Towards the optimization of water resource use in the Upper Blue Nile river basin

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Abstract: The Nile River is a source of water for millions of people. The continuously growing water demand in combination with the population growth and the lack of water resource management in the basin have led to enormous water scarcity. In order to provide water security, sufficient water resource management is required. For the integrated water resource management of one of the two main Nile sources, the Upper Blue Nile River basin in Ethiopia, the NIMA-NEX project is proposed. The goal is to develop a tool called NIMA-NEX (NIle MAnagement Nexus EXpert tool) to optimize the water resources within the basin. The optimization is achieved in terms of a nexus approach. Thus, water, food and energy are considered as three elements that interact with each other continuously. The present study deals with MA-NEX, the management and optimization module of NIMA-NEX. Within MA-NEX, the system of reservoirs and other projects, as well as the water allocation among the various uses in the Upper Blue Nile River basin are optimized. The study focuses on the maximization of ecological, economic and social benefits, and the political stability. For the simulation and optimization of the system, the model Hydronomeas is used. Various development and management scenarios are investigated and Pareto fronts are proposed for the Upper Blue Nile River basin.

Key words: water resources optimization, water resources management, water allocation, Pareto optimization, Hydronomeas

1. INTRODUCTION

The Nile River, the longest river in the world, is a source of water for millions of people. The continuously growing water demand in combination with the population growth, as well as the lack of water resource management, have led to enormous water scarcity in the basin. Among the countries that share the Nile River basin and compete for its resources is Ethiopia, in which one of the two Nile’s main sources, the Upper Blue Nile River flows.

For the sustainable management of water resources in the Upper Blue Nile River (UBNR) basin, the NIMA-NEX project was proposed. This study deals with MA-NEX (part of NIMA-NEX) whose objectives are: (1) the management and optimization of the reservoirs and other projects in the UBNR, and (2) the optimization of water allocation among domestic, industrial, livestock, hydropower (energy) and irrigation (food) purposes. Both objectives focus on the maximization of ecological, economic and social benefits, as well as the political stability and the water resource optimization in the basin, using the nexus approach. According to nexus, water, food and energy are considered as three elements that interact with each other continuously. To achieve these objectives, a research procedure is applied that consists of the following 7 steps: (1) A literature review is conducted and a proper model is chosen. (2) Required data are collected and analyzed. (3) Development and management scenarios (policies) are defined. (4) The UBNR system is schematized in the selected model. (5) Model simulations are performed for all scenarios. (6) Objective functions are defined; model optimization is performed and Pareto solutions are developed for all scenarios. (7) Development and management scenarios are evaluated.

Five development scenarios are investigated (Table 1); these range from the natural state of the river (Scenario S0) to its full development (Scenario S4). Management scenarios are developed during the system simulation and optimization.
Table 1. Development Scenarios for the UBNR basin for implementation in Hydronomeas

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario S0</td>
<td>Baseline Scenario</td>
<td>without any man-made changes</td>
</tr>
<tr>
<td>Scenario S1</td>
<td>Current Situation</td>
<td>in 2015 operating irrigation and hydropower projects, and water supply</td>
</tr>
<tr>
<td>Scenario S2</td>
<td>Medium-term Future Situation</td>
<td>until 2020 constructed and operating irrigation and hydropower projects, and increased water supply</td>
</tr>
<tr>
<td>Scenario S3</td>
<td>Long-term Future Situation</td>
<td>50% of all irrigation and hydropower projects of the full developed river basin, and increased water supply</td>
</tr>
<tr>
<td>Scenario S4</td>
<td>Full Development</td>
<td>all planned irrigation and hydropower projects, and increased water supply</td>
</tr>
</tbody>
</table>

The scenarios were developed to study the downstream effect of future irrigation and hydropower projects, as well as the increase in water demand for domestic, industrial and livestock purposes (linked to population growth), and to draw conclusions for the feasibility, impacts and benefits of the projects and targets in the system in order to optimize it. In the present work, preliminary results for the current conditions (Scenario S1) are presented and discussed.

2. THE AREA OF STUDY: THE UPPER BLUE NILE RIVER BASIN

The UBNR basin, the so-called Abbay in Ethiopia, covers an area of approximately 199,812 km² (Yilma and Awulachew, 2009) and is of great importance for Ethiopia, since it supplies the country with water for hydropower, irrigation, domestic, industrial, livestock and touristic purposes. MA-NEX deals with the 14 sub-basins of the UBNR basin: Tana, Beshilo, Welaka, Jemma, North Gojam, Muger, Guder, Finchaa, South Gojam, Anger, Didaessa, Wenbera, Dabus and Beles.

