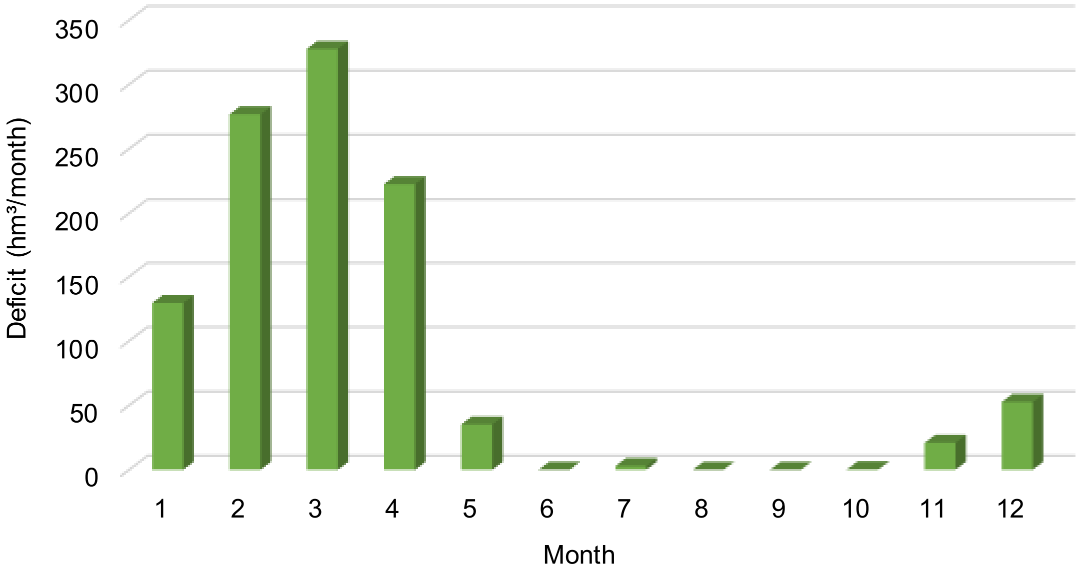

Figure 5.65 Variation of the irrigation deficit (hm³/month) for Pareto solution F9

3. The average annual discharge at the border was calculated equal 44.2 km³/y (1,401 m³/s) almost evenly distributed throughout the year; this corresponds to a

reduction of 10.3% of the river discharge in natural conditions. Figure 5.66 shows the variation of the discharge at the border (m³/s) throughout the year for the natural conditions and Pareto solution F9. The standard deviation of the discharge at the border equals 1,932 m³/s (124 % of the average value) for the natural conditions and 11 m³/s (0.8% of the average value) for the Pareto solution F9.

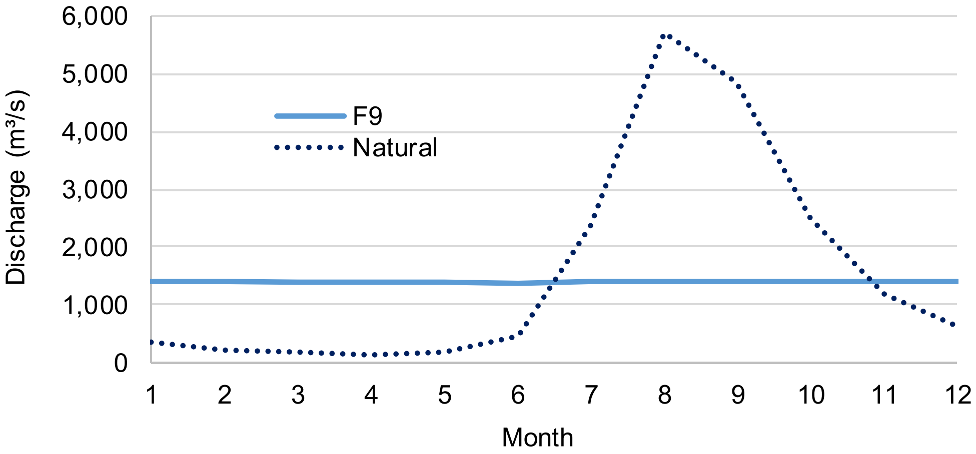

Figure 5.66 Monthly variation of the discharge at the border (m³/s) for the natural conditions and Pareto solution F9

4. The benefit from hydropower was calculated equal to 3,340 million US$/y (92,305 ETB/y).

5. The three most important crops of Pareto solution F9 that make together almost 50% of the total irrigated area, are: maize (21%), sugarcane (14%) and wheat (10%). Figure 5.67 shows the percentage of area that each crop occupies, compared to the total irrigated area.

