Optimization of Water Resource Use within the Blue Nile River basin, Ethiopia

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Abstract

The Nile River is a source of fresh water for millions of people. The continuously growing water demand in combination with the population growth have led to enormous water scarcity in the Nile River basin. Among the countries that share the Nile's water, this study is concentrating on Ethiopia and more specifically on the Blue Nile River basin. Different aspects of the Blue Nile River basin as well as information on the current and future water resource development of the basin will be discussed.

The NIMA-NEX project (NIle MAnagement Nexus EXpert tool) was developed with the aim to optimize the use of water resources along the Blue Nile River. The optimization will be achieved in terms of a nexus approach (nexus: the act of binding together). MA-NEX, comprising a part of the NIMA-NEX project, is concentrating on the reservoir and energy management as well as on the water allocation among the competing users. Consequently, MA-NEX will result in the optimization of the water resource use within the Blue Nile River basin, so as to maximize the ecological, economic and social benefits. In the present study, three main parts of MA-NEX will be discussed, namely the model selection and description, data collection and analysis as well as the development of the Blue Nile River system in the selected model.

1 Introduction

The Nile River, the longest river in the world, is a source of water for millions of people. Eleven African countries share its basin and compete for its resources. The continuously growing water demand in combination with the population growth have led to enormous water scarcity in the basin. Among the countries that share the Nile River basin, this study is concentrating on Ethiopia and more specifically on one of the two Nile's main sources: the Blue Nile River.

Sufficient and integrated water resource management is required to provide water security in a river basin. For the sustainable management of water resources in the Blue Nile River basin, the NIMA-NEX project was proposed. The project's goal is to develop a tool called NIMA-NEX (NIle MAnagement Nexus EXpert tool) to optimize the use of water resources within the Blue Nile River basin. The optimization is to be achieved in terms of a nexus approach. Thus, the project considers water, food and energy as three elements that interact with each other continuously (nexus: derived from Latin, "the act of binding together").

The present study is concentrating on MA-NEX, the management module of the NIMA-NEX project. The objectives of MA-NEX as well as the overall aims of NIMA-NEX are summarized in Figure 1 and described below. The first objective of MA-NEX is the optimization of the system of reservoirs in the Blue Nile River basin in Ethiopia. The second objective, which partially depends on the first, is the optimal allocation of water among municipalities and industry as well as energy and food production in the basin. With these two objectives, the MA-NEX tool aims at achieving the greater goal of NIMA-NEX: the optimization of water resource use and the maximization of the ecological, economic and social benefits in the Blue Nile River basin.

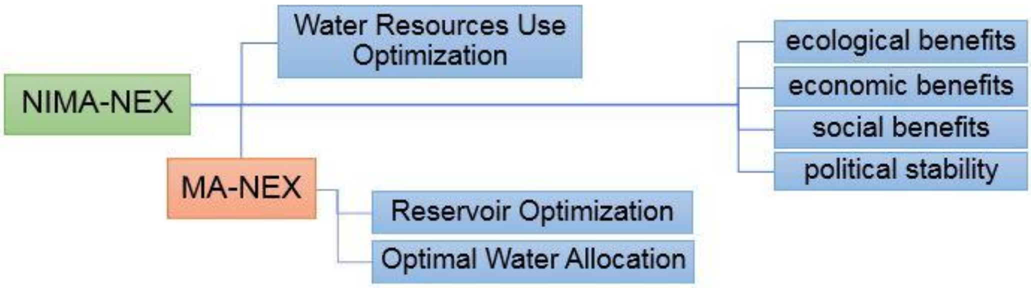

Fig. 1 Main aims and objectives of NIMA-NEX and its management module MA-NEX

The NIMA-NEX project is supported by the TUM International Graduate School of Science and Engineering (IGSSE). The main partners of NIMA-NEX are TUM (Prof. Peter Rutschmann and Prof. Markus Disse) and the University of Alberta, Canada (Prof. Thian Yew Gan).