The basin topography has two significant features: the highlands in the center and eastern part of the basin, and the lowlands in the western part. There are several meteorological and hydrological stations in the basin. However, data availability is limited and records are sometimes incomplete. Furthermore, the coverage of improved water supply and sanitation facilities to the population within the basin is very low. The basin has great hydropower potential, from which however only a small percentage is exploited. Additionally, its irrigation potential accounts for a major share of the total irrigation potential in Ethiopia. Agriculture comprises the largest part of the Ethiopian economy, since it is contributing 50 percent of GDP and employing 85 percent of its population. The water use management in the basin is event driven and not subject to any sophisticated decision support system, a fact that shows the necessity of a management tool, like MA-NEX.

3. MATERIALS AND METHODS

3.1 The model HYDRONOMEAS

Throughout recent decades, different simulation-optimization models have been developed to enhance the management of water resource systems. A literature review was carried out to choose the most appropriate model for the simulation and optimization of the UBNR system. The investigated models share two main characteristics: they include the aspect of simulation and optimization, and are generalized models. The model Hydronomeas (Koutsoyiannis et al., 2001) was chosen, as the most appropriate for the study purposes.

Hydronomeas is a decision support tool for the planning and management of complex multi-reservoir multi-purpose systems, which was developed by the Department of Water Resources of the National Technical University of Athens (NTUA); it is capable of proposing management policies, which maximize the system yield as well as the overall operational benefit, and minimize the operating cost as well as the risk of decision making. The mathematical framework of
Hydronomeas is based on the parameterization-simulation-optimization scheme proposed by Nalbantis and Koutsoyiannis (1997).

### 3.2 Input data and analysis

Data collection was one of the most important, challenging and difficult tasks of the present work; data were collected by means of the international literature, but mainly during visits in Ethiopia and specifically to local authorities (Ministry of Water, Irrigation and Electricity, Abbay Basin Authorities), engineering offices (e.g. Eastern Nile Technical Regional Office), project sites, and via discussions with experts and researchers from the Addis Ababa University, Bahir Dar University, and the International Water Management Institute (IWMI). Collected data is categorized as: river discharges, water supply, irrigation and hydropower.

Most river discharge data were obtained from IWMI (Awulachew et al., 2012) and they refer to the flows in specific river locations, such as in tributaries’ confluence with the main river. Water supply data were obtained from the Ministry of Water, Irrigation and Electricity and include domestic as well as livestock and industry demands and are categorized in urban and rural water supply. Although agriculture in the UBNR basin is mainly rain-fed, the basin has great irrigation potential. The irrigation projects are divided in three categories: small (<200 ha), medium (200-3,000 ha) and large scale (>3,000 ha). By considering various criteria (investment, operation and maintenance cost, distance and difference in attitude between source and destination, slope of irrigable land) the maximum irrigable area amounts to approximately 680,000 ha of gross irrigable land (medium and large projects); this is equivalent to approximately 578,000 ha of net area, whereas average water requirements are calculated at 4,895 Mm³/year. Information on the main irrigation projects (gross and net potential area, water requirement and efficiency) was obtained from the Abbay River Master Plan Project (BCEOM, 1998). The Blue Nile’s hydropower potential accounts for more than 70,000 GWh/year; hydropower data (head, discharge capacity, installed capacity, number and type of units, annual energy production) was obtained from the Abbay Basin Authority, reports collected from the Ministry of Water, Irrigation and Electricity, project site visits and the Abbay River Master Plan Project (BCEOM, 1998). Figure 1 shows the existing and potential irrigation and hydropower projects, as well as dam sites investigated in this study. Apart from these, the Abbay Basin Authority distinguishes possible hydropower development from already identified irrigation projects. This is considered in the full development scenario of the study.

### 4. CALCULATIONS AND DISCUSSION OF RESULTS

Figure 2 shows the schematization of the UBNR system in Hydronomeas for Scenario S1 (current situation) with its essential parameters that include topology, reservoirs, hydropower and irrigation projects, tributary inflows, targets and constrains. In the calculations, water is transported from the resources i.e. reservoirs and tributary inflows, to the water users for irrigation, hydropower and environmental preservation. In optimization mode Hydronomeas defines the optimum water allocation step by step, while considering the quantities in the system, the operating rules and the targets (Koutsoyiannis et al., 2001); the time step in all calculations was equal to one month.