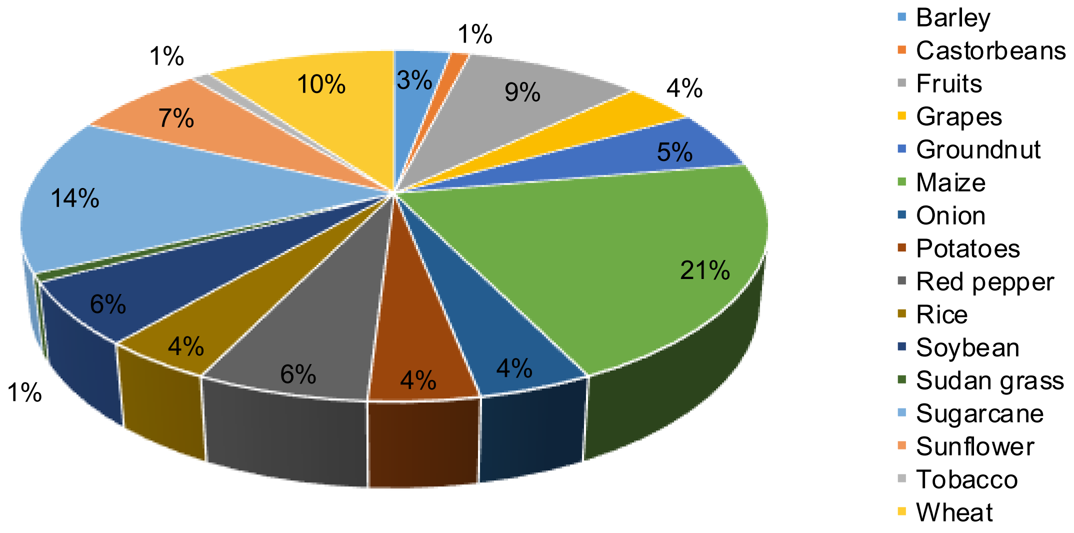

Figure 5.67 Percentage of area per crop (%) compared to the total irrigated area

6. The total non-irrigated area was calculated equal to 45,602 ha. Most of the non-irrigated area belongs to the crops: maize (17%), rice (12%), sugarcane (18%), sunflower (9%) and wheat (10%). Figure 5.68 shows the percentage of non-irrigated area per crop, compared to the total non-irrigated area.

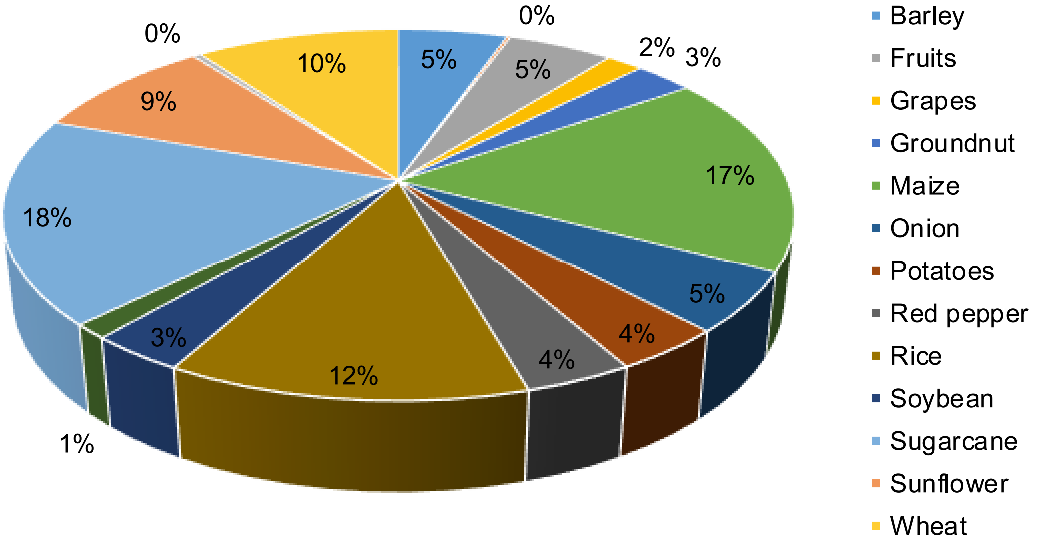

Figure 5.68 Percentage of non-irrigated area per crop (%) compared to the total non-irrigated area

7. The total non-produced quantity of crops was calculated equal to 573,140 ton/y. Most of the non-produced quantity of crops belongs to sugarcane (73%). Figure 5.69 shows the percentage of non-produced quantity per crop, compared to the total non-produced quantity.