2 Methodology

To achieve the objectives of MA-NEX, the Blue Nile River system will be simulated and optimized according to a series of predefined steps. The methodology is summarized in Figure 2 and described as follows. The MA-NEX module begins with the selection of the proper model for the management of the Blue Nile River water resources. Information on several simulation-optimization models is to be gathered by means of literature review, with the most suitable model selected as a basis for the study (1). In a second step, the model of the hydrosystem is to be developed. Thus, the Blue Nile River system is to be schematized and the required input data to be defined (2). Then, all required information is to be collected (3). The different scenarios to be simulated within the study will then be defined, using both the system's schematization and the input data as a basis. A possible climate change as well as the different water users may be taken into account while defining the scenarios. Subsequently, using the selected model, the system will be simulated for the different scenarios (4).

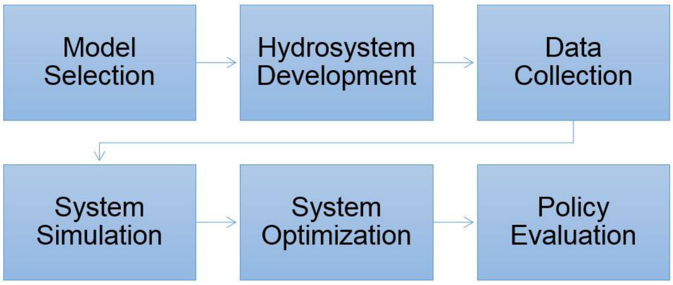

Fig. 2 Methodology of MA-NEX

The overall goal is to propose different policies that will satisfy the water needs of conflicting uses and users. Through the optimization of the system, objective functions will be defined and pareto solutions will be developed for each policy (5). The last step of the study is to evaluate the different policies. The key point during this step will be the societal effect of these policies on the different users (6). Throughout the entire study, with emphasis on the fifth and sixth step, the main focus will address effective ways to integrate the social factors into the optimization procedure. The present study will concentrate on three main parts of MA-NEX, the selection of the most suitable model for the study purposes and its description, the data collection and analysis as well as the schematization of the Blue Nile River system in the selected model.

3 Model Selection

Throughout recent decades, different models have been developed to enhance the management of water resource systems. A literature review was carried out in order to choose the most appropriate model for the simulation and optimization of the Blue Nile River system. The research conducted concentrated on 15 different models, as shown in Table 1. These models share two main characteristics: they include both the aspect of simulation and optimization (so-called simulation-optimization models), and they are generalized models that may be used for different case studies.

Tab. 1 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 Management Model

From these 15 models, the Hydronomeas model was chosen as the most appropriate one for the purpose of this work for the following reasons. WEAP and WRIMS were excluded because they do not include a separate optimization module (Sieber and Purkey, 2011; Parker, 2012). Furthermore, six other models, namely AQUATOOL, AQUATOR, Hec-ResPRM, MIKE HYDRO BASIN, OASIS and RiverWare, were excluded because no modifications are allowed on their source code (UPV, 2015; Oxford Scientific Software Ltd, 2015; O'Connell and Harou, 2011; DHI, 2015; HydroLogics, Inc., 2009; UCB, 2014). Although WASP has the capability of readily modelling a wide range of water supply systems, it is not able to model those with hydropower (Kuczera and Diment, 1988). WaterWare was excluded because it is a web-based system (ESS GmbH, 2010). Finally, among the remaining models, Hydronomeas was chosen because it belongs to a system of co-operating software applications which the user may take advantage of (e.g. CASTALIA for the generation of synthetic time series) (Karavokyros et al., 2001).