In order to optimize the UBNR basin of Figure 2 in Hydronomeas, targets have to be assigned for the hydropower projects (HP) Tana Beles, Finchaa and Neshe with installed capacities of 420, 134 and 97 MW, respectively, as well as the Tis Abbay 1 and 2 that operate as stand-by stations, and for the irrigation projects (IR) Koga, Finchaa and Neshe with gross irrigation areas of 6,000, 7,300 and 8,490 ha, respectively. Furthermore, constraints have to be set for the minimum-ecological/environmental outflow (EF) from Koga reservoir and Lake Tana (Tana Abbay Out) and for the reservoir outflow (Out) for hydropower production from Lake Tana (Tana Beles HP), Amerti, Finchaa and Neshe. A priority is assigned to each target and constraint, with “priority 1”
representing most important; by assigning priorities to targets and constraints, ecological, social and political factors can be taken into account directly or indirectly. Ecological factors are taken into account by setting minimum-ecological flows downstream of reservoirs aiming at river preservation and thus meeting the long-term needs of people; the minimum flow requirement serves also touristic purposes, e.g. Blue Nile Falls, and it is also linked to social factors. Social factors are also considered, by assigning different priorities to hydropower and irrigation projects, upstream and downstream projects, and projects close to and away from large cities. Furthermore, the political factor can be taken into account by setting a minimum flow at the border between Ethiopia and Sudan, i.e. to downstream countries that enhances political stability.

Figure 1. Existing and potential irrigation, hydropower and dam projects in UBNR (Yilma and Awulachew, 2009)

Figure 2 shows that there are some main conflicting targets and constraints in the system (hydropower production, irrigation demand and minimum flow requirements). The aim is to optimize all targets and thus the optimization problem involves more than one objective function to be optimized. Since the targets and constraints are conflicting, there is no “one single solution” that optimizes all objectives simultaneously. In order to deal with that issue, the Pareto optimal solutions are introduced; these are solutions in which none of the objectives can be improved without degrading the others. By restricting attention to a set of choices, that forms the so-called Pareto front, the decision maker can make trade-offs within this set, rather than considering the full range of every parameter.

Figure 3 depicts the monthly hydropower production (GWh) of the UBNR system for Scenario S1 (current situation). It is assumed that the firm hydropower is the hydropower produced at 99% of the time. Furthermore, the mean annual irrigation deficit for the given situation equals to 3.37 million m³. The irrigation deficit shows the amount of water that does not reach the irrigation projects and thus represents the failure of the given target. The irrigation project that is most affected in the current scenario is Koga, due to the fact that its reservoir is located on a tributary of the UBNR that flows into Lake Tana and thus is conflicting with the target of hydropower production at the two lake outlets. The mean annual flow at the border between Ethiopia and Sudan for the current situation equals to 48.3 billion m³.

It is worth mentioning that the two objectives are not conflicting in terms of water consumption, since hydropower is not consuming water, but due to the fact that water, which is consumed for irrigation purposes upstream, is then not available for hydropower production further downstream. The same procedure is performed for economic factors by assigning monetary values e.g. to each kWh generated from hydropower and to each crop earned from irrigation practices.
Figure 2. Schematization of the UBNR basin in Hydronomeas for Scenario S1

Figure 3. Duration curve of the monthly hydropower production for Scenario S1
5. CONCLUSIONS

From the preliminary results of the study, it is shown that only a few projects are currently operating in the UBNR basin, namely three irrigation and three hydropower projects. The basin has great irrigation and hydropower potential and since the resources allow it, it is worth implementing new projects, which will increase the life standards of the people in the region and help the development of the UBNR basin. The management and optimization of these projects is of great importance for the sustainable development of the basin, and to gain social, ecological and economic benefits and political stability in the region. The MA-NEX study is due to be completed at the end of 2017. After validating the model for Scenario S1, synthetic time series of 1,000 years are generated using the tool Castalia for the current and future development scenarios. The development scenarios are evaluated and management scenarios are developed, each with a new Pareto front. The tool Hydrognomon is used for the input data pre-processing and the results analysis.

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