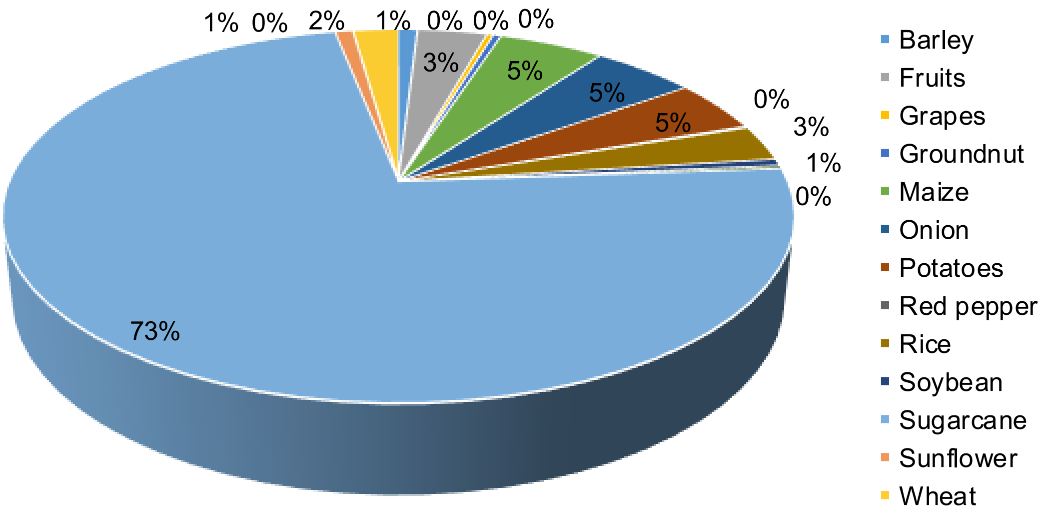

Figure 5.69 Percentage of non-produced quantity per crop (%) compared to the total non-produced quantity

8. The total cost of irrigation deficit was calculated equal to 75.3 million US$/y (2,079.9 ETB/y). The crops that bring in the highest cost of irrigation deficit are: maize (6%), onion (12%), rice (7%), sugarcane (52%) and wheat (5%). Figure 5.70 shows the percentage of cost of irrigation deficit per crop, compared to the total cost.

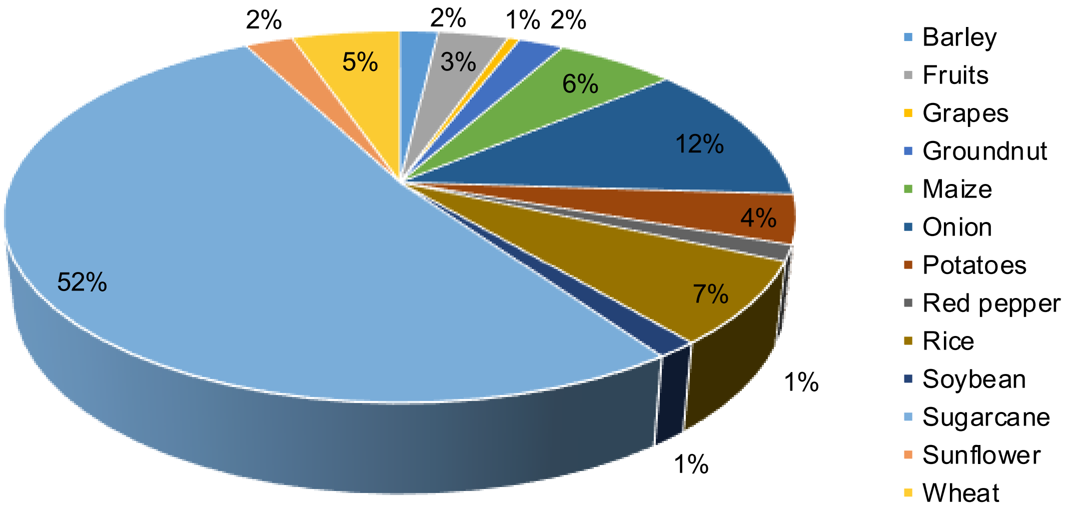

Figure 5.70 Percentage of cost of irrigation deficit per crop (%) compared to the total cost

9. The EAC and O&M costs for the irrigation projects were calculated equal 282 and 108 million US$/y, respectively.

10. The EAC and O&M costs for the HPPs were calculated equal 1,647 and 285 million US$/y, respectively.

11. The net benefit was calculated equal to 944 million US$/y (26,065 ETB/y).

5.7.6 Discussion on the Proposed Solution

The calculation results of the proposed Pareto solution F9 for the cost of irrigation deficit using the program IRIDE are compared to the results of the Pareto solutions F1 and F4. The solutions F1 and F4 were chosen for the comparison, because F1 represents the other extreme solution (minimum firm hydropower production, minimum irrigation deficit), while F4 represents an intermediate solution. Figure 5.71 shows the non-irrigated area per crop for the Pareto solutions F1, F4 and F9, while the total non-irrigated area equals 8,533, 12,769 and 45,602 ha, respectively. Figure 5.72 shows, furthermore, the percentage of non-irrigated area per crop compared to the total non-irrigated area for the Pareto solutions F1, F4 and F9. The three crops with the highest non-irrigated area are maize, rice and sugarcane for all three solutions F1, F4 and F9.