4 Hydronomeas

Hydronomeas is a model for the simulation and optimization of hydrosystem management that was developed by the Department of Water Resources of the National Technical University of Athens (NTUA), in cooperation with NAMA Consulting Engineers and Planners SA and Marathon Data Systems. It is part of HYDROGAEA, a system of co-operating software applications that is suitable for the Integrated Management of Water Resources. Hydronomeas was designed to be applied within the framework of projects in the area of water resource management. Actual or hypothetical cases (scenarios) may be examined. The software proposes management policies and the results are presented in the form of tables and graphs. Simulations may be dynamically visualized. During a simulation in Hydronomeas, water is transported from the resources (reservoirs, boreholes, rivers, inflows) to the water users (water supply, irrigation, hydropower generation, environmental preservation etc.). Hydronomeas defines the optimum water allocation step by step, while considering the quantities in the hydrosystem, the operating rules as well as the targets. The visualization of the simulation procedure may be performed in both real time and retrospection. After a simulation run, the results may be shown. Three different result categories exist: the failure forecast (and their time distribution) for each target, the water and energy balances (reservoir water balance, node water balance, aqueduct and river water balance as well as energy consumption and production) and the forecast of reservoir storage. (Karavokyros et al., 2007)

Hydronomeas was applied in two major hydrosystems in Greece: the Acheloos-Thessalia reservoir system (western Greece) and the Greater Athens Water Supply reservoir system (central-eastern Greece). The two hydrosystems transport water from the West to the East (almost semiarid), where most people and most activities are concentrated. The two hydrosystems have many differences concerning the general design conception and project characteristics as well as the management policies, the operation constrains and the goals (Karavokyros et al., 2001). This indicates that Hydronomeas is capable of simulating different kinds of projects.

5 Blue Nile River basin in Ethiopia

The Blue Nile River basin is located in Ethiopia and Sudan and covers an area of 311,437 km² (Yilma and Awulachew, 2009). The Blue Nile River exits Lake Tana on its southern-east side and flows initially south- and then westwards through Ethiopia until its border with Sudan. In Sudan, the river flows to the North-west until it reaches its confluence with the White Nile River in Khartoum, the capital city of Sudan (Yilma and Awulachew, 2009). The two rivers flow then as Nile River through the remaining part of Sudan and Egypt until they reach the Mediterranean Sea. Figure 3 illustrates the Ethiopian part of the Blue Nile River basin.

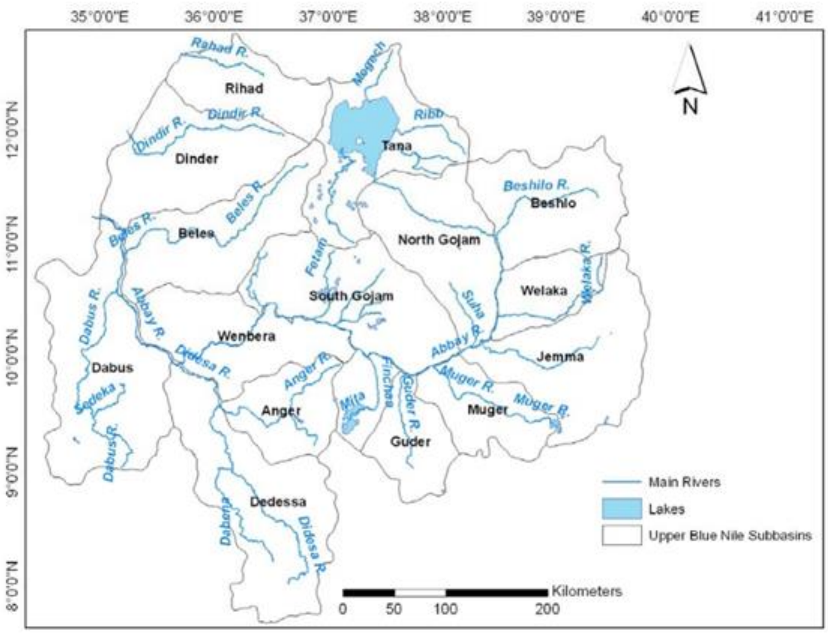

Fig. 3 The Ethiopian Blue Nile River basin and its sub-basins (Yilma and Awulachew, 2009)

The Blue Nile River basin may be divided into 18 sub-basins. The present study is concentrating on 14 out of them – namely Tana, Beshilo, Welaka, North Gojam, Jemma, Muger, Guder, South Gojam, Finchaa, Anger, Didessa, Wenbera, Dabus and Beles – that are located in Ethiopia. About 35% of the total population of Ethiopia is living in the Blue Nile River basin (2008). The basin covers three Ethiopian regional states, namely the Amhara, Oromia and Benishangul-Gumus regional states (Yilma and Awulachew, 2009).