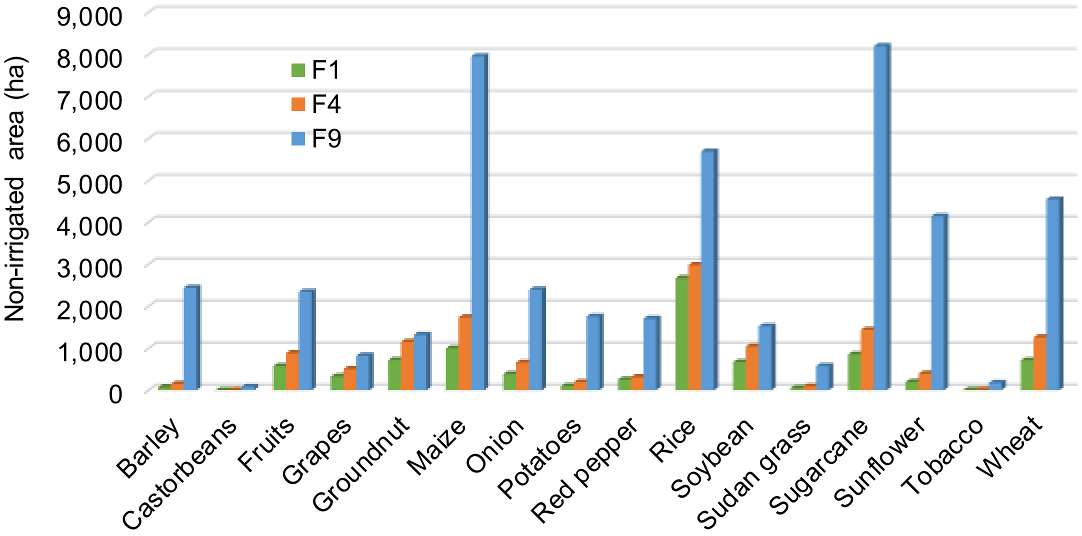

Figure 5.71 Non-irrigated area per crop (ha) for Pareto solutions F1, F4 and F9

Figure 5.73 shows the percentage of non-produced quantity of each crop compared to the total non-produced quantity for the Pareto solutions F1, F4 and F9, while the total non-produced quantity was calculated equal to 72,200, 117,270 and 573,140 ton/y, respectively. The three crops with the highest non-produced quantity for the solutions F1 and F4 are onion, rice and sugarcane, while for the solution F9 maize, onion and sugarcane. Figure 5.74 shows, furthermore, the percentage of the cost of irrigation deficit of each crop compared to the total cost of irrigation deficit for the Pareto solutions F1, F4 and F9, while the total cost was calculated equal to 11.8, 18.4 and 75.3 million US$/y, respectively. The three crops with the highest cost of irrigation deficit are onion, rice and sugarcane for all three solutions F1, F4 and F9.

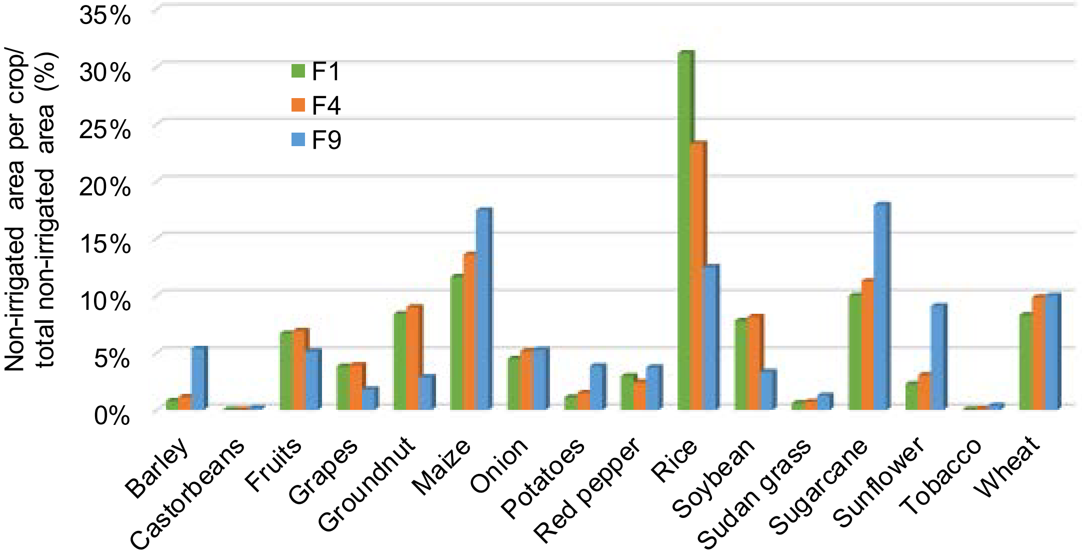

Figure 5.72 Percentage of non-irrigated area per crop to total non-irrigated area (%) of Pareto solutions F1, F4 and F9

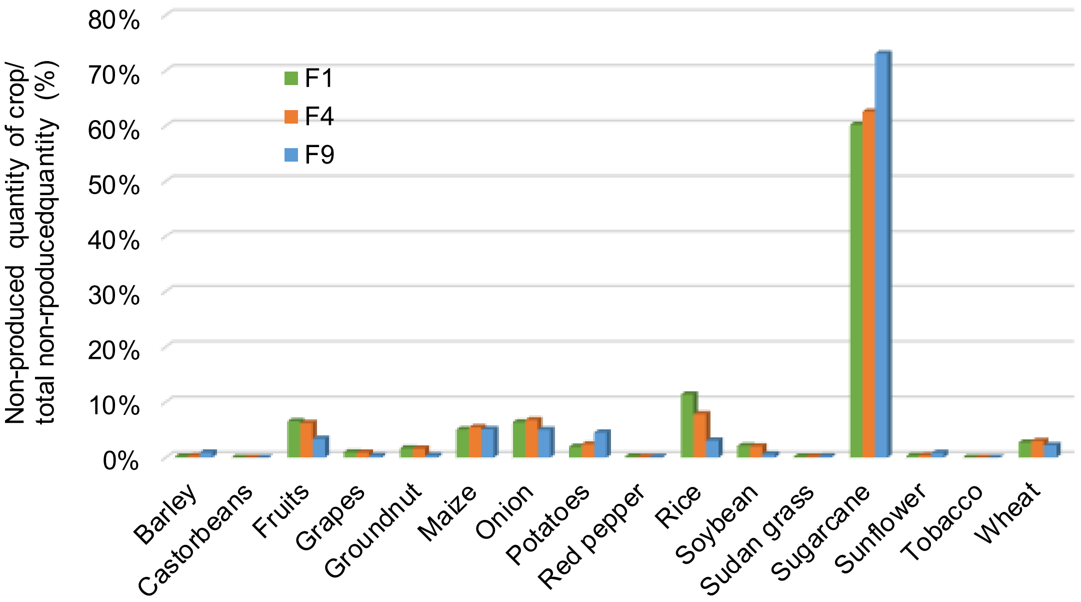

Figure 5.73 Percentage of non-irrigated area per crop to total non-irrigated area (%) of Pareto solutions F1, F4 and F9

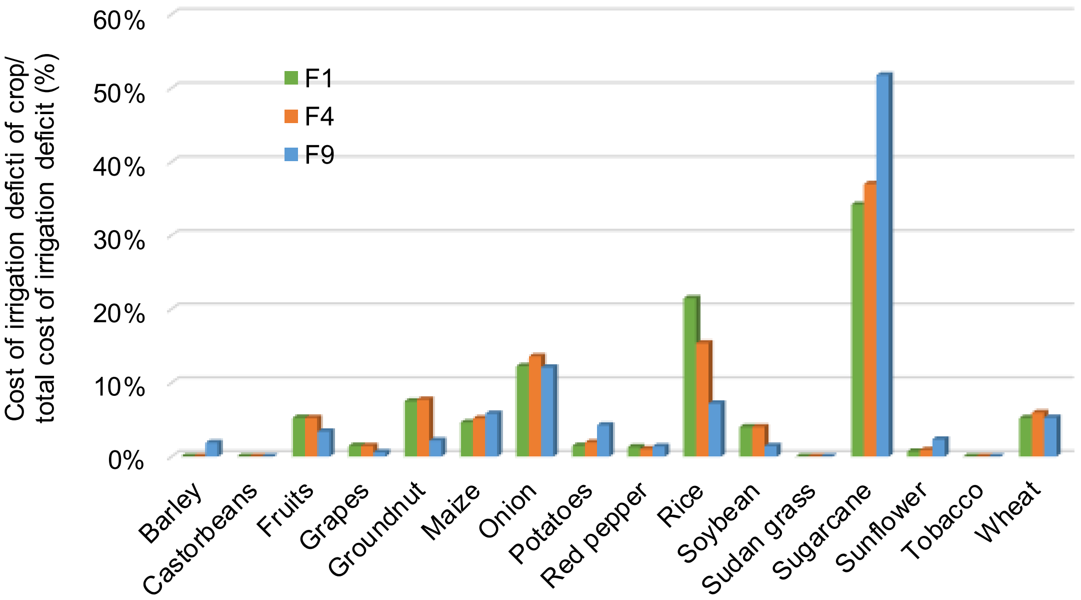

Figure 5.74 Percentage of cost of irrigation deficit per crop to the total cost of irrigation deficit (%) for Pareto solutions F1, F4 and F9

5.8 Expected Downstream effects – Hydro-politics

The downstream effects of the proposed solution are summarized as follows:

1. The 221,452 hm³ storage in the 37 reservoirs of the UBNR system, including the 62,336 hm³ of the GERD, provides increased control over the natural flow pattern that allows (Ethiopian NPoE 2013, Wheeler et al. 2016):
    a. The standard deviation of the monthly discharges is dramatically reduced from 1,932 m³/s (124% of the average value) for the natural conditions to 11 m³/s (0.8% of the average value) resulting to
        i. the reduction of the risk for flooding and droughts (especially during dry-low flow years) to Sudan and Egypt,
        ii. the potential increase of availability of water discharges and reliability of flows for Sudan and Egypt (Blackmore and Whittington 2008),
    b. reduction of sediment in the river, which currently challenges the management of reservoirs and agricultural schemes,
    c. hydropower efficiency benefits for Sudanese reservoirs,
    d. improved depth for navigation and reduced pumping costs for water users.
2. The 23 HPPs of a total installed production capacity equal to 14,214 MW, including the 6,000 MW of the GERD, produces hydropower that is equal to 47,749 GWh/y; this is likely to be a significant step change for the region as a whole with respect to access to electricity (NBI 2012, Whittington et al. 2014) and reduction of the electricity cost.
3. The 10.3% decrease of available downstream discharges, due to higher water consumptions for irrigation and higher evaporation losses in the higher number of reservoirs is expected to (Beyene 2013; Egyptian Chronicles 2013):
    a. increase the risk of reduced downstream water availability and reduced Egyptian hydropower,
    b. increase the likely loss of recession agriculture in Sudan,
    c. increase the losses to the brick production industry that uses the sediment deposits, and

d. reduce land fertility due to the reduction of nutrient-rich sediment.