Although the geology of the Blue Nile River basin signifies different formations, such as basalt, alluvium, lacustrine deposits, sand stone, granite and marble, basalt dominates. The eastern part of the basin is characterized by dominantly cultivated land, while grass land, wood lands and forest prevail in the West. The major soil types in the Blue Nile River basin are alisols and leptisols, followed by nitosols, vertisols, cambrisols, fluvisols and luvisols. The agro-ecology of the basin is divided into three major climatic zones, namely cold to very cold, tepid to cold and hot to warm that may be further divided into moist, sub-moist, humid and sub-humid. (Yilma and Awulachew, 2009)

Based on its topography, the Blue Nile River basin in Ethiopia can be divided into two parts. The basin comprises both highlands, which are located in the central and eastern part, and lowlands that are located in the western part of the basin. Figure 4 shows the elevation of the basin that ranges from 498 m in lowlands to 4261 m in highlands (Yilma and Awulachew, 2009).

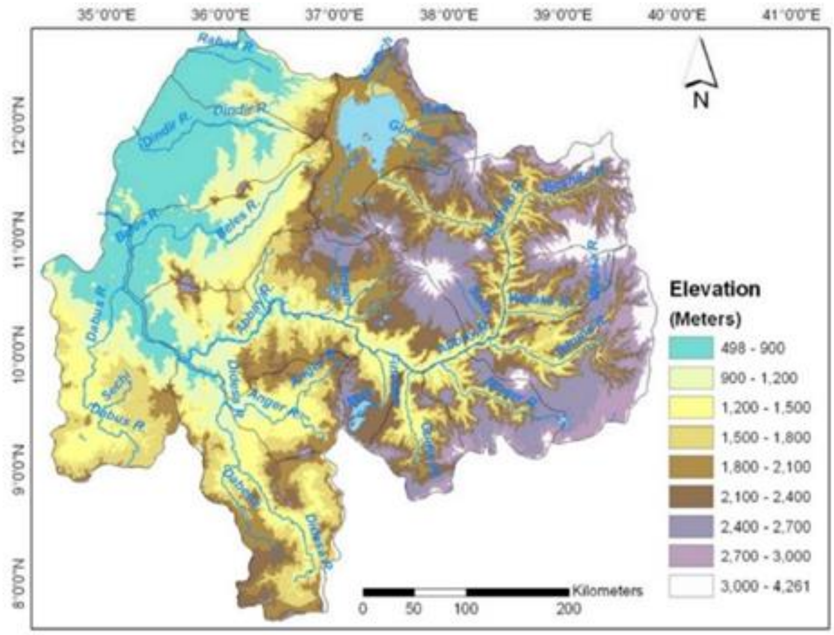

Fig. 4 Elevations of the Blue Nile River basin in Ethiopia (Yilma and Awulachew, 2009)

Only limited data are available for the 94 georeferenced meteorological stations in the Blue Nile River basin in Ethiopia. According to Yilma and Awulachew (2009), rainfall in the Blue Nile River basin ranges from 787 to 2,200 mm per year. Higher rainfall values (1,500 mm to 2,200 mm) are observed in highlands, whereas rainfall reaches values lower than 1,500 mm per year in lowlands. The lowest rainfall values (< 1,000 mm/year) are observed in Beshilo, Welaka, Jemma, Muger and Guder. Furthermore, as far as temperature is concerned, higher values are observed in the northern-west part of the basin, namely in parts of Beles and Dabus (max: 28°C to 38°C, min: 15°C to 20°C). Lower temperature values are observed in the central and eastern part of the basin, where highlands are located (max: 12°C to 20°C, min: -1°C to 8°C).

Finally, potential evapotranspiration (PET) in the Blue Nile River basin ranges from 1,056 to 2,232 mm per year. High PET values (1,800 mm to 2,232 mm per year) are observed in the northern-west parts of the basin, namely in parts of Beles and Didessa. Lower PET values are observed in the eastern and southern parts of the basin (1,200 mm to 1,800 mm per year). The lowest PET values (<1,200 mm per year) are observed in some parts of highlands.

According to the Water Atlas of ENTRO (Eastern Nile Technical Regional Office, 2006), the Blue Nile River is the largest contributor of the Eastern Nile Basin system, since it accounts for 67 % of the inflow at Aswan in Egypt (56 BCM/year). Figure 5 shows the average gross run-off depth in mm for the different sub-basins of the Blue Nile River basin in Ethiopia. The flow of the Blue Nile River has two main characteristics: extreme seasonal and extreme inter-annual variability (Awulachew et al., 2012). More specifically, during the flood season from July to October more than 80 % of the flow occurs. Respectively, only 4 % of the flow occurs during the dry season from February to May (Awulachew et al., 2012, Awulachew et al., 2008).

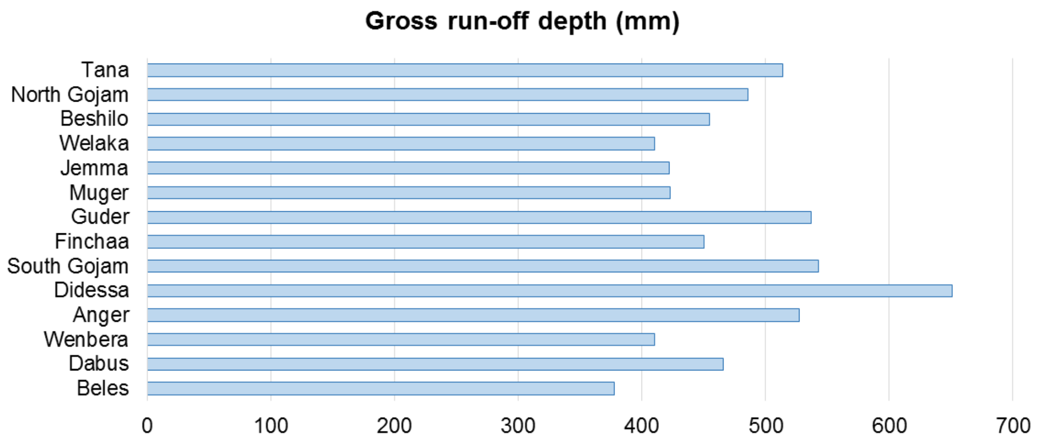

Fig. 5 Gross average run-off depth in mm for the different sub-basins of the Blue Nile River

6 Data Collection and Analysis

All information included in this study were collected by conducting a literature review on the Blue Nile River basin, visiting the Ministry of Water Resources and Irrigation of Ethiopia as well as ENTRO (Eastern Nile Technical Regional Office) and interviewing experts from the Addis Ababa University and the Abbay Basin Authority. Collected data are categorized in: irrigation, hydropower and inflow data. The data collection in Ethiopia is a great challenge. It is worth mentioning that, due to the political situation in the region, the data collection especially for the Blue Nile River consists a major difficulty. The inflow data into the main stem of the Blue Nile River are to be provided by Polanco (TUM, Chair of Hydrology and River Basin Management).