4. The procedure of reservoir filling (Wheeler et al. 2016, Mulat and Moges 2014, Block and Strzepek 2010) is expected to create water availability problems to the downstream countries due to the large volumes of the reservoirs; for example, the reservoir volume of GERD that is equal to 62,336 hm^3, and thus, 1.3 times the average annual flow for the natural conditions. Thus, reservoir filling should be performed with caution to minimize these problems (Wheeler et al. 2016, Mulat and Moges 2014, Block and Strzepek 2010).

As already noted by other researchers (Bates et al. 2013, MIT 2014), there is certainly a need for more independent studies and assessments within the Nile Basin, as well as for political discussion taking into account objectively all factors and economic pressures (Whittington et al., 2005).

6 Conclusions and Recommendations for Further Research

6.1 Conclusions

The main conclusions of the present work are the following:

1. The Upper Blue Nile River (UBNR) basin is characterized by a very high potential for water resources development. The present work focuses on the full development scenario that is anticipated before the year 2060, when 37 reservoirs of a total volume equal to 221,452 hm³, 23 HPPs with an installed total capacity of 14,214 MW and 117 irrigation projects that are categorized into 69 irrigation project groups of a total net area equal to 584,110 ha, are expected to be completed.

    a. Full development. There are nine reservoirs that irrigate more than 10,000 ha of net irrigation area each; these are: Lake Tana (48,337 ha), Gilgel Abbay (12,687 ha), Ribb (19,925 ha) and Gumara (13,976 ha) in the Tana sub-basin, Neshe (11,153 ha) in the Finchaa sub-basin, Anger (14,450 ha) and Nekemte (11,220 ha) in the Anger sub-basin, Negesso (22,815 ha) in the Didessa sub-basin, and Dangur (85,000 ha) in Beles sub-basin. Other important irrigation project groups (without reservoir) are located in the sub-basins: Jemma (29,163 ha), N. Gojam (22,366 ha), Guder (21,313 ha), S. Gojam (51,166 ha), Wonbera (11,899 ha), Anger (19,089 ha), Didessa (37,718 ha) and Beles (62,220 ha).

        The four most important HPPs are located in the main river of the UBNR and are: Karadobi (1,600 MW), Mabil (1,400 MW), Mendaia (2,000 MW) and GERD (6,000 MW); their total capacity is equal to 11,000 MW (77% of the full development capacity). From the remaining 19 HPPs, only two have a capacity that is higher than 300 MW; these are Tana-Beles (460 MW) and Upper Dabus II (326 MW).

    b. Current conditions. Currently (year 2016), there are five reservoirs (total volume = 40,192 hm³), five HPPs (total capacity = 776 MW) and three irrigation project groups (total net area = 18,522 ha). The percentages of total figures for the HPP installed capacity and irrigation area are equal to 5.5% and 3.2%, respectively, verifying the very high potential for water resources development in the UBNR region.

   c. Short- to medium-term development. In the period 2016-2020, i.e. before the year 2020 that corresponds to the short- to medium-term development, only two additional reservoirs and five additional irrigation projects are expected to be completed, while no new HPPs will be implemented; the percentages of total figures for the HPP installed capacity and irrigation area are equal to 5.5 and 21.3%, respectively.

This conclusion summarizes the answer to the first research question “Which are the most likely water resources development scenarios for the UBNR basin?” Four scenarios are identified that are: (S0) natural conditions, (S1) current conditions, (S2) short- to medium-term development and (S3) full development.

2. There is an immediate need for proper water management. The very high potential for water resources development in the UBNR basin combined with the facts that (1) current water resource management is largely reactive to flooding or drought, leaving both water resource managers and the local population at the mercy of natural events, and (2) 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, demonstrated the immediate need for proper water resources management that will take into account the interactions within the Water-Energy-Food (WEF) nexus.

Based on the above-mentioned need, the main objectives of the present work are the following: (1) the management and optimization of water resources in the river basin, and specifically of reservoirs, HPPs and irrigation projects within the WEF nexus concept, and (2) the optimization of water allocation to hydropower (energy) and irrigation (food), taking into account economic, ecological and social aspects.

3. Proper water management tools should be selected. To achieve the optimal management of water resources three methods/tools were employed and are described below:

   a. Hydronomeas. Based on a detailed comparison amon available mathematical models, it was decided to use Hydronomeas that was developed in the National Technical University of Athens (NTUA). Hydronomeas is a non-commercial tool for investigating future water resources development in a river basin that is supported by the requested theoretical background and optimization techniques. Hydronomeas is used to investigate the current conditions, the short- to medium-term and the full development in the

UBNR basin, optimizing water resources and considering them as three continuously interacting sectors following the WEF nexus approach.

  b. Pareto fronts. The optimized solutions calculated by Hydronomeas are used to generate Pareto optimal fronts of the (i) firm hydropower production and (ii) irrigation deficit for both short- to medium-term and full development. Using the Pareto fronts, a relatively small number of optimized solutions are identified for further examination.