6.1 Irrigation in the Blue Nile River basin, Ethiopia

Although agriculture in the Blue Nile River basin is mainly rain-fed, the basin has a great irrigation potential and accounts for a major share of the total irrigation potential in Ethiopia. Figure 6 shows the existing and potential irrigation as well as dam sites of the Blue Nile River basin. The potential irrigation sites of Figure 6 were identified by a study conducted by the Ministry of Water Resources of Ethiopia (Yilma and Awulachew, 2009). The irrigation schemes of the Blue Nile River basin can be divided into three categories: small, medium and large scale irrigation schemes. According to Haile and Kasa (2015), irrigation schemes are considered to be of small scale when they consist of a net area of less than 200 ha. Furthermore, medium scale irrigation schemes have a net area of 200 to 3,000 ha. Finally, in the case of a net area larger than 3,000 ha, the irrigation scheme is considered to be large. The present work will concentrate on the medium and large irrigation schemes of the Blue Nile River basin in Ethiopia.

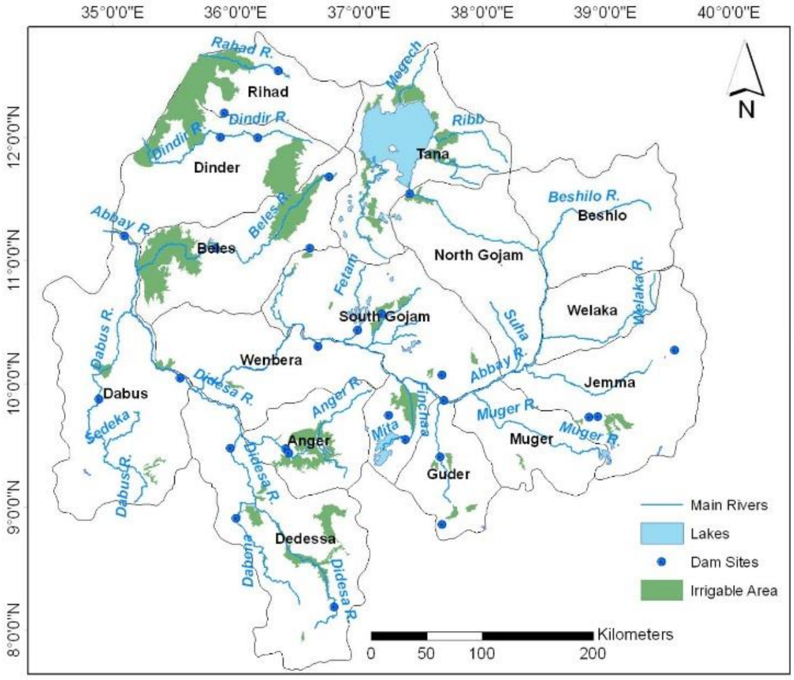

Fig. 6 Existing and Potential irrigation areas in the Blue Nile River basin in Ethiopia (Yilma and Awulachew, 2009)

Only two large irrigation schemes, namely the Koga irrigation scheme (Tana sub-basin) and the Finchaa irrigation scheme (Finchaa sub-basin), exist currently (2015) in the Blue Nile River basin. Table 1, which summarizes the gross potential and net irrigation area in ha of each sub-basin of the Blue Nile River in Ethiopia, was created based on the Abbay River Basin Integrated Development Master Plan (BCEOM, 1998). Table 2 includes as well Dinder and Rahad that are not part of the present study. In the Beshilo sub-basin no irrigation was identified. Furthermore, the crop water requirements for each irrigation scheme were provided by ENTRO.

Tab. 2 Existing and potential irrigation areas (ha) in the Ethiopian Blue Nile River basin

Sub-basin	Gross Potential Area (ha)	Net Irrigation Area (ha)
Tana	139,309	118,419
North Gojam	22,030	18,728
Welaka	1,271	1,080
Jemma	36,924	31,387
Muger	7,444	6,327
Guder	30,834	26,209
Finchaa	20,421	17,358
South Gojam	76,641	65,149
Didessa	86,623	73,631
Anger	52,658	44,759
Wenbera	13,998	11,899
Dabus	18,170	15,444

Beles	173,200	147,220
(Dinder/Rahad)	123,000	104,350
Total	**802,523**	**681,960**

6.2 Hydropower in the Blue Nile River basin, Ethiopia

The topography of the Blue Nile River basin in Ethiopia, characterized by an elevation that ranges from 498 m in lowlands to 4261 m in highlands (Figure 4), signifies great hydropower potential. According to the Ministry of Water Resources of Ethiopia, the estimated technical hydropower potential in the basin accounts for 72,000 GWh/year (Awulachew et al., 2008). However, only about 1% is tapped so far (BCEOM, 1998).