  c. Social cost-benefit analysis. Social Cost-Benefit Analysis (SCBA) is applied to compare the Pareto optimal solutions and identify the most preferable using the net social benefits (NSB) criterion. The benefit (hydropower production) and the cost (irrigation deficit) are quantified in terms of net economic benefit by using measurable economic units as follows:

     i. Benefit from hydropower production, which are calculated by multiplying the annual GWh generated from the HPPs by the export price of each kWh.

     ii. Cost of irrigation deficit, which is calculated via a relatively complicated calculation procedure that takes into account the characteristics (e.g. areas, prices) of all non-irrigated irrigated crops; for this calculation the computer program IRIDE in FORTRAN was constructed.

  d. The proposed methodology is general and can be applied to other river basins with similar characteristics.

4. Conclusions derived by the calculations of Hydronomeas. Calculations were performed for the four scenarios. The main conclusions are summarized as follows:

  a. Natural conditions. Calculations were performed for the natural UBNR hydro-system that consisted of Lake Tana and 13 tributaries using historical data of the period 1968-1992 and a monthly time step.

     i. The calculated water mass balance for the natural UBNR hydro-system verifies Hydronomeas.

     ii. The most important tributaries are South Gojam, Wonbera, Dabus and Anger-Didessa contributing 58.6% of the discharge at the border between Ethiopia and Sudan.

    iii. At the border, the mean annual run-off is calculated equal to 49.3 km^3/y (1,562 m^3/s). Annual discharges vary from 37.2 km^3/y (1,179 m^3/s) to 67.0 km^3/y (2,123 m^3/s), while the seasonal distribution of flows is very marked; 40.6 km^3/y that is 82.4% of the annual discharge is concentrated during the period July-October due to the summer monsoon, while only 3.6% of the flow occurs during the dry season (February-May).

The above-mentioned values are in agreement with values quoted in many other studies.

b. Hydropower production.

    i. For the current conditions (five HPPs), the annual hydropower production was calculated equal to 3,251 GWh/y; this value is higher than the values determined by other researchers (1,383-2,500 GWh/y), who performed their investigations at earlier stages, and without taking into account two or three (Tana-Beles, Finchaa and Neshe) of the currently existing HPPs.

    ii. In the short- to medium-term development (five HPPs) the hydropower production is reduced to 2,777 GWh/y (by 15%), because a part of the available water is not used by the HPPs (whose number remains the same), but it is consumed in irrigation that shows a 6.7-fold increase in irrigated area.

    iii. In the full development (23 HPPs), the hydropower production was calculated equal to 46,620 GWh/y, i.e. it is 14 times higher than the amount produced in the current conditions.

c. Irrigation demand and deficit.

    i. The annual irrigation demand for the current conditions (three projects; irrigated area = 18,522 ha), short- to medium-term development (eight projects; irrigated area = 124,210 ha), and full development (69 projects; irrigated area = 584,110 ha) were determined equal to 164 hm^3/y, 1,144 hm^3/y, and 4,568 hm^3/y, respectively. In the full development, the 32 times increase of the irrigated area compared to the current conditions, results in a 28-fold increase of the annual irrigation demand.

These values amount 0.3%, 2.3% and 9.3% of the average natural river discharge (49.3 km^3/y), respectively.

   ii. The actual irrigation amount of water for the current, short- to medium-term and full development was calculated equal to 164 hm^3/y, 1,045 hm^3/y and 4,332 hm^3/y, respectively; this results to an irrigation deficit of 0 hm^3/y, 98 hm^3/y and 236 hm^3/y, respectively.

Based on the above-mentioned figures, the irrigation deficit for the current, short- to medium-term and full development are calculated equal to 0%, 8.6% and 5.2% of the annual irrigation demand, respectively.

  d. Discharge at the border. The average annual discharge at the border was calculated equal to 49.0 km^3/y (1,551 m^3/s), 47.4 km^3 (1,501 m^3/s) and 42.3 km^3 (1,339 m^3/s) for the current, short- to medium-term and full development, respectively. These values correspond to reductions of 0.6%, 3.9% and 14.2% of the river discharge in natural conditions.

5. Conclusions derived by the Pareto fronts.

   a. For the short- to medium-term development, calculations of the optimization procedure with Hydronomeas were performed eleven times for different sets of weights and six Pareto optimal solutions (M1 to M6) were identified. The extreme cases, in which the irrigation deficit and the firm hydropower production are more important, respectively, were: M1 (162.6 GWh/month, 86.7 hm^3/y) and M6 (194.2 GWh/month, 111.0 hm^3/y). The intermediate points M2 to M5 represent solutions with different weighting of the two objectives.

   b. For the full development, calculations of the optimization procedure with Hydronomeas were performed 101 times for different sets of weights and nine Pareto optimal solutions (F1 to F9) were identified. The extreme cases, in which the irrigation deficit and the firm hydropower production are more important, respectively, were: F1 (1966.9 GWh/month, 162.0 hm^3/y) and F9 (3479.6 GWh/month, 1069.0 hm^3/y). The intermediate points F2 to F8 represent solutions with different weighting of the two objectives.