Five hydropower projects were commissioned in the Blue Nile River basin in Ethiopia, namely the Tis Abbay 1, Tis Abbay 2, Finchaa, Neshe-A and Tana-Beles hydropower projects. Table 3, which summarizes the existing and potential hydropower projects of the Ethiopian Blue Nile River basin, was created based on information from the Abbay Basin Authority. Apart from these sites, the Abbay basin authority distinguishes as well possible hydropower development projects from some of the identified irrigation projects.

Tab. 3 Existing and potential hydropower projects in the Blue Nile River basin in Ethiopia

Sub-basin	Hydropower project	Sub-basin	Hydropower project
North Gojam	Tis Abbay 1	Didessa	Dabana
	Tis Abbay 2		Lower Didessa
Jemma	Aleltu East	Anger	Upper (Arjo) Didessa
	Aleltu West		Nekemte
Guder	Lower Guder	Wenbera	Mandaia
Finchaa	Finchaa	Dabus	Lower Dabus
	Neshe A		Upper Dabus
	Neshe B		Upper Dabus (diversion)
South Gojam	Chemoga Yeda	Beles	Beles Multipurpose
	Mabil		(Lower) Beles Dangur
	Fettam	Border	Grand Ethiopian Renaissance Dam (GERD)
	Karadobi / Beko Abo		

7 Schematization of the Blue Nile River system

The first step in designing the model of a hydrosystem is to design the network and define its main characteristics. For this purpose, different design tools and network components exist in Hydronomeas. The network components may be distinguished into autonomous and dependent. Autonomous components are those, which may exist regardless the presence of other components (i.e., reservoir, river junction and aqueduct junction). Dependent components are the components that have to be connected to one or more network components (i.e., aqueducts, river segments, pump, turbines, boreholes, inflows and targets – water supply, irrigation, maximum/minimum or constant aqueduct flow, maximum/minimum reservoir storage, avoidance of reservoir spill and hydroelectric power generation). Hydronomeas allows for multiple targets that may be competitive to each other. The algorithm identifies the water discharges and finds the best possible way of transport to the water use components of the system. All targets are assigned a priority by the user. (Karavokyros et al., 2007)

In order to study the downstream effects of different planned irrigation and hydropower projects of the Blue Nile River basin, various scenarios were developed in Hydronomeas. The simplest scenario, the baseline scenario, includes only the natural lakes and flows of the hydrosystem, without any man-made changes. Scenario S1 represents the current situation, the currently (2015) operating irrigation and hydropower projects. The medium-term future scenario (S2) includes all irrigation and hydropower projects that will be operating by 2020. Finally, Scenario S3 represents the fully developed Blue Nile River basin and includes all irrigation schemes and hydropower projects that are planned to be built sometime in the future. Figure 7 shows the proposed schematization of the Blue Nile River basin in Ethiopia as an example to be used for the medium-term future scenario (S2) for the simulation and optimization of the water resources in Hydronomeas.