This conclusion summarizes the answer to the second research question “What are the optimal solutions to allocate water resources between the conflicting users?”

6. Conclusions based on the social cost-benefit analysis - The proposed solution.

    a. The social cost-benefit analysis (SCBA) is applied to compare the nine Pareto optimal solutions (F1 to F9), and F9 was identified as the most preferable solution according to the chosen socio-economic criteria, because it yields the highest net benefit for the UBNR basin that is equal to 944 million US$/y; thus, the solution F9 is proposed.

    b. The proposed solution F9, which consists of 37 reservoirs with a total volume equal to 221,452 hm^3, 23 HPPs with an installed total capacity of 14,214 MW and 69 irrigation project groups of a total net area equal to 584,110 ha, has the following main characteristics:

        i. The hydropower production is equal to 47,749 GWh/y, i.e. almost 15 times higher than the amount produced in the current conditions.

        ii. The annual irrigation demand is determined equal to 4,568 hm^3/y; this amount is equal to 9.3% of the average river discharge of the natural conditions (49.3 km^3/y). The actual irrigation amount was calculated equal to 3,499 hm^3/y; i.e. the irrigation deficit is equal to 1,069 hm^3/y, which is equal to 23% of the annual irrigation demand.

        iii. The average annual discharge at the border was calculated equal to 44.2 km^3/y (1,401 m^3/s); this value corresponds to a reduction of 10.3% of the river discharge compared to the natural conditions. The run-off is practically equally distributed throughout the year; its standard deviation is equal to 11 m^3/s (0.8% of the average value), while the corresponding value for the natural conditions is equal to 1,932 m^3/s (124% of the average value).

    c. This conclusion is expected to apply to other river basins with similar characteristics, i.e. river basins with high hydropower potential or river basins that belong to Transboundary Rivers, where hydropower is preferred.

This conclusion summarizes the answer to the third research question “How can decision makers choose the most preferable among the optimal solutions?”

7. Downstream effects. The downstream effects of the proposed solution are summarized as follows:

a. The 221,452 hm³ storage in the 37 reservoirs of the UBNR system, including the 62,336 hm³ of the GERD, provide increased control over the natural flow pattern of the river that means (Ethiopian NPoE 2013, Wheeler et al. 2016):

   i. The standard deviation of the monthly discharges is dramatically reduced from 1,932 m³/s (124% of the average value) for the natural conditions to 11 m³/s (0.8% of the average value) for the solution of the full development, resulting to (1) the reduction of the risk for flooding and droughts (especially during dry-low flow years) to Sudan and Egypt, and (2) the potential increase of availability of water discharges and reliability of flows for Sudan and Egypt (Blackmore and Whittington 2008).

   ii. Reduction of sediment in the river, which currently challenges the management of reservoirs and agricultural schemes.

   iii. Hydropower efficiency benefits for Sudanese reservoirs.

   iv. Improved depth for navigation and reduced pumping costs for water users.

b. The 23 HPPs of a total installed capacity equal to 14,214 MW, including the 6,000 MW of the GERD, produce hydropower that is equal to 47,749 GWh/y; this is likely to be a significant change for the region as a whole with respect to access to electricity (NBI 2012, Whittington et al. 2014).

c. The 10.3% decrease of available downstream discharges, due to higher water consumptions for irrigation and higher evaporation losses in the higher number of reservoirs is expected to (Beyene, 2013; Egyptian Chronicles, 2013):

   i. increase the risk of reduced downstream water availability and reduced Egyptian hydropower,

   ii. increase the likely loss of recession agriculture in Sudan,

   iii. increase the losses to the brick production industry that uses the sediment deposits,

   iv. reduce land fertility due to the reduction of nutrient-rich sediment.

d. The downstream effects are expected to be observed in other river basins with similar characteristics, where high potential for future expansion is observed, while current development is minor.

This conclusion summarizes the answer to the fourth research question “At which extent are downstream countries affected by different management policies in the UBNR basin?”

6.2 Recommendations

The present work can be extended along the following axes:

1. Investigation of the proposed solution taking into account the effects of climate change and comparison of its results with previous similar works. This investigation can be based and compared with existing significant publications (Block and Strzepek 2010, Jeuland and Whittington 2014, Wondimagegnehu and Tadele 2015, Conway 2000).

2. Investigation of the proposed solution taking into account the transient conditions of reservoir filling (Wheeler et al. 2016, Mulat and Moges 2014, Block and Strzepek 2010). It is noted that the present work has been performed assuming steady-state conditions.

3. Performance of a very detailed cost-benefit analysis among the optimal Pareto solutions taking into account all important factors, such as the following:

    a. Detailed analysis of the construction sequence and costs of the projects.

    b. Operation and maintenance cost of the dams, when they are completed.

    c. Opportunity cost of the energy produced by the dams.

    d. Marginal water values that signal, e.g. water scarcity (Tilmant et al. 2012).

    e. Revenue from Energy Production.

    f. Environmental costs and benefits, including downstream effects (see Section 5.8).

    g. Benefit from saved costs of carbon emitted from the current sources of energy (burning of coal).

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