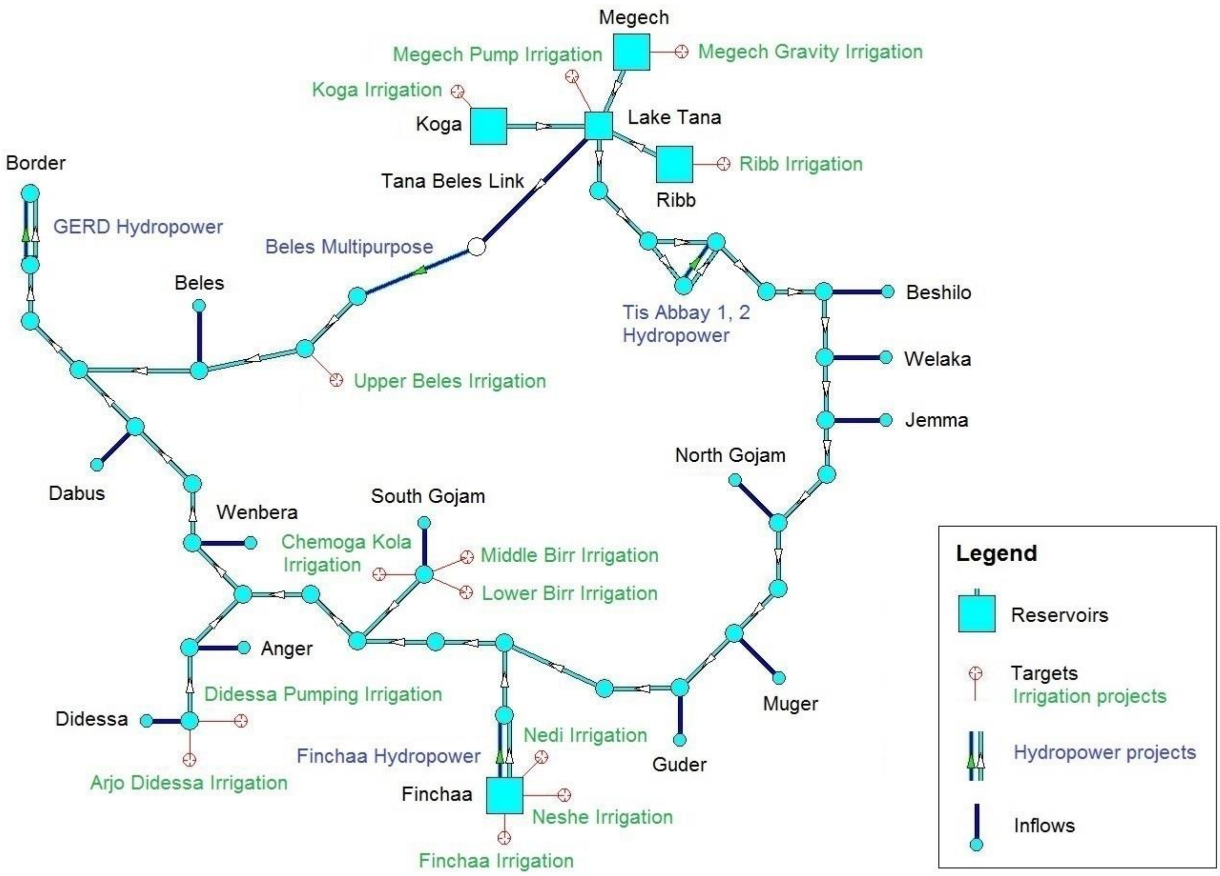

Fig. 7 Proposed schematization of the Ethiopian Blue Nile River basin in Hydronomeas to be used in the MA-NEX study (medium-term future scenario, S2)

8 Conclusions

The NIMA-NEX (NIle MAnagement Nexus EXpert tool) project and its management module, MA-NEX, were created with the aim to optimize the use of water resources within the Blue Nile River basin, Ethiopia. The Blue Nile River basin has a great irrigation and hydropower potential. Only a part of this potential has been tapped so far. Information was collected for the various irrigation and hydropower projects that have been identified for the Blue Nile River basin in Ethiopia during the Abbay River Basin Integrated Development Master Plan (BCEOM, 1998). A summary of the collected data is presented in the present study.

The simulation-optimization model Hydronomeas was chosen through a literature study to achieve optimal water allocation in the basin and to study the downstream effects of the different planned irrigation and hydropower projects. Various scenarios were developed and the Blue Nile River system was schematized in Hydronomeas. The schematization of the Ethiopian Blue Nile River system in Hydronomeas is presented as an example for the medium-term future scenario that includes all irrigation and hydropower projects that will be operating by 2020.